Annual Report

Leibniz-Institut für Kristallzüchtung

im Forschungsverbund Berlin e.V.

2018

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Preface

Liebe Leser*innen,

das Jahr 2018 am IKZ war ohne Zweifel ein besonders spannendes, war es doch durch eine besondere Intensität der Aktivitäten auf allen wissenschaftlichen, technologischen und administrativen Ebenen gekennzeichnet.
Mit der Nominierung des wissenschaftlichen Direktors im Februar 2018 endete eine mehr als vierjährige Vakanz dieser zentralen Managementposition, so dass wir auf vielen Ebenen wichtige, oft strategische Entscheidungen zu treffen hatten. Die wichtigsten Entwicklungen im Hause finden Sie in meinem kurzen Beitrag: „Unser Institut 2018 – Vom Reagieren zum Agieren“ ausgeführt.

Besondere Aufmerksamkeit erforderte natürlich vor diesem Geschäftsbetrieb des Hauses die alle sieben Jahre erfolgende Leibniz Evaluierung des IKZ im Dezember 2018; es gibt wohl wenig Beispiele in der Leibniz Gemeinschaft, wo die Evaluierung des Hauses mit dem Startjahr des wissenschaftlichen Direktors im Institut zusammenfällt.
Wir waren somit aufgefordert, eine moderne Strategie für das Haus zu entwickeln, die die Stärken des Hauses befördert und diese zugleich an künftige nationale und internationale Wissenschafts- und Technologieentwicklungen anknüpft. Dieser Prozess war von vielen, manchmal auch intensiv geführten Diskussionen gekennzeichnet; die Etablierung einer offenen Kultur des Austausches mit dem Direktor war hierbei ohne Zweifel ein wichtiger Erfolg.
Das IKZ Institutskonzept 2019 wurde in diesem Prozess erarbeitet und legt die nachlesbare, damit nachvollziehbare Basis für die Weiterentwicklung unseres Hauses.
Als wichtiges Ergebnis möchte ich herausstellen: Das IKZ erweitert seine Strategie und das klassische Arbeitsfeld unseres Hauses „Innovationen in kristallinen Materialien“ (Züchtung / Anlagenbau / Simulation) wird verstärkt durch den künftigen Aufbau der Thematik „Innovationen durch kristalline Materialien“ (Lieferfähigkeit prototypischer Kristallkompenenten für Elektronik und Photonik).
Für beide Gebiete ist die moderne Materialforschung in unserem Haus ein wichtiges Element für den Erfolg.

Das Ergebnis der IKZ Evaluierung 2018 wird offiziell durch den Senat der Leibniz Gemeinschaft voraussichtlich im Sommer 2019 veröffentlicht. Der IKZ Geschäftsführung liegt der offizielle, noch vertrauliche Bericht vor und es darf an dieser Stelle sicher verraten werden: Wir waren erfolgreich! Die internationale Begutachtungsgruppe unterstützt in vollem Umfang unsere neue Strategie und die hierzu von uns benannten, erforderlichen Maßnahmen einschliesslich unseres Sondertatbestandes „Kristalltechnologie“.

Wir danken allen IKZ Mitarbeitern für ihr Engagement für unser Haus und wünschen allen Lesern eine interessante Lektüre des IKZ Jahresberichtes 2018 mit vielen spannenden Einblicken.

Mit freundlichen Grüßen

Thomas Schröder

Preface

Dear Readers,

the year 2018 at IKZ was without doubt particularly exciting and was characterized on all science, technology and administrative levels by a high intensity of activities. With the nomination of the new scientific director in February 2018, a more than four years period came to an end where this central management positon was vacant. In consequence, we had to take on many levels important, often strategic decisions. For the interested reader, you can find further information about central developments at IKZ in my brief report: “Our Institute 2018 – From Reacting to Acting” here in this IKZ Annual Report 2018.

Special attention was requested, besides the daily business tasks in our institute, for the upcoming IKZ Leibniz evaluation scheduled for December 2018; probably there are not many examples within the Leibniz Association that the all seven years occuring Leibniz institute evaluation coincides with the starting year of the new scientific director. We were thus confronted with the task to set up a modern, convincing strategy for our institute which promotes the strengths of our IKZ expertise and simultaneously connects this leading knowledge to upcoming opportunities within the (inter) national science / technology research & development landscape. This strategy process was characterized by many, often intensive discussions; in my opinion, the establishment of an open and transparent discussion culture of IKZ staff members with the director was thereby a central achievement of this process. The IKZ Institute Concept 2019 was elaborated and sets – as a written document – the comprehensible basis for the future development of our institute. As most important result, I would like to point out: IKZ extends its strategy and our traditional research field „innovations in crystalline materials“ (growth / plant engineering / process simulation) will be extended by building up the future research topic „innovations by crystalline materials“ (prototyping capability of crystal components for electronics and photonics). In both cases, a modern materials science at IKZ is a key asset for success.

The result of the IKZ Leibniz evaluation 2018 will probably be published by the Leibniz Senate in summer 2019. IKZ management received an official, yet unpublished version of the IKZ evaluation report. Without doubt, it is allowed to state here: We were successful! The international review board fully supports our new strategy and explicitly endorses all outlined action points to make this strategy successful (including our extraordinary item of expenditure “Crystal Technology”).

We thank all IKZ staff members for their dedicated work for the institute in 2018 and we wish all readers many interesting insights by reading our IKZ Annual Report 2018.

Yours Sincerely,

Thomas Schröder

Content

The Institute

Photo: Lothar M. Peter © IKZ

Leibniz-Institut für Kristallzüchtung im Forschungsverbund Berlin e.V.

Founded 1992
Part of Forschungsverbund Berlin e.V.
Member of the Leibniz Association

The Institute

Das Leibniz-Institut für Kristallzüchtung (IKZ)

ist eine in Europa einzigartige Forschungs- und Service-Einrichtung, die sich experimentell und theoretisch mit den wissenschaftlich-technischen Grundlagen des Wachstums, der Züchtung, der Bearbeitung und der physikalisch-chemischen Charakterisierung von kristallinen Festkörpern beschäftigt. Dies reicht von der Grundlagenforschung bis hin zum Vorfeld industrieller Entwicklung. Die zurzeit entwickelten Materialien finden vorwiegend Verwendung in der Mikro-, Opto- und Leistungselektronik, der Photovoltaik, in Optik und Lasertechnik, in der Sensorik und Akustoelektronik.

Das Forschungsgebiet des IKZ umfasst Volumenkristalle, kristalline Schichten und Nanostrukturen sowie die Entwicklung von materialübergreifenden Kristallzüchtungstechnologien.

Arbeitsschwerpunkte des Institutes sind

- *Entwicklung von Züchtungs-, Bearbeitungs- und Charakterisierungsverfahren für Massivkristalle sowie kristalline Gebilde mit Abmessungen im Mikro- und Nanometerbereich sowie von materialübergreifenden Kristallzüchtungstechnologien*
- *Bereitstellung von Kristallen mit besonderen Spezifikationen für Forschungs- und Entwicklungszwecke*
- *Modellierung und Erforschung der Kristallwachstums- und Kristallzüchtungsprozesse*
- *Experimentelle und theoretische Untersuchungen zum Einfluss von Prozessparametern auf Kristallzüchtungsvorgänge und Kristallqualität*
- *Erforschung von Verfahren zur Kristallbearbeitung und der dabei ablaufenden Vorgänge*
- *Physikalisch-chemische Charakterisierung kristalliner Festkörper und Entwicklung geeigneter Methoden bis hin zur atomaren Ebene; Aufklärung des Zusammenhangs zwischen Struktur und Eigenschaften kristalliner Materialien*
- *Entwicklung und Bau von Anlagenkomponenten für die Züchtung, Bearbeitung und Charakterisierung von Kristallen*

Als Züchtungsverfahren werden Methoden der Züchtung aus der Schmelze, aus der Lösung, aus der Gasphase und davon abgeleitete Verfahren zur Herstellung kristalliner Schichten verwendet.

The Leibniz-Institut für Kristallzüchtung

is a unique research and service institute in Europe, which is theoretically and experimentally investigating the scientific-technical fundamentals of crystal growth, processing and physico-chemical characterisation of crystalline solids. This ranges from explorative fundamental research to pre-industrial development. The materials presently in development are of fundamental importance in micro-, opto- and power electronics, in photovoltaics, in opto- and laser technology, in acousto-electronics and sensor technology as well as for fundamental research.

The research activities of the institute include bulk single crystals as well as crystalline layers and nanostructures, but also the development of comprehensive crystal growth technologies.

The research and service tasks of the institute include

- Development of technologies for growth, processing and characterization of bulk crystals and of crystalline structures with dimensions in the micro- and nanometer range and of comprehensive growth technologies
- Supply of crystals with non-standard specifications for research and development purposes
- Modelling and investigation of crystal growth processes
- Experimental and theoretical investigations of the influence of process parameters on crystal growth processes and crystal quality
- Development of technologies for the chemo-mechanical processing of crystalline samples and scientific investigation of related processes
- Physico-chemical characterisation of crystalline solids and development of suitable methods; investigation of the correlation between crystalline structures and properties
- Development and construction of components for growth, processing and characterization of crystals

Crystals are grown from the melt, from solutions and from the vapour phase and new techniques are developed and improved for the preparation of crystalline layers.

The Institute

Durch die mögliche Synergie zwischen Volumenkristallzüchtung und der Abscheidung von Schichten verfügt das Institut über ideale Voraussetzung zur Herstellung von Substrat/Schicht-Kombinationen mit maßgeschneiderten Eigenschaften.

Materialien

- *Halbleiter mit großem Bandabstand (Oxide, Aluminiumnitrid) für Hochtemperatur-, Leistungs- und Optoelektronik*
- *Oxidische und fluoridische Kristalle für Lasertechnik, Optik, Sensorik und Akustoelektronik*
- *Silizium-Kristalle für Mikro- und Leistungselektronik und Photovoltaik*
- *Silizium/Germanium Kristalle für Strahlungsdetektoren und Beugungsgitter, kristalline Si/Ge-Schichten für thermoelektrische Anwendungen*
- *Silizium Schichten auf amorphen Unterlagen für die Photovoltaik*
- *Ferroelektrische und halbleitende Oxidschichten für die Mikro- und Leistungselektronik, Sensoren und Datenspeicher*

Das IKZ als familienfreundlicher Arbeitgeber

Das IKZ möchte seinen Beschäftigten ein offenes, kooperatives und familienfreundliches Arbeitsumfeld bieten. Das Institut unterstützt daher seine Mitarbeiterinnen und Mitarbeiter bei der Vereinbarkeit von Arbeit und Familie, z.B. durch flexible Regelungen zur täglichen Arbeitszeit oder durch variable Regelungen zu Teil- und Vollzeitbeschäftigung.

Seit 2015 ist das Institut zertifiziert durch das audit berufundfamilie. Damit verbunden hat es Ziele einer familienbewussten Personalpolitik definiert, die in den folgenden drei Jahren umgesetzt wurden. Das Institut wurde in 2018 zum zweiten Mal auditiert. Das Audit steht unter der Schirmherrschaft der Bundesfamilienministerin und des Bundeswirtschaftsministers, nähere Informationen finden sich unter www.beruf-und-familie.de

With the combination of bulk crystal growth and layer deposition, the institute possesses ideal conditions to produce customized substrate/layer-combinations.

Materials presently in development

- Wide band gap semiconductors (aluminium nitride, oxides) for high temperature, power- and optoelectronics
- Oxide and fluoride crystals for acousto-electronics, laser-, opto- and sensor technology
- Silicon for power electronics and photovoltaics
- Gallium arsenide for wireless communication and in high-frequency technology
- Silicon/germanium-crystals for radiation detectors and diffraction gratings, crystalline Si/Ge layers for thermoelectric devices
- Silicon layers an amorphous substrates for photovoltaics
- Ferroelectric and semiconducting oxide layers for micro- and power electronics, sensor applications or data storage

IKZ as family-friendly employer

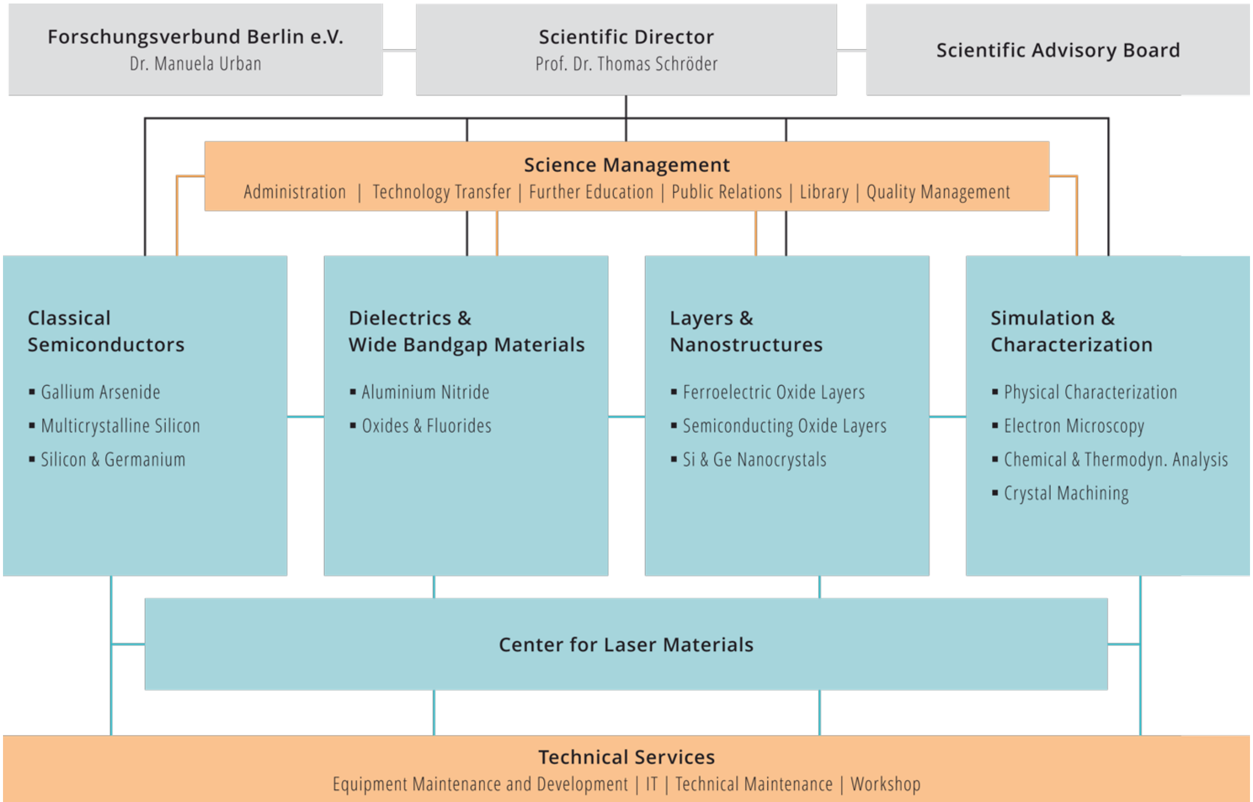
The institute intends to create a co-operative and open working environment for all employees. It places special emphasis on the reconcilability of job and family, offering flexible working time models as well as full or part-time employments. In 2015, the institute has been awarded the audit berufundfamilie certificate for its family-friendly human resources policy. During the following three years, we have been implementing the objectives defined in this process. The audit was conducted for the second time in 2018.

The certificate is issued under the auspices of the German Federal Minister for Families and the German Federal Economics Minister. More information is available under www.beruf-und-familie.de

Zertifikat seit 2015
audit berufundfamilie

The Institute

Organigramm Organisation Chart



Wissenschaftlicher Beirat 2018
Scientific Advisory Board 2018

apl. Prof. Dr.-Ing. Michael Heuken (until October, chair)
Faculty of Electrical Engineering and Information Technology, RWTH Aachen University & Vice President of Research and Development AIXTRON SE, Aachen

Dr. Martin Strassburg (chair)
Osram Opto Semiconductors GmbH, Regensburg

Prof. Dr. Saskia Fischer (vice chair)
Department of Physics, Humboldt-Universität zu Berlin

Dr. Hubert Aulich
SC Sustainable Concepts GmbH, Erfurt

Dr. Martin Frank
IBM, Thomas J. Watson Research Center, NY, USA

Prof. Dr. Michael Kneissl
Institute of Solid State Physics, Technische Universität Berlin

Prof. Dr. Darrell Schlom
Cornell University, NY, USA

Dr. Georg Schwalb
Siltronic AG, Burghausen

Prof. Dr. Thomas Südmeyer
Université de Neuchâtel, Schweiz

Prof. Dr. Götz Seibold
Brandenburgische Technische Universität Cottbus-Senftenberg

Representative of the State of Berlin

Dr. Björn Maul
Senatsverwaltung für Wirtschaft, Technologie und Forschung, SenWTF Berlin

Representative of the Federal Republic

Dr. Tim Schneider
Bundesministerium für Bildung und Forschung, BMBF Bonn / Berlin

Unser Institut 2018 – Vom Reagieren zum Agieren
Our Institute 2018 – From Reacting to Acting

Sicher intensiver als in den vergangenen Jahren war das Jahr 2018 von Veränderungen im Institut geprägt. Mit der Berufung des wissenschaftlichen IKZ Direktors ging eine mehr als vierjährige Vakanz dieser Position zu Ende. Infolge der langen Interimsphase stauten sich sowohl auf der Ebene der administrativen / technischen Dienste als auch der wissenschaftlichen Abteilungen wichtige, oftmals strategische Entscheidungen auf. Es galt also erst einmal den ins Direktorenzimmer hereinbrechenden „Tsunami" der nicht erledigten Dinge möglichst elegant zu „surfen", sprich dringend anstehenden Anliegen zeitnah abzuarbeiten.

Probably more intensive than in recent years, the year 2018 was characterized by changes in our institute. With the nomination of the new scientific director in February 2018, a more than four years long period came to an end where this central management position was vacant. Based on this extraordinarily long interim phase, we had to face impressively long "To do" lists on administrative / technical as well as scientific levels, including often strategic decisions on staff and invests. In other words, we had to first "surf the tsunami" of undecided issues at our institutes, breaking down in the first weeks and months on the director office.

Float Zone Anlage des IKZ bei PVA Tepla in Jena bei der technischen Diskussion

IKZ Float Zone plant at PVA Tepla in Jena at the technical discussion

Administrative & technical services

On the administrative level, the personnel division requested staff decisions for all areas of our institute. In close collaboration with IKZ´s works council, whose members we wish to thank on this occasion for their dedicated and team oriented work, the institute could hire on permanent contract basis a number of highly qualified staff members and bond in this way important expertise to our institute. Simultaneously, in order to keep our mission on the qualification of skilled experts for future labour markets active, we hired a new generation of PhD students, which deserve today our full support for carrying out their graduation studies at our institute. Strategic decisions were required in particular in the area of equipment investments. The highlight in 2018 is certainly given by our positive decision on realizing the heavily delayed invest opportunity based on a specific extraordinary item of expenditure from 2012/2013, namely to purchase an up to 8" Float Zone (FZ) Si crystal growth tool. This invest project, given the dimensions of the tool, is among the most complex projects currently taking place in our institute and many colleagues are involved. By this research and development tool, IKZ strengthens the position of its excellent FZ group by closing the gap towards industry. The goal is to support European / German industry to set up the high quality FZ materials basis for the booming market of Si power electronics, as currently in worldwide demand by energy transition programs for the decarbonization of our economies.

The Institute

Administrative & technische Dienste

Auf der Ebene der Verwaltung waren insbesondere im Bereich Personal Entscheidungen für alle Bereiche des Hauses zu treffen. Gemeinsam mit dem IKZ Betriebsrat, dessen Mitgliedern an dieser Stelle für ein konstruktives Miteinander und seine Arbeit gedankt sei, konnte das Institut eine Reihe wertvoller, hochqualifizierter Mitarbeiter binden und damit wichtige Expertise im Hause halten und verstetigen. Gleichzeitig galt es, die Belegschaft zu verjüngen und den Qualifizierungscharakter des Institutes sichtbar zu halten. Es gelang uns, eine neue Generation von Promovierenden für das Haus zu gewinnen, denen nun unsere Unterstützung für ihre Qualifizierungsarbeiten gilt. Strategische Entscheidungen waren ebenfalls im Bereich der Investitionen zu treffen. Hier ragt insbesondere die Freigabe des lange verzögerten, spezifischen Sondertatbestandes heraus, nämlich die Beschaffung einer 8" Float Zone (FZ) Si Kristallzuchtanlage. Dieses Installationsprojekt ist aufgrund der Größe der Anlage äußerst komplex und viele Kollegen sind hier involviert; mit dieser Investition schließt das Institut mit seiner exzellenten FZ Expertise zur Industrie auf. Gemeinsame Forschungs- und Entwicklungsprojekte im Bereich der Materialbasis für die boomende Si Leistungselektronik stehen hier im Fokus, wie sie etwa für die Energiewende benötigt wird.

Die Technischen Dienste starteten ferner ein intensives Modernisierungsprogramm zur Neuordnung der Labore, um experimentelle Versuchsbedingungen an vielen Orten im Hause durchgreifend zu optimieren. Teilweise wurde in der Vergangenheit Laborfläche mit teurer Medienversorgung mangels Alternative als Bürofläche genutzt worden. Um diese Fehlentwicklung zu korrigieren, wurde der Umzug der IT-Gruppe des Forschungsverbunds aus dem IKZ zur Rudower Chaussee mit der Gemeinsamen Verwaltung verhandelt und durchgeführt. Das IKZ gewann auf diese Weise zusätzliche Büroräume für seine gestiegene Mitarbeiterzahl. Basierend auf einem BMBF Verwertungsprojekt wurde die Basis für ein kontinuierlich arbeitendes Public Relation Team geschaffen, um die Kommunikation innerhalb des Hauses (insbesondere mittels eines monatlichen IKZ Newsletters) und die Darstellung des Hauses nach außen (insbesondere mittels Pressemitteilungen) zu professionalisieren. Die Lange Nacht der Wissenschaft 2018 war eine zentrale Veranstaltung und wurde mit Hilfe von vielen Kollegen sehr erfolgreich gestaltet; wir konnten den über 1000 Besuchern das hohe Potential unserer Forschungsarbeit zeigen, um öffentliche Aufmerksamkeit für Wissenschaft & Technologie zu befördern.

Furthermore, the technical services started an intensive program on the modernization of our laboratories to substantially improve in many places experimental work conditions. In the past, due to missing space, some laboratories with expensive supply installations for scientific instruments were used as office space. To correct this development, we triggered the move of our IT colleagues of the Forschungsverbund from IKZ to the joint administration in the Rudower Chaussee so that IKZ gained by this step additional office space for its increasing staff number. Based on a former BMBF transfer project, we established in 2018 a continuously working puplic relation team at IKZ to improve communication inside (in particular monthly IKZ newsletter) and outside (in particular press releases) our institute. The "Long Night of Sciences 2018" was a major event and successfully put in place by many helping hands of our staff; more than 1000 visitors demonstrate the high potential of our research activities to create public awareness for science & technology.

Aufbau der neuen Oxidzüchtungshalle am IKZ während und nach der Installation

Set-up of the new oxide growth lab during and after installation

Wissenschaftliche Abteilungen

Im Bereich der Wissenschaftlichen Abteilungen sind viele Entwicklungen aus dem Jahre nennenswert, doch seien aus diesen nur die folgenden beispielhaft genannt:

Die Thematik Nanostrukturen & Schichten krönte ihre langjährigen Arbeiten 2018 im Bereich der epitaktischen, ferroelektrischen Schichten durch die Verleihung des Marthe–Vogt Preises des FVB an Frau Dr. Dorothee Braun für ihre exzellente Doktorarbeit auf diesem Gebiet; diese Verleihung erfolgte erstmalig an eine IKZ Doktorandin seit der Einführung des Preises. Zum weiteren Ausbau dieser Arbeiten erfolgt der Aufbau eines EFRE-geförderten Applikationslabors für die Oxidelektronik. Ein schönes Ergebnis ist im Jahre 2018 die Einwerbung eines Leibniz-Wettbewerb Projektes zu ^{28}Si Schichten für Quantentechnologien; dieser Erfolg legt den Grundstein für die thematische Neuausrichtung der SiGe Schichtaktivitäten am IKZ unter Nutzung der im Hause verfügbaren Expertise zu isotopenreinen Si und Ge Kristallen.

^{28}Si-Kristall für die Neudefinition des Kilogramms
^{28}Si for the new definition of the kilogram

Scientific departments

Many activities and achievements took place in our scientific departments in 2018, worthwhile to be mentioned. Please allow me to select among these the following few ones to give a short overview only:

The colleagues in the area of Nanostructures & Layers, after many years of high level research & education activities, received the positive message that the former PhD student Dr. Dorothee Braun was awarded the FVB Marthe-Vogt Price 2018 for her excellent PhD thesis on strain-engineered, ferroelectric thin layer systems. Since the introduction of this scientific price in the FVB, it is the very first time that a female PhD student from IKZ was selected. To further promote these research activities to device levels, IKZ is currently setting up an application laboratory for oxide electronics, funded by EFRE financial means. A further nice result in 2018 is given by the funding of a new science project on 28Si layer systems for future quantum technologies within the Leibniz Competition. This success is particularly important because it is a central milestone to redirect IKZ´s SiGe nanostructure & thin film activities towards the upcoming quantum materials topics in Germany and Europe, benefiting strongly in a synergetic way from IKZ´s in-house expertise on isotope pure Si & Ge crystals.

Volume crystals are the “unique selling point” of IKZ and scientific results were achieved here in 2018 which received international acknowledgement. A clearly, extraordinary achievement was the successful end of the long-term Avogadro & Kilogram – projects, carried out in particular in close collaboration with the German “Physikalisch Technische Bundesanstalt (PTB)” for the new definition of the kilogram. Our crystal growth colleagues at IKZ were able to achieve in many years of challenging research work the high precision needed to redefine the kilogram on the basis of isotope pure, defect free 28Si crystals. Since November 2018 we know that these IKZ crystals – besides the alternative “Kibble balance” approach – form the basis for the new definition of the kilogram, a result which will be put to practice on the World Metrology Day on 20th May 2019. In the area of oxide crystals, our work on the Czochralski growth of gallium oxide creates worldwide attention. These materials studies benefit from an increasing interest and need for a new power semiconductor material in the high performing sector. Given our internal collaboration by volume growth & thin film deposition plus materials science, IKZ became over the last years an international “hot spot” for gallium oxide research & development.

The Institute

Das Themenfeld Volumenkristalle ist der „unique selling point“ des Hauses und hier wurden Ergebnisse erzielt, die weltweit Beachtung fanden. Herausstechend ist der erfolgreiche Abschluss der langjährigen Avogadro & Kilogramm-Projekte gemeinsam mit der Physikalisch Technischen Bundesanstalt (PTB) zur Neudefinition des Kilogramms. Die Züchter am IKZ konnten im Bereich der isotopenreinen ^{28}Si Kristalle in langjähriger Arbeit die gebotene Genauigkeit erzielen. Seit November 2018 ist gewiss, dass diese IKZ Kristalle – neben dem alternativen Ansatz der Kibble Waage – die Grundlage für die Neudefinition des Kilogramms ab dem Weltjahrestag der Metrologie (20.Mai 2019) bilden. Im Bereich der Oxidkristalle sind die Arbeiten zur Czochralski-Züchtung von Galliumoxid hervorzuheben, die das IKZ international ins Rampenlicht rücken aufgrund des weltweiten Interesses an diesem Material für die Leistungselektronik. Durch die hausinterne Kombination aus Volumenkristallzüchtung, Dünnfilmepitaxie und Materialcharakterisierung hat das IKZ sich hier international einen herausragenden Platz erarbeitet.

Die wichtige Schlüsselkompetenz Materialwissenschaft bearbeitet die experimentelle Charakterisierung sowie die fundamentale Beschreibung kristalliner Materialsysteme. Die Leibniz Gemeinschaft betrachtet die Vernetzung mit Universitäten als zentralen Baustein ihrer Strategie und ein solches Vorhaben wird von unseren Kollegen hier in diesem Bereich aktiv umgesetzt, nämlich – gemeinsam mit dem Paul Drude Institut (PDI) – mittels des Leibniz Science Campus „Grafox (Growth and fundamentals of oxides for electronic applications)“. Weiterhin ist die strukturelle Charakterisierung der kristallinen Materialsysteme eine tragende Säule für diese Arbeiten, so dass hier von uns weiter in den Ausbau einer modernen Elektronenmikroskopie und Röntgendiffraktometrie investiert wurde. Die fundamentale Beschreibung kristalliner Materialsysteme fokussiert sich bis dato auf die numerische Simulation von Züchtungsanlagen und -prozessen, gemeinsam mit Züchtern und dem Anlagenbau. Themen der künstlichen Intelligenz wie neuronale Netzwerke, die in den letzten Jahren begonnen wurden, werden künftig einen Schwerpunkt bilden; darüber hinaus strebt das Institut an, die Festkörpertheorie im Hause zu stärken, indem wir uns stärker mit dem Institut der Physik der Humboldt Universität vernetzen.

The central key expertise on materials science at our institute focusses on the experimental characterization and fundamental description of crystal properties and growth phenomena. The Leibniz Association considers activities to set up bridges towards university partners of central importance for its strategy and such an activity is put in place here, namely – in close collaboration with Paul-Drude-Institut (PDI) – by the Leibniz Science Campus “Grafox (Growth & fundamentals of oxides for electronic applications)”. Certainly, advanced methods for structure characterization of crystalline materials is a central need at IKZ and we therefore invested further in 2018 in modern electron microscopy as well as X-ray diffraction methods. Traditionally, the fundamental description of growth phenomena at IKZ is focused, in close collaboration with experimental crystal growth and plant engineering activities, on the numerical simulation of fluid dynamic processes. In future, we will shift this focus further to the upcoming topic of artificial intelligence by neural networks, on which research activities had already begun in the last years. Furthermore, we wish to strengthen the role of solid state theory in our institute by linking our activities stronger to the Institute of Physics at the Humboldt Universität zu Berlin.

The European and national R & D landscape offers in the field of electronic & photonic key technologies a wide range of opportunities for IKZ´s high performance crystal systems. This includes also the perspective to promote by focussed application science activities the important transfer of innovative research results to society. For this purpose, IKZ needs to move a step further and develop in addition to the well-established skills for research materials a new quality level in the delivery of prototyping materials. First steps were initiated in this direction in the past: The BMBF funded ´Zentrum für Lasermaterialien (ZLM) is meanwhile installed as a structural unit within IKZ´s strategy. It is the very aim of our ZLM to act as ´one stop shop` for national and international R & D partners in the area of visible and infrared lasers based on rare earth doped oxide and fluoride crystals. Besides crystal growth, increasing precision in crystal preparation equipment and skills are of central importance for success here. This is not only true for optical crystal components but holds equally true also for innovative epitaxy substrates in electronics. An example is given here by aluminium nitride (AlN) epitaxy substrates: IKZ successfully applied in 2018 for further third party funding within the national “Advanced UV for Life“ consortium and, in addition, we heavily invested IKZ funds in the improvement of our growth equipment for the success of this important topic.

The Institute

Die europäische und nationale F & E Landschaft bietet im Bereich der elektronischen & photonischen Schlüsseltechnologien vielfältige Möglichkeiten für die Hochleistungs-Kristallsysteme des IKZ. Dies beinhaltet auch die Perspektive, mittels fokussierter Anwendungsforschung den wichtigen Transfer in die Gesellschaft zu befördern. Hierzu muss das IKZ strategisch einen Schritt weiter gehen und neben den im Hause etablierten Fähigkeiten zu Forschungsmaterialien eine neue Qualität zur Lieferfähigkeit in der Prototypenforschung aufbauen. Erste Schritte wurden im Hause unternommen und an dieser Stelle ist das Zentrum für Lasermaterialien (ZLM) zu nennen. Dieses wurde mittels einer BMBF-Förderung initiiert und nun in der Strategie des Hauses als Struktureinheit verankert. Das ZLM hat den Anspruch, nationaler Ansprechpartner für sichtbare und infrarote Festkörperlaserkristalle auf der Basis von Seltenerd-dotierten Oxid- und Fluoridkristallen zu sein. Neben der Züchtung und Charakterisierung spielen gestiegene Anforderungen in der Kristallpräparation eine entscheidende Rolle für den Erfolg. Dies gilt neben optischen Kristallkomponenten für die Photonik ebenso für innovative Epitaxie-Substrate in der Elektronik. Ein Beispiel dazu stellen Aluminiumnitrid (AlN) Epitaxie-Substrate dar; das IKZ hat in 2018 ein weiteres Förderprojekt in dem nationalen „Advanced UV for Life“ Konsortium eingeworben und investierte 2018 weitere Hausmittel in die Züchtungstechnik für den Erfolg dieser wichtigen Thematik.

AlN Sublimationslabor
AlN sublimation lab

Leibniz Evaluierung 2018

Alle diese Aktivitäten liefen parallel zu den laufenden Vorbereitungen zur alle sieben Jahre erfolgenden Leibniz Evaluierung des IKZ, die das Institut mit der Beantragung eines kleinen strategischen Sondertatbestandes „Kristalltechnologie“ verband. Letzterer zielt darauf ab, unter Einbeziehung aller Bereiche des IKZ für ausgewählte Materialien eine stabile und zuverlässige Prototypenlieferfähigkeit zu ermöglichen. Wir wollen das Haus mit dieser Maßnahme anschlussfähig machen für gemeinsame Forschungsprojekte mit externen Partnern – insbesondere Institute mit Technologieplattformen (z.B. aus der Forschungsfabrik Mikroelektronik Deutschland) und Industrieunternehmen – zur mittel- und langfristigen elektronischen und photonischen Technologieentwicklung.
Mit anderen Worten: Wir gehen einen Schritt weiter und erweitern unsere Strategie!

Leibniz evaluation 2018

These activities were carried out in parallel to the intensive preparation of our institute for the IKZ Leibniz evaluation, which takes place all seven years. We combined the IKZ Leibniz evaluation this time with the request for an extraordinary item of expenditure called “Crystal Technology”. The goal of this research initiative “Crystal Technology” is the reliable evaluation and benchmarking of innovative crystalline materials for future electronic & photonic applications. Here, we wish to make use of IKZ´s full added value chain to achieve for a carefully selected number of crystalline materials a stable delivery chain for electronic & photonic prototyping purposes. By achieving this capability, we will be able to interconnect our institute with the help of common R & D projects to external partners with technology platforms, e.g. research institutes within the German “Forschungsfabrik Mikroelektronik Deutschland” or directly to industry companies. In other words: We move one step ahead and extend our strategy!

The Institute

Traditionell ist das IKZ weltweit renommiert mit seiner Expertise zu Innovationen in kristallinen Materialien, die neben der hochqualitativen Züchtungsexpertise (inkl. Anlagenkonstruktion und numerischer Simulation) auch eine in den letzten Jahren modern aufgestellte, wissenschaftlich ausgerichtete Materialcharakterisierung einschließt. Künftig wollen wir diese Stärken des Hauses nutzen, um auch – wie oben durch den Sondertatbestand „Kristalltechnologie“ dargestellt – mit Partnern Innovationen durch kristalline Materialien voranzutreiben. Damit antworten wir auf wichtige Impulse aus Wirtschaft und Politik, das Haus als wesentliche Größe im Materialbereich der europäischen Technologiesouveränität zu positionieren. Ausführlich stellten wir diese Strategie im IKZ Institutskonzept 2019 dar, das natürlich kein statisches Dokument darstellt, sondern in den folgenden Jahren ständig gemäß den aktuellen Entwicklungen angefasst und angepasst werden muss.

Die Begehung des IKZ durch eine internationale Expertenkommission fand im Dezember 2018 statt und das offizielle Ergebnis wurde im Sommer 2019 veröffentlicht. Mittlerweile liegt der IKZ-Geschäftsführung der offizielle, aber noch vertrauliche Leibniz Evaluierungsbericht vor. Es darf sicherlich an dieser Stelle verraten werden, dass das IKZ die Leibniz Evaluierung 2018 erfolgreich bestanden hat und die Gutachtergruppe diese neue IKZ Strategie und den Sondertatbestand Kristalltechnologie vollumfänglich unterstützt. Die IKZ-Geschäftsführung wird nun alle notwendigen Schritte zur weiteren Umsetzung mit Partnern aus Politik und Verwaltung ergreifen und ich freue mich drauf – nach den vielen Notwendigkeiten des Reagierens – nun aktiv auf Agieren umzustellen, um unsere wichtigen F & E „Communities“ durch die europäische Flaggschiffrolle unseres Institutes zu unterstützen.

Wir danken allen Mitarbeitern des IKZ für ihren Beitrag in 2018 zu diesen spannenden Entwicklungen.

Thomas Schröder

Traditionally, IKZ´s worldwide scientific & technological reputation is based on innovations in crystalline materials. Our high quality expertise in crystal growth (including plant engineering and process simulation) is complemented by a modern material characterization platform with a strong academic basis. In future, we wish to use these strengths of our institute to promote – as sketched above by the extraordinary item of expenditure “Crystal Technology” – with partners also innovations by crystalline materials. By this action, we respond to important impulses by economy and politics to position our institute as a key player in materials to enable Europe´s future technology sovereignty. The IKZ Institute Concept 2019 explains this strategy in detail; certainly, this is not a static document but will be updated and adjusted over the years to include latest developments and trends.

IKZ was visited by the international Leibniz review board in December 2018 and the official decision was published published by the Leibniz Senate in summer 2019. Meanwhile, the IKZ management received the official but still unpublished IKZ Leibniz evaluation report. Surely, it is allowed to state here that IKZ successfully passed the Leibniz evaluation 2018; even more, the international review board explicitly endorses the new IKZ strategy and fully supports the funding of the extraordinary item of expenditure “Crystal Technology”. IKZ’s management will take all necessary steps together with partners from politics and administration to put this strategy and invest request in practice. In consequence, after many weeks of reacting on requests from the past, I am looking now forward to start acting on shaping IKZ´s European flagship role for our R & D communities.

We thank all our staff members for their contributions on these exciting developments in 2018.

Thomas Schröder

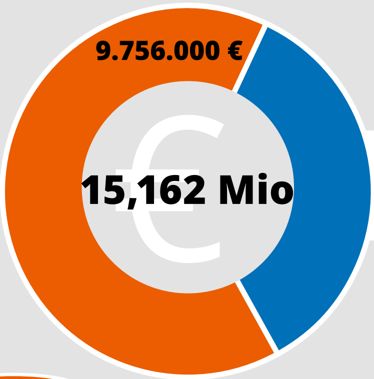
The Institute

2018 in Zahlen
2018 in figures

Budget

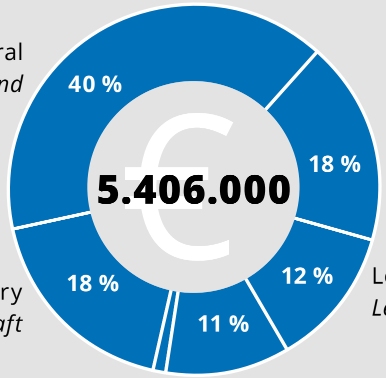
Gesamt
Total

Institutional funding
Institutionelle Förderung



5.406.000 €
Third-party funding
Drittmittelförderung

Drittmittelförderung
Third-party funding



Lehre
Education

3

Master and Bachelor projects completed.
Abgeschlossene Master- und Bachelorarbeiten.

22

Running PhD projects (as of 31.12.2018)
2 PhD theses were defended.
Laufende Promotionsprojekte (zum 31.12.2018).
2 Dissertationen wurden verteidigt.

Publikationen
Publications

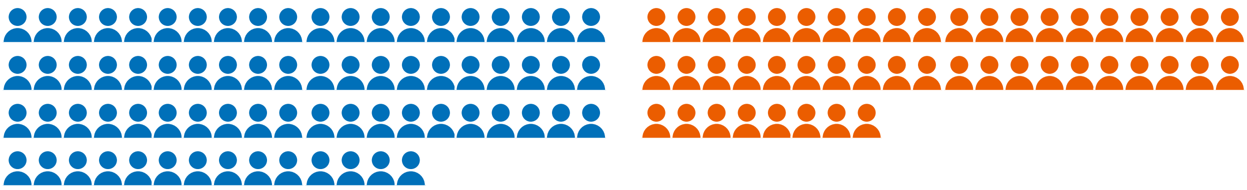
74

Published peer-review scientific articles.

Artikel in referierten (peer-review) Journalen.

Personal gesamt
Staff total*

122

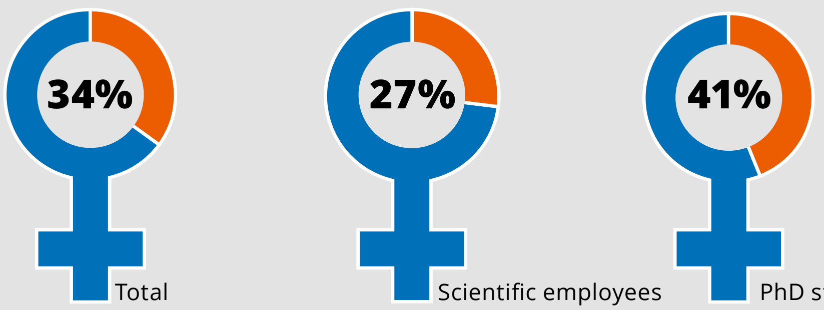


61 % Scientific employees
Wissenschaftliche Mitarbeiter/innen

39% Infrastructure personnel
Infrastrukturpersonal

* not including Bachelor-/Master students and student assistants.
ohne Bachelor-/Masterstudenten und studentische Hilfskräfte.

Frauenanteil
Female proportion

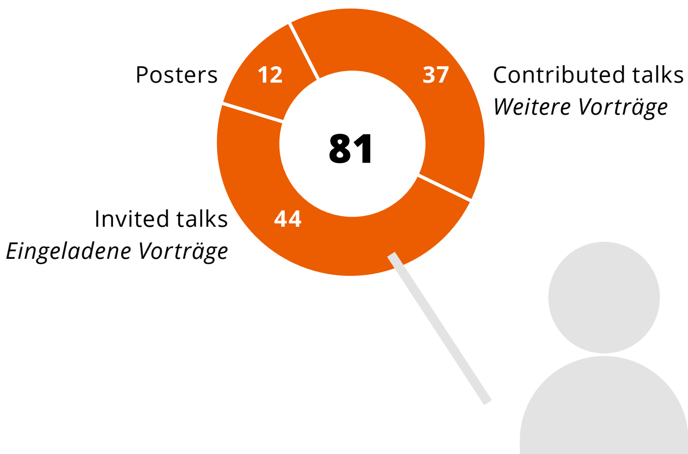


Total
Gesamt

Scientific employees
Wissenschaftliche Mitarbeiterinnen

PhD students
Doktorandinnen

Beiträge auf internationalen Konferenzen
Contributions in international conferences



Kommunikation und Öffentlichkeitsarbeit am IKZ 2018

IKZ communication and public relation work in 2018

Die Presse- und Öffentlichkeitsarbeit am IKZ wurde im Jahr 2018 neu ausgerichtet. Ziel der Public Relation (PR) ist es, den internen Informationsfluss unter den Mitarbeitern zu verbessern und die externe Kommunikation mit der Öffentlichkeit zu intensivieren.

Insgesamt empfing das IKZ in diesem Jahr annähernd 1800 Gäste von Schulen, Universitäten, Partnern und Interessierten im Rahmen von Institutsbesichtigungen / Führungen. Unter anderem wurde die Lange Nacht der Wissenschaften im Juni von den IKZ Mitarbeitern genutzt, um dem breiten Publikum die aktuelle Forschung zu präsentieren. Im September lud das IKZ zur Sommerschule mit dem Thema „Solid-State Lasers“. Die Teilnehmenden, zur Hälfte Nachwuchsforscher und Studenten von externen Einrichtungen, waren teilweise aus dem Ausland angereist – ein Beleg für die Aktualität dieser erst in den letzten Jahren am IKZ etablierten Forschungsthematik.

Im Bereich der Nachwuchsförderung bot das IKZ Schülerinnen und Schülern, sowie Studierenden verschiedene Möglichkeiten, ihr Interesse für technische Berufe, insbesondere im physikalischen Bereich, zu entdecken. Neben Veranstaltungsformaten wie dem „Girls´Day - Girls in Science and Technology“ beteiligte sich das Institut am Programm „CyberMentor“, bei dem junge, technisch interessierte Mädchen von Mitarbeiterinnen des Instituts ein Jahr lang online begleitet werden, z.B. während der Studienwahl. Auch bot das Format „Get Connected“ den Studierenden die Möglichkeit, sich über unser Institut zu informieren. Das IKZ nutzte die Gelegenheit, sich in Kurzvorträgen zu präsentieren und den Studierenden einen Einblick in die wissenschaftliche Arbeit an unserem Institut zu geben. Einen ähnlichen Service bot das Institut auf der Konferenz „I, Scientist“ an. Junge Wissenschaftlerinnen konnten sich an einem Informationsstand des IKZ über aktuelle Karrieremöglichkeiten informieren. Darüber hinaus gab das Schüler-Kristallographie-Labor in Zusammenarbeit mit dem wissenschaftlich orientierten Oberstufenzentrum Lise-Meitner-Schule in Berlin den Schülerinnen und Schülern einen Einblick in die Kristallzüchtung und Kristallographie (www.kristall-lab.de).

Press and public relations work at the IKZ was newly organized in 2018. The aim is to improve internal information flow among staff and intensify external communication with the public.

This year, the IKZ welcomed a total of almost 1800 guests from schools, universities, partners and other interested parties on guided tours through the institute. The IKZ staff also used the Long Night of Science in June to present current research to the general public. In September, the IKZ hosted a Summer School on the topic “Solid-State Lasers”. Some of the participants came from abroad, half of whom were young researchers and students from external institutions – proving the up-to-dateness of this research topic, which was only established at the IKZ in recent years.

In the area of promoting young talents, the IKZ offered various opportunities for pupils and students to inform them about technical professions, especially in the fields of natural sciences. In addition to event formats such as “Girls´Day - Girls in Science and Technology” - the institute participated in the “CyberMentor” programme, in which young, technically interested girls are accompanied online by employees of our institute for one year, e.g. during the choice of studies. The “Get Connected” format also offered students the chance to inform themselves about our institute. The IKZ used this opportunity to present itself in short lectures and gave students insights into the scientific work at our institute. The institute offered a similar service at the conference “I, Scientist”. Young female scientists could inform themselves about current career opportunities at the IKZ by visiting an IKZ information booth. Furthermore, the Lise-Lab Kristallographie in cooperation with the scientifically oriented upper school center Lise-Meitner-Schule in Berlin gave students an insight into crystal growing and crystallography (www.kristall-lab.de).

The Institute

„Was genau geschieht eigentlich beim Aufwachsen dünner Schichten?“ IKZ Wissenschaftler in der Erklärung beim Girls´Day 2018

“What actually happens when thin layers are growing?” IKZ scientist in discussion with young pupils at Girls´Day 2018

Ein weiteres Highlight 2018: Die Verleihung des Marthe-Vogt-Preises an die IKZ-Wissenschaftlerin Dorothee Braun. Für ihre mit Auszeichnung abgeschlossene Dissertation im Bereich der Entwicklung von ferroelektrischen Materialien wurde Frau Braun vom Forschungsverbund Berlin e.V. (FVB) mit dem begehrten Preis ausgezeichnet.

Als ein wichtiges internes Kommunikationsinstrument hat sich der monatlich erscheinende IKZ Newsletter etabliert. Neben der Herausgabe von Pressemitteilungen und monatlichen News ist die PR aber auch bestrebt, die Öffentlichkeit über verschiedene Kanäle zu aktuellen Ergebnissen und Projekten zu informieren. Zusätzlich soll eine sich derzeit in der Konzeption befindliche, und für 2020 geplante, Ausstellung im Eingangs- und Foyerbereich zukünftig Besucher in die Kristallwelt einladen. Der Eingangsbereich und das Foyer des Instituts werden zur Verbesserung der Außenwahrnehmung hierzu komplett umgebaut und ein Willkommens- und Meeting-Bereich erstellt. Im Foyer wird eine Ausstellung über die Kristallzüchtung gezeigt, die es den Gästen ermöglicht, einen Einblick in die Arbeit des Instituts zu erhalten. Neben der Aufwertung der Außenfassade zu einer moderneren Wahrnehmung wird auch das Außenbild des Instituts durch eine Neugestaltung des Logos verbessert.

Another highlight in 2018: The IKZ scientist Dorothee Braun was awarded the Marthe Vogt Prize. For her doctoral thesis in the field of the development of ferroelectric materials, which she completed with distinction, Ms. Braun was awarded this prestigious prize by the Forschungsverbund Berlin e.V. (FVB).

The monthly IKZ Newsletter has established itself as an important internal communication tool for our staff to spread news about ongoing activities in the institute. In addition to press releases and monthly news, PR aims to inform the public about current results and projects through various media. Furthermore, an exhibition currently under conception and planned for 2020 in the entrance and foyer area is to invite visitors to the crystal world in future. The entrance area and the foyer of the institute will be completely reorganized to improve the external perception by setting up a welcome and meeting area. In the foyer, there will be in addition an exhibition on crystal growth R & D which will allow visitors to gain insights into the work of our institute for society. In addition to an upgrade of the external facade to a more modern perception, the external image of the institute will also be improved by redesigning the logo.

IKZ Mitarbeiterin beim Demonstrationsversuch „Hot Ice“ bei der Langen Nacht der Wissenschaften 2018

IKZ employee during demonstration experiment “Hot Ice” at the Long Night of Sciences 2018

Chronik: Überblick 2018 im IKZ
Timeline: Overview of 2018 in IKZ

Februar

Thomas Schröder als neuer Direktor des Leibniz-Institutes für Kristallzüchtung berufen

Zum 1. Februar 2018 hat Prof. Dr. Thomas Schröder die Leitung des Leibniz-Instituts für Kristallzüchtung (IKZ) in Berlin-Adlershof übernommen. Damit verbunden ist die Professur „Kristallwachstum" an der Humboldt-Universität zu Berlin. Seit 2013 hatte Prof. Dr. Günther Tränkle, Direktor des Ferdinand-Braun-Institutes für Höchstfrequenztechnik (FBH), das Institut kommissarisch geleitet, unter dessen Führung das IKZ seinen Anspruch als führendes Zentrum für Kristallzüchtung in Europa weiter verfestigen und ausbauen konnte.

Thomas Schröder hielt seit 2012 eine Professur für Halbleitermaterialien an der Brandenburgischen Technischen Universität (BTU) Cottbus-Senftenberg und war seit 2009 Leiter der Abteilung Materialforschung am Leibniz-Institut für innovative Mikroelektronik (IHP) in Frankfurt (Oder). Hier betrieb er mit seinem Team eine moderne Materialforschung im Bereich der „More than Moore" Silizium Mikroelektronik. Als studierter Chemiker und Physiker erlangte Thomas Schröder seine Promotion im Bereich der physikalischen Chemie von Dielektrika an der Humboldt-Universität sowie dem Fritz-Haber-Institut der Max-Planck-Gesellschaft in Berlin.

February

Thomas Schröder appointed as new director of the Leibniz-Institut für Kristallzüchtung

On February 1, 2018, Prof. Dr. Thomas Schröder became director of the Leibniz-Institut für Kristallzüchtung (IKZ) in Berlin-Adlershof. This position is associated with the professorship "Crystal Growth" at the Humboldt-Universität zu Berlin. Since 2013, Prof. Dr. Günther Tränkle, Director of the Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), had been acting as temporary director of the institute. Under his management, the IKZ was able to further consolidate and expand its position as the leading center for crystal growth in Europe.

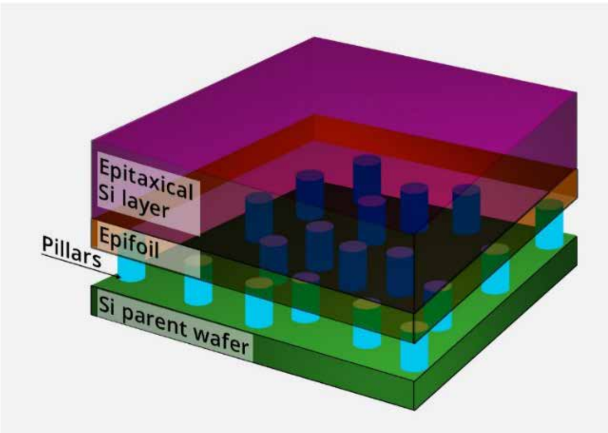
Thomas Schröder held a professorship for semiconductor materials at the Brandenburg Technical University (BTU) Cottbus-Senftenberg since 2012 and was head of the materials research department at the Leibniz Institute for Innovative Microelectronics (IHP) in Frankfurt (Oder) since 2009. Here he and his team conducted modern materials research in the field of „More than Moore" silicon microelectronics. Thomas Schröder studied chemistry and physics and obtained his doctorate in the field of physical chemistry of dielectrics at the Humboldt University and the Fritz Haber Institute of the Max Planck Society in Berlin.

Mai

Projekt CHEETAH erfolgreich beendet: in Richtung Zukunft der Photovoltaik durch europäische Zusammenarbeit

Das von der EU geförderte Projekt CHEETAH wurde in 2018 erfolgreich abgeschlossen. Das Projekt bündelte die Kompetenzen von 33 Mitgliedseinrichtungen der Europäischen Energieforschungsallianz (EERA), zu denen auch das IKZ gehört.

Das Vorhaben zielte darauf ab, neue Verfahren für die Photovoltaik zu entwickeln, um Kosten und Materialverbrauch im Vergleich zur bestehenden multi- und polykristallinen Siliziumtechnologie zu verringern. Die Gruppe „SiGe-Nanostrukturen" beteiligte sich an zwei Projekten: Zum einen an der Züchtung dünner einkristalliner Silizium-Schichten auf porösem Silizium bzw. auf Glas für Dünnschicht-Siliziumsolarzellen in Kooperation mit den Partnern IMEC (Belgien), INES (Frankreich), SINTEF (Norwegen), ECN (Niederlande) und ISE (Deutschland). Zu einem zweiten Projekt trug die Gruppe mit der kontrollierten Abscheidung von Kupfer-Indium-Gallium-Diselenid (CIGSe)-Mikrokristallen mit einem Durchmesser von ca. 50 µm bei. Diese Technologie kann für Mikrokonzentrator-Solarzellen verwendet werden. Das IKZ kooperierte in diesem Bereich mit ENEA (Italien), der Universität Estland, INL (Portugal) sowie dem Helmholtz-Zentrum Berlin und der Bundesanstalt für Materialforschung und -prüfung (BAM) aus Berlin.



May

Project CHEETAH successfully concluded: towards the future of photovoltaics through European collaboration

The EU-funded project CHEETAH was successfully completed in 2018. The project combined the competencies of 33 member institutions of the European Energy Research Alliance (EERA), including the IKZ.

The project aimed at developing new processes for photovoltaics in order to reduce costs and material consumption compared to the existing multicrystalline and polycrystalline silicon technology. The SiGe Nanostructures group participated in two projects: First, the growth of thin monocrystalline silicon layers on porous silicon or on glass for thin-film silicon solar cells in cooperation with partners IMEC (Belgium), INES (France), SINTEF (Norway), ECN (Netherlands) and ISE (Germany). In a second project, the group contributed to the controlled deposition of copper indium gallium diselenide (CIGSe) microcrystals with a diameter of about 50 µm. This technology can be used for microconcentrator solar cells. For this purpose, the IKZ cooperated with ENEA (Italy), the University of Estonia, INL (Portugal), the Helmholtz-Zentrum Berlin für Materialien und Energie (HZB) and the Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin.

Juni

Eine Sommernacht in der Kristallwelt

Am 9. Juni öffnete das IKZ wieder die Türen für die Besucher der Langen Nacht der Wissenschaften – eine jährliche Veranstaltung, die das Bewusstsein für Wissenschaft und Technik fördert.

Trotz der tropischen Hitze in Berlin kamen am Samstagabend 1452 Besucher an das Leibniz-Institut für Kristallzüchtung, um sich über Kristallzüchtung, moderne Kristalle und ihre Anwendung in der Technik zu informieren.

June

A summer night in the world of crystals

On 9 June, the IKZ again opened its doors to visitors of the Long Night of Sciences – an annual event that promotes awareness of science and technology.

Despite the tropical heat in Berlin, 1452 people visited the Leibniz-Institut für Kristallzüchtung on Saturday evening to learn about crystal growth, modern crystals and their applications in technology.

Overview

Zertifikat seit 2015
audit berufundfamilie

September

Familienfreundlicher Arbeitgeber: Leibniz-Institut für Kristallzüchtung erfolgreich im audit berufundfamiwlie

Das IKZ wird für weitere drei Jahre das Zertifikat zum audit berufundfamilie erhalten. Damit wird das Institut für sein Engagement im Bereich der strategisch ausgerichteten familien- und lebensphasenbewussten Personalpolitik ausgezeichnet.

Die erneute Zertifizierung zeigt, dass das IKZ kontinuierlich an einer familienfreundlichen Personalpolitik arbeitet. Das Institut hat es sich zur Aufgabe gemacht, die Rahmenbedingungen für seine Beschäftigten zu verbessern und ihnen Instrumente an die Hand zu geben, mit denen sich Familie/Privatleben und Beruf besser miteinander vereinbaren lassen. Hierzu gehören z.B. flexible Möglichkeiten zur Gestaltung der Arbeitszeit, ob es sich dabei um die tägliche Arbeitszeit oder eine (vorübergehende) Teilzeitbeschäftigung handelt. Ein Eltern-Kind-Zimmer steht Beschäftigten für die Überbrückung von kurzzeitigen Engpässen zur Verfügung.

September

Family-friendly employer: Leibniz-Institut für Kristallzüchtung successful in the audit workandfamily

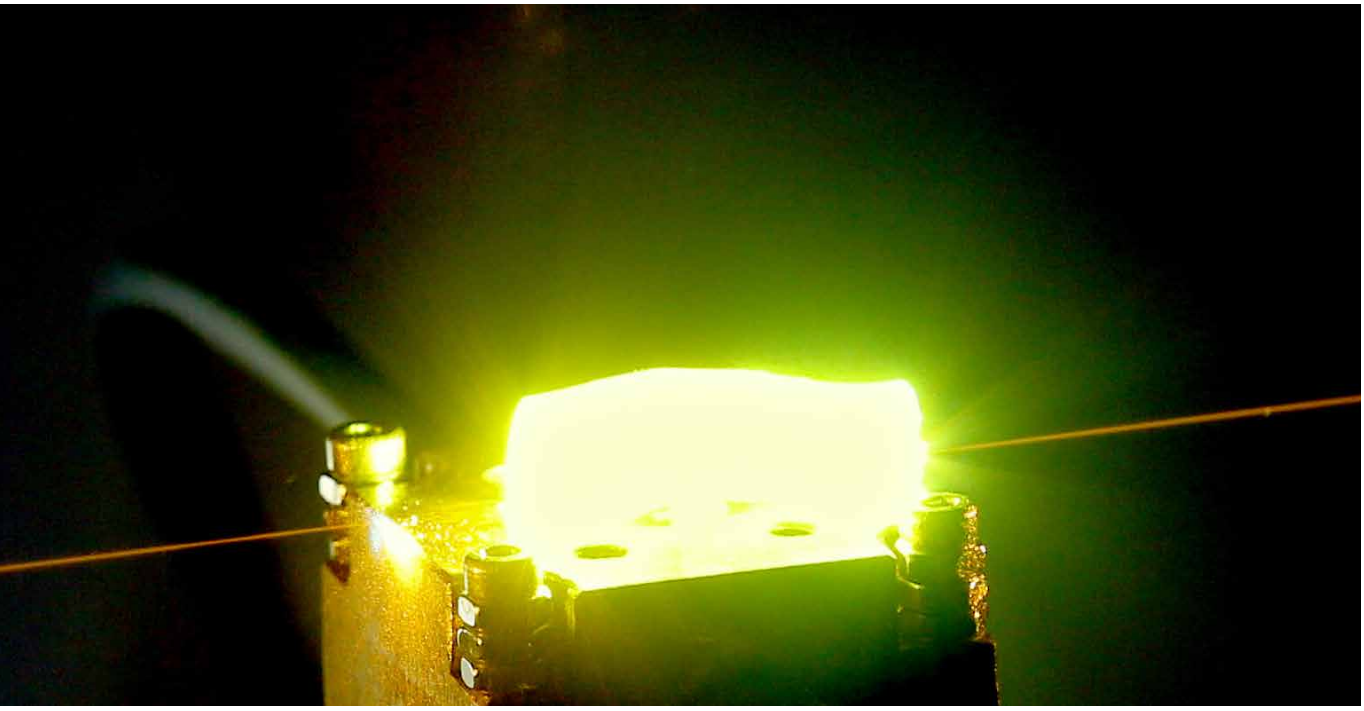
The IKZ will receive the berufundfamilie audit certificate for another three years. This award recognizes the institute's commitment to strategically oriented family and life-phase personnel policies.

The renewed certification shows that the IKZ is continuously pursuing a family-friendly personnel policy. The institute is committed to improving the general conditions for its employees and to providing them with tools to better reconcile family/private life and career. This includes, for example, flexible options for the working time, whether it be daily working hours or (temporary) part-time employment. A parent-child room is available to employees to bridge short-term bottlenecks in childcare.

September

IKZ Sommerschule Solid-State Lasers

Vom 24. - 26. September 2018 lud das IKZ zur Sommerschule mit dem Thema „Solid-State Lasers" ein. Die mehr als 50 Teilnehmer waren zur Hälfte Nachwuchsforscher/innen und Studierende von externen Einrichtungen aus dem In- und Ausland – ein Beleg für die Aktualität dieser erst im letzten Jahr am IKZ etablierten Forschungsthematik.



Overview

Während des dreitägigen Workshops behandelte der Dozent Prof. Dr. Günter Huber von der Universität Hamburg grundlegende Aspekte der Laserphysik und des Wachstums von Seltenerd-dotierten Laserkristallen. Im weiteren Verlauf wurden diese Grundlagen anhand vieler konkreter Beispiele vertieft und intensiv diskutiert.

Neben dem Dank an den Dozenten Prof. Dr. Günter Huber gebührt dieser auch allen an der Organisation der Sommerschule beteiligten, insbesondere den Kollegen vom Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie für die interessante Laborführung.

September

IKZ Summer School on Solid-State Lasers

From 24 - 26 September 2018 the IKZ hosted its summer school on the topic "Solid-State Lasers". Half of the more than 50 participants were young researchers and students from external institutions, some even from abroad - proof of the topicality of this research topic, which was only established at the IKZ last year. During the three-day workshop, lecturer Prof. Dr. Günter Huber from the Universität Hamburg dealt with fundamental aspects of laser physics and the growth of rare earth-doped laser crystals. These fundamentals were further deepened and intensively discussed by means of many practical examples.

We would like to thank Prof. Dr. Günter Huber and all those involved in the organization of the summer school, including the colleagues from the Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy for the interesting laboratory tour.

September

IKZ leitet Initiative zur Entwicklung von UV-Leuchtdioden

Das IKZ koordiniert ein neues Verbundprojekt, das im Rahmen des BMBF-Konsortiums „Advanced UV for Life" gefördert wird. In den nächsten drei Jahren wird die Arbeitsgruppe „Aluminiumnitrid" mit ihren Partnern die Wertschöpfungskette aufbauen und entwickeln, um die kommerzielle Fertigung von UV-Leuchtdioden (UV-LEDs) mit ultrakurzen Wellenlängen um 230 nm auf AlN-Substraten zu ermöglichen. Solche Bauelemente sind für neue Anwendungen in der Gas- und biochemischen Sensorik, Medizin- und Umwelttechnik, Wasser-, Oberflächen- und Luftdesinfektion wichtig, aber noch nicht auf dem Markt verfügbar.

Zusätzlich zur Herstellung defektarmer AlN-Kristalle enthält der gemeinsame Arbeitsplan des IKZ und seiner Partner – Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), AG Nanophotonik (Prof. Kneissl) an der Technischen Universität Berlin sowie die Firmen Freiberger Compound Materials GmbH und CrysTec GmbH – die Konfektionierung in epitaxietaugliche Wafer, die Epitaxie pseudomorph verspannter Schichtsysteme und die Entwicklung der spezifischen Bauelementtechnologie.

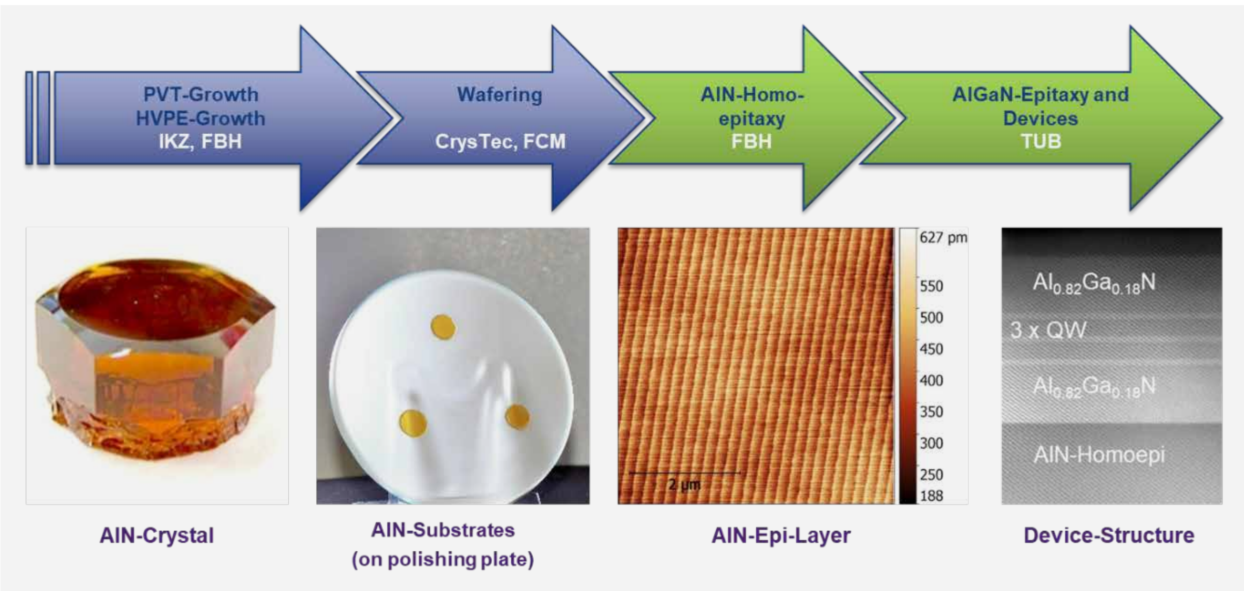


Foto: IKZ; C. Kuhn (TU Berlin)

September

IKZ heads initiative to develop UV-LEDs

The IKZ is coordinating a new joint project funded by the BMBF consortium “Advanced UV for Life”. Over the next three years, the “Aluminium Nitride” working group and its partners will establish and develop the value chain to enable the commercial production of UV LEDs with ultra-short wavelengths around 230 nm on AlN substrates. Such components are important for new applications in gas and biochemical sensor technology, medical and environmental technology, water, surface and air disinfection, but are not yet commercially available.

In addition to the production of low-defect AlN crystals, the joint work plan of the IKZ and its partners – Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH), AG Nanophotonik (Prof. Kneissl) at the Technical University of Berlin as well as the companies Freiberger Compound Materials GmbH and CrysTec GmbH - includes the fabrication of epitaxy-suitable wafers, the epitaxy of pseudomorphically strained layer systems and the development of a specific device technology.

September

Symposium „Epitaktische Oxidfilme für elektronische Anwendungen“ auf dem EMRS Herbsttreffen

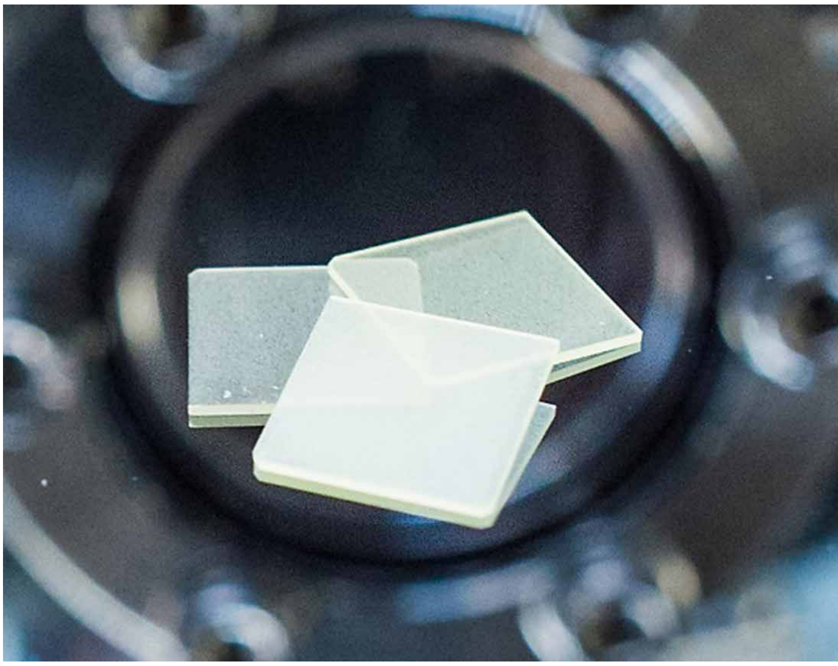
Vom 16. bis 20. September 2018 bot die EMRS-Fachtagung ein spannendes Programm von 34 eingeladenen Vorträgen, 29 weiteren Vorträgen und 16 Posterpräsentationen zum hochmodernen Forschungsthema der funktionellen Oxid-Elektronik. Das Symposium wurde organisiert von IKZ-Abteilungsleiter Matthias Bickermann und seinen Mitorganisatoren Pavlo Zubko (London), Debdeep Jena (Cornell, USA) und Ulrike Diebold (Wien).

Eine Besonderheit des Symposiums war die Breite des Themenspektrums: dieses reichte von Wachstum, Charakterisierung und Bauelementdemonstration von Galliumoxid-Halbleiterschichten über leitfähige Oxidgrenzflächen und Dünnfilme, Perowskit- und Übergangsmetalloxid-Heterostrukturen, Ferroelektrika bis hin zu Defekten und resistiv schaltenden Schichten.

September

Symposium “Epitaxial oxide films for electronic applications” at the EMRS Fall Meeting

From 16 to 20 September 2018, the EMRS symposium offered an exciting programme of 34 invited lectures, 29 further lectures and 16 poster presentations on the ultra-modern research topic of functional oxide electronics. The symposium was organized by IKZ department head Matthias Bickermann and his co-organizers Pavlo Zubko (London), Debdeep Jena (Cornell, USA) and Ulrike Diebold (Vienna). One of the special features of the symposium was the wide range of topics: this ranged from growth, characterization and device demonstration of gallium oxide semiconductor layers to conductive oxide interfaces and thin films, perovskite and transition metal oxide heterostructures, ferroelectrics to defects and resistively switching layers.



Overview

Oktober

IKZ-Wissenschaftlerin Dorothee Braun mit dem Marthe-Vogt-Preis 2018 ausgezeichnet

Für ihre mit Auszeichnung abgeschlossene Dissertation im Bereich der Entwicklung von ferroelektrischen Materialien wurde Frau Dr. Dorothee Braun der Marthe-Vogt-Preis des Forschungsverbund Berlin e.V. (FVB) verliehen.

Frau Braun untersuchte in ihrer Doktorarbeit Materialien mit ferro- und piezoelektrischen Eigenschaften, wie sie für elektronische Anwendungen, z.B. für Drucksensoren, nicht-flüchtige Speicherbauelemente oder Ultraschallgeräte eingesetzt werden. Kristalline Kaliumniobat-Schichten könnten eine Alternative bilden zu den derzeit verwendeten, bleihaltigen Materialien. Dorothee Braun legte mit ihrer Doktorarbeit die Basis für die weitere, zielgerichtete Forschung an der Struktur-Eigenschafts-Beziehung von Oxidschichten, insbesondere von solchen mit Perowskitstruktur. Die experimentellen und theoretischen Arbeiten wurden in der AG Ferroelektrische Oxidschichten, unter der Betreuung von Dr. Jutta Schwarzkopf, durchgeführt.

October

IKZ scientist Dorothee Braun receives the Marthe Vogt Award 2018

Dr. Dorothee Braun received the Marthe Vogt Award of the Forschungsverbund Berlin e.V. for her outstanding dissertation on the development of ferroelectric materials. In her doctoral thesis, Dorothee Braun investigated materials with ferroelectric and piezoelectric properties which are used for electronic applications, e.g. for pressure sensors, non-volatile memory devices or ultrasonic devices. Crystalline potassium niobate layers could provide an alternative to the lead-containing materials currently in use. With her doctoral thesis, Dorothee Braun laid the foundation for further, targeted research on the structure-property relationship of oxide layers, in particular with perovskite structure. The experimental and theoretical work was carried out in the AG Ferroelektrische Oxidschichten under the supervision of Dr. Jutta Schwarzkopf.

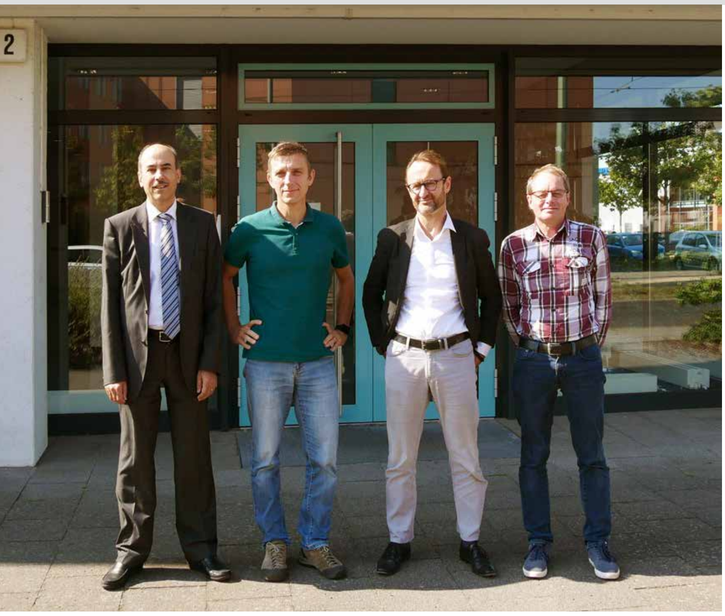
Oktober

Kooperation mit Kistler Instrumente AG soll erneut verlängert werden

Bereits seit 25 Jahren verbindet das IKZ eine erfolgreiche Zusammenarbeit mit der Firma Kistler Instrumente AG. Diese langjährige Kooperation soll nun erneut verlängert werden.

Der Fokus wird auch in Zukunft auf der Forschung zur Volumenkristallzüchtung von piezoelektrischen Hochtemperaturkristallen für Druck-, Kraft- und Beschleunigungssensoren liegen. Diese finden vor allem Anwendung in der industriellen Prozesskontrolle sowie in der Forschung und Entwicklung für die Automobilindustrie. „Für Kistler hat diese Zusammenarbeit eine sehr große Bedeutung, bilden doch die piezoelektrischen Kristalle das Herz der Sensoren“, so Dr. Claudio Cavalloni, Kistler Instrumente AG. Weitere Forschungsaktivitäten sind im Bereich der Kristallbearbeitung geplant, sobald das IKZ seine Fähigkeiten durch das anwendungsorientierte Programm für Kristalle für die Elektronik und Photonik erweitert hat.

Overview



October

Long-term cooperation with Kistler Instrumente AG to be extended again

Since 25 years the IKZ has been working together successfully with the company Kistler Instrumente AG. This long-standing partnership is now to be extended again.

The focus will remain on research on volume crystal growth of piezoelectric high-temperature crystals for pressure, force and acceleration sensors. These crystals are mainly used in industrial process control as well as in research and development for the automotive industry. “For Kistler, this cooperation is very important, since piezoelectric crystals form the heart of the sensors”, says Dr. Claudio Cavalloni, Kistler Instrumente AG. Further research activities are planned in the field of crystal processing as soon as the IKZ has expanded its capabilities with the application-oriented program for crystals for electronics and photonics.

November

Am IKZ gezüchtete Einkristalle ermöglichen die Neudefinition der Kilogramm-Masseeinheit

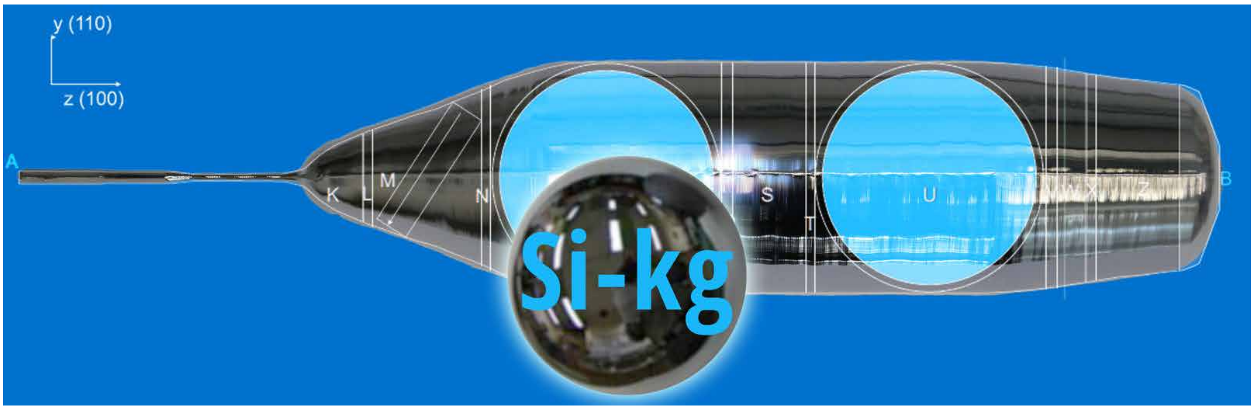
Am 16. November 2018 hat die Generalkonferenz für Maße und Gewichte in Paris die neue Definition der Basiseinheiten im Internationalen Einheitensystem (SI) beschlossen. Damit wird jetzt auch das Kilogramm auf eine Naturkonstante zurückgeführt: das Plancksche Wirkungsquantum.

Hochperfekte Kristalle aus nahezu isotopenreinem Silizium-28 waren für diese Neudefinition von entscheidender Bedeutung. Bei diesen Kristallen haben nahezu alle Atome die gleiche Masse und sind in einem regelmäßigen dreidimensionalen Gitter angeordnet, was eine sehr genaue Zuordnung zwischen der Masse des Kristalls und der Zahl seiner Atome ermöglicht. Aus diesem Zusammenhang kann der Wert der Avogadro-Konstante mit nie dagewesener Präzision abgeleitet werden. Diese ermöglicht die genaue Bestimmung der Planck Konstante, die damit als fundamentale Naturkonstante zur Definition des Kilogramms herangezogen werden kann. Mehr dazu findet sich auf Seite 38 dieses Berichts.

November

Single crystals grown at the IKZ enable the redefinition of the kilogram mass unit

On 16 November 2018, the General Conference on Weights and Measures in Paris adopted the new definition of basic units in the International System of Units (SI). As a result, the kilogram is now also attributed to a natural constant: the Planck constant.



Overview

Highly perfect crystals of almost isotopically pure silicon-28 were of decisive importance for this project. In these crystals, almost all atoms have the same mass and are arranged in a regular three-dimensional lattice, which enables a very precise correlation between the mass of the crystal and the number of its atoms. From this correlation, the value of the Avogadro constant can be derived with unprecedented precision. This allows the exact determination of the Plack constant, which in turn can be used as a fundamental natural constant to define the kilogram. More information can be found on page 38 of this report.

Dezember

SiGeQuant: Kooperatives Bestreben zur Weiterentwicklung der Siliziumquantentechnologie

Das Projekt SiGeQuant, unter der Leitung der IKZ-Abteilung „Schichten & Nanostrukturen", wurde im Rahmen des Leibniz-Wettbewerbs ausgewählt und wird in den nächsten drei Jahren mit 998 T€ gefördert. In diesem Projekt bündeln zwei Leibniz- und zwei RWTH-Hochschulinstitute ihre Kompetenzen, um hochreine isotopenangereicherte Si- und Si/Ge-Strukturen zu untersuchen und Bauelemente für die Quantenelektronik herzustellen.

Das IKZ bringt hierbei seine Expertise für die Entwicklung eines epitaktischen Wachstumsprozesses von hochreinen, elastisch verspannten, versetzungsfreien SiGe/^{28}Si/SiGe-Stapeln mittels Molekularstrahl-Epitaxietechnik (MBE) ein, sowie für die Untersuchung der elektrischen, optischen und strukturellen Eigenschaften dieser gewachsenen Schichten.

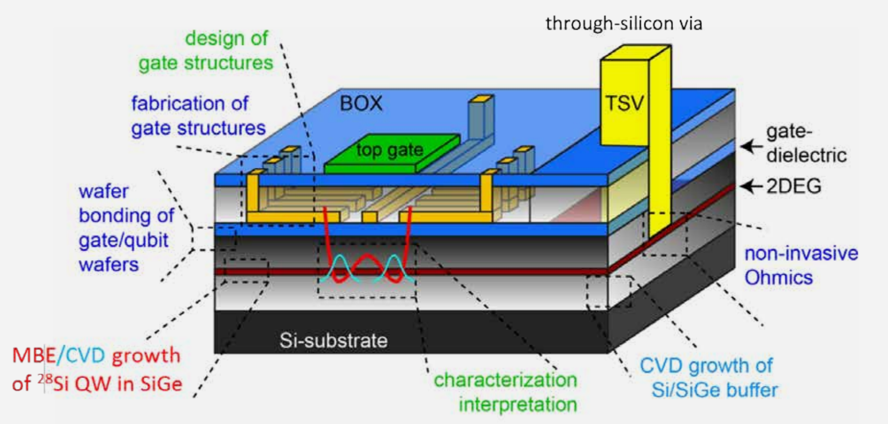
Das Leibniz-Institut für innovative Mikroelektronik (IHP) wird komplementäre Wachstums- und Charakterisierungstechniken entwickeln, während das Institut für Halbleitertechnik (IHT) und das Institut für Quanteninformation (IQI) der RWTH Aachen Quantenpunktbauelemente im Wafer-Maßstab auf Basis dieser Strukturen herstellen und charakterisieren werden.

December

SiGeQuant: Cooperative effort for further development of the silicon quantum technology

The SiGeQuant project, led by the IKZ department "Layers & Nanostructures", was selected in the Leibniz competition and will be funded with 998 T€ over the next three years. In this project, two Leibniz and two RWTH university institutes combine their competencies to investigate highly pure isotope-enriched Si and Si/Ge structures and to develop components for quantum electronics.

The IKZ will contribute to the development of an epitaxial growth process of high-purity, elastically strained, dislocation-free SiGe/28Si/SiGe stacks using molecular beam epitaxy technology (MBE) and to the investigation of the electrical, optical and structural properties of these grown layers. The Leibniz Institute for Innovative Microelectronics (IHP) will develop complementary growth and characterization techniques, while the Institute for Semiconductor Technology (IHT) and the Institute for Quantum Information (IQI) of RWTH Aachen University will develop and characterize wafer-scale quantum dot devices based on these structures.



Sketch: Lars Schreiber, IQI, RWTH Aachen

Bericht der Doktorandinnen und Doktoranden des IKZ
Report of the doctoral students of the IKZ

Mit Thomas Schröder als neuem Direktor ist auch eine neue Generation an Doktorandinnen und Doktoranden im IKZ eingezogen. So hat sich die Zahl der Promovierenden bis heute von 16 auf 22 erhöht. Seit Langem sind bei uns monatlich stattfindende Doktorandenseminare üblich, bei denen alle Neuzugänge vorgestellt werden. Anschließend besprechen wir dort einerseits alle uns betreffenden Themen basisdemokratisch und verbessern andererseits unsere Präsentationsfähigkeiten durch gegenseitiges Feedback. Im Sommer kommen monatliche Grillabende in lockerer Atmosphäre hinzu. Zudem gab es dieses Jahr ein besonderes Gruppen-Event: Um Thomas Schröder besser kennenzulernen, haben wir im Sommer einen gemeinsamen Bootsausflug unternommen. Ausgestattet mit Grill und Badehose ging es morgens auf einen kleinen Kahn, mit dem wir vom Stadtzentrum bis zum Müggelsee fuhren um uns dort abzukühlen. Nach der Rückfahrt haben wir den Abend beim gemeinsamen Fußball-WM Public Viewing ausklingen lassen.

Das angenehme Betriebsklima unter uns Promovierenden wird durch die vielfältigen Weiterbildungsmöglichkeiten, die uns das IKZ bietet, ergänzt. Sei es durch Tages-Exkursionen an andere Institute, bei denen man die Arbeitsweisen und Techniken kennenlernen und neue Kooperationen knüpfen kann, oder gar mehrmonatige Forschungspraktika um diese Kooperationen zu intensivieren und direkt vor Ort Forschungsprozesse begleiten zu können. Weiterbildung findet aber auch direkt im IKZ vor Ort statt. So bot sich uns im Herbst ein interaktiver Soft-Skill Workshop zum Thema „Projektmanagement“, der von allen Teilnehmern als sehr nützlich und förderlich befunden wurde. Bei dem eintägigen Workshop wurden viele hilfreiche Tipps im Hinblick auf die Planung einer Promotion gegeben, aber auch Fragen zur effektiven Gestaltung von Meetings besprochen. Diese Tipps wurden direkt in die Praxis umgesetzt, unter anderem dadurch, dass wir die Struktur unseres Doktorandenseminars verbessert haben und nun jeden Monat eine Doktorandin oder ein Doktorand die Rolle des „Chairs“ zu Übungszwecken übernimmt.

With Thomas Schröder as the new director, a new generation of doctoral students has also started at the IKZ. To date, the number of doctoral students increased from 16 to 22. For a long time now, we have held monthly doctoral seminars at which all new doctoral candidates are introduced. Subsequently, we discuss all topics that concern us there in a grassroots democratic manner and improve our presentation skills through mutual feedback. In summer, we also organize monthly barbecue evenings in a relaxed atmosphere. In 2018, there was also a special group event: In order to get to know Thomas Schröder better, we took a boat trip together in summer. Equipped with barbecue and swimming trunks we went on a small boat in the morning, with which we drove from the city centre to the Müggelsee to cool down there. After the return trip we let the evening end together at the football World Cup Public Viewing.

The pleasant working atmosphere among us doctoral students is complemented by the wide range of further qualification opportunities offered by the IKZ. This may be by one-day excursions to other institutes, where you can learn about working methods and techniques and establish new cooperations, or even research internships lasting several months in order to intensify these cooperation and to be able to accompany research processes directly on site. In addition, IKZ also offers internal training courses. In autumn, for example, we attended an interactive soft skill workshop on “project management”, which was found to be very useful and beneficial by all participants. During the one-day workshop many helpful tips were given regarding the planning of a doctorate, but also questions regarding the effective organization of meetings were addressed. We put these tips directly into practice, for example by improving the structure of our doctoral seminar, so now every month one doctoral student assumes the role of “chair” for practice purposes.

The Institute

In Vorbereitung auf die Instituts-Evaluierung zum Ende des Jahres gaben sich die Doktorandinnen und Doktoranden gegenseitig Führungen durch ihre einzelnen Labore, um die Arbeitsbereiche besser kennen zu lernen. Zudem übernehmen wir seitdem in Zusammenarbeit mit der Öffentlichkeitsarbeit die Führungen von externen Partnern und interessierte Studentengruppen, um die Arbeit am IKZ nach außen zu präsentieren sowie die eigenen Forschungsschwerpunkte darzustellen.

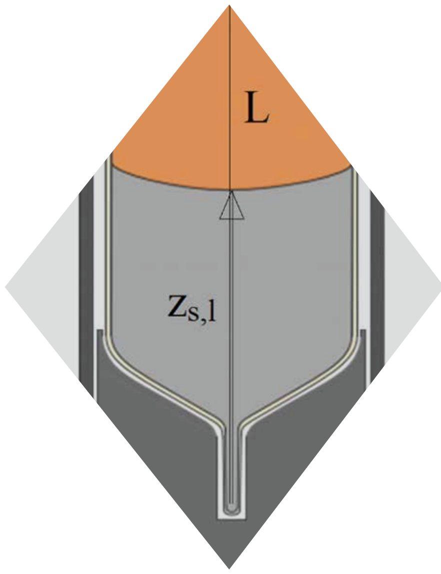
Mit der Berufung von Thomas Schröder als neuen Direktor ergab sich für uns die Gelegenheit, die Rahmenbedingungen der Doktorandinnen und Doktoranden anzupassen. Die Promotionsrichtlinien – ein Leitfaden für die Arbeits- und Promotionsbedingungen am IKZ – wurden modernisiert. Zusätzlich zu dem bereits bestehenden guten Qualitätsmanagement durch individuelle Betreuungskommissionen wurden die Vertragsmodalitäten erheblich verbessert. Einerseits gab es eine Gehaltserhöhung, dabei wurde die Vergütung von einer zweistufigen Lösung zu einer dauerhaften Vergütung mit 75% Stellen nach TVöD angehoben. Andererseits wurde mit einer nun festgelegten Vertragsdauer von 3+1 Jahren für Planungssicherheit gesorgt. Zudem wurde ein Willkommensschreiben für neue Doktorandinnen und Doktoranden verfasst, um für einen angenehmen Start am IKZ zu sorgen. Zusätzlich gibt es für internationale Doktorandinnen und Doktoranden ein Informationsblatt mit allen wichtigen Adressen und Telefonnummern um sich in Berlin ein Leben aufbauen zu können.

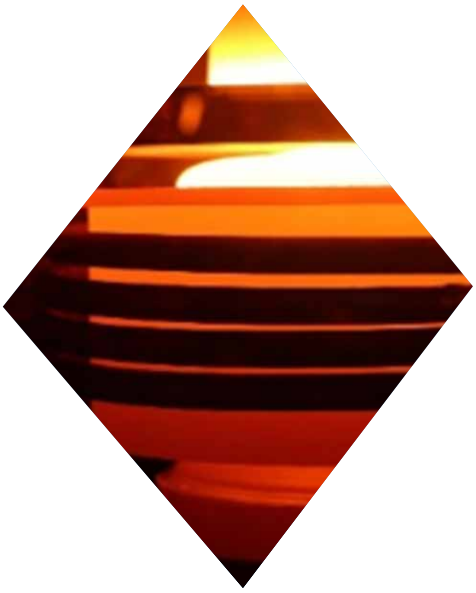
Auch für das kommende Jahr sind wieder viele Dinge geplant, so wird es zum Beispiel im Herbst ein von uns organisiertes Treffen mit Vertretern aus Industrie, Verwaltung und Politik geben. Dort soll die Möglichkeit gegeben werden, alle nötigen Informationen für eine Karriere nach der Promotion aus erster Hand zu erhalten.

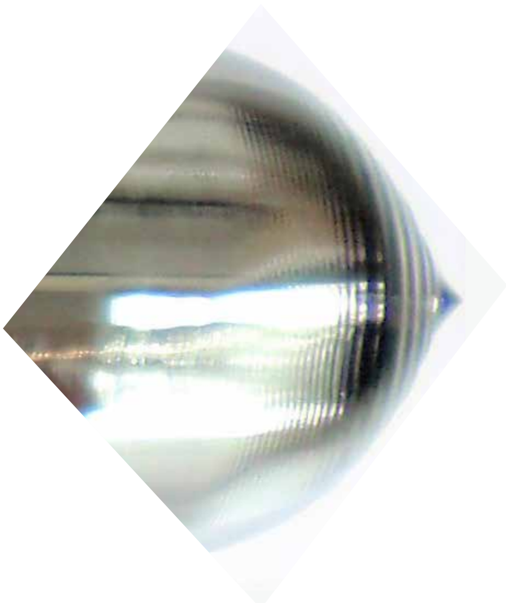
In preparation for the evaluation of the institute at the end of the year, the doctoral students gave each other guided tours through their individual laboratories in order to get to learn more about the research areas at the institute. Since then, the PhD students have also taken on guided tours from external partners and interested student groups in cooperation with the public relations department in order to present the work at the IKZ to the outside world and to present their own research topics.

With the appointment of Thomas Schröder as the new director, we had the opportunity to review the PhD students' general conditions. The doctoral guidelines – a guideline for working and doctoral conditions at the IKZ – were adjusted. In addition to the existing good quality management through individual supervision commissions, the contract modalities have been considerably improved. On the one hand there was a salary increase, whereby the remuneration of the doctorate was increased from a two-stage solution to a permanent remuneration with 75% posts according to TVöD. On the other hand, the now fixed project duration of 3+1 years provides planning security. In addition, a welcome letter was written for new doctoral students to ensure a smooth start at the IKZ. An information sheet comprising all important addresses and telephone numbers was prepared to help international students to build a life in Berlin.

Many things are also planned for the coming year, for example a meeting with representatives from industry, administration and politics will be organized by us in autumn. There will be the opportunity to get all necessary information for a career after the doctorate from first hand.







Classical Semiconductors

Artificial intelligence in crystal growth

N. Dropka[1], M. Holena[2], S. Ecklebe[3], C. Frank-Rotsch[1] and J. Winkler[3]

[1]Leibniz-Institut für Kristallzüchtung, Berlin, Germany
[2]Leibniz Institute for Catalysis, Rostock, Germany
[3]Institute of Control Theory, TU Dresden, Dresden, Germany

A next generation of smart crystal growth factories will use artificial intelligence (AI) and automation to keep costs low and profits high. The AI based on artificial neural networks (ANNs) is trying to mimic biological processes in the human brain by detecting the patterns and relationships in data and by experimental learning. ANNs represent a powerful modeling technique, especially for non-linear data sets, which are common in crystal growth processes. ANN has the ability to correlate very high numbers of variables and to work in the stand-alone mode with high accuracy in predictions. ANNs can describe both static and dynamic data, where the latter implies that ANN can have a memory. In that case, ANN response at any given time depends not only on the current input, but on the history of the input sequence.

Based on these facts, there are especially two feasible applications of ANN in crystal growth:
1) pattern recognition by static ANN
2) crystal growth process automation by dynamic ANN.

The pattern recognition means to find complex correlations between static process parameters as well as crystal size/deflection of crystallization front/crystal quality. Once derived, ANN can be used for the fast optimization for the growth of perfect crystals. Application in process automation means to use ANN for fast real time predictions of the transient growth process parameters e.g. temperatures at various points in the growth furnace, the shape and position of crystallization front using certain growth recipes etc. These real time predictions are necessary for the process control, since their direct measurement, particularly in the melt and crystal may cause contamination and therefore is not feasible.

The bottleneck for the application of ANNs results from the demand of a large database that is needed for their generation and training. Fortunately, crystal growth data can be obtained experimentally or by numerical CFD simulations.

Our recent results [1,2] on the application of various ANNs to the optimization of electro-magnetic parameters of magnetic driven vertical gradient freeze growth (VGF) and to fast forecasting of common VGF crystal growth processes showed that ANN predictions were in good agreement with our previous experimental and 3D simulation results, particularly for the static case [1]. In case of dynamic crystal growth process (Fig.1-3) where ANN was trained on a database consisting of 500 growth recipes, the prediction of simple growth recipes was successfully [2]. Nevertheless, for practical applications, more complicate growth recipes will require more data, and data based on by close-to-real transient 2D CFD models using power of heaters as input variables.

Publications

[1] N. Dropka, M. Holena, Ch. Frank-Rotsch, TMF optimization in VGF crystal growth of GaAs by artificial neural networks and Gaussian process models, Proceedings of XVIII International UIE-Congress on Electrotechnologies for Material Processing, Eds. E. Baake, B. Nacke, Hannover, June 6 - 9, 2017, p.203-208.

[2] N. Dropka, M. Holena, St. Ecklebe, Ch. Frank-Rotsch, J. Winkler, Fast forecasting of VGF crystal growth process by dynamic neural networks, Journal of Crystal Growth 521 (2019), 9-14

Acknowledgements

This work was funded by the German Research Foundation DFG (contract-no. FR 3671/1-1 and WI 4412/1-1) and by the Czech Science Foundation (grant 17-01251).

Classical Semiconductors

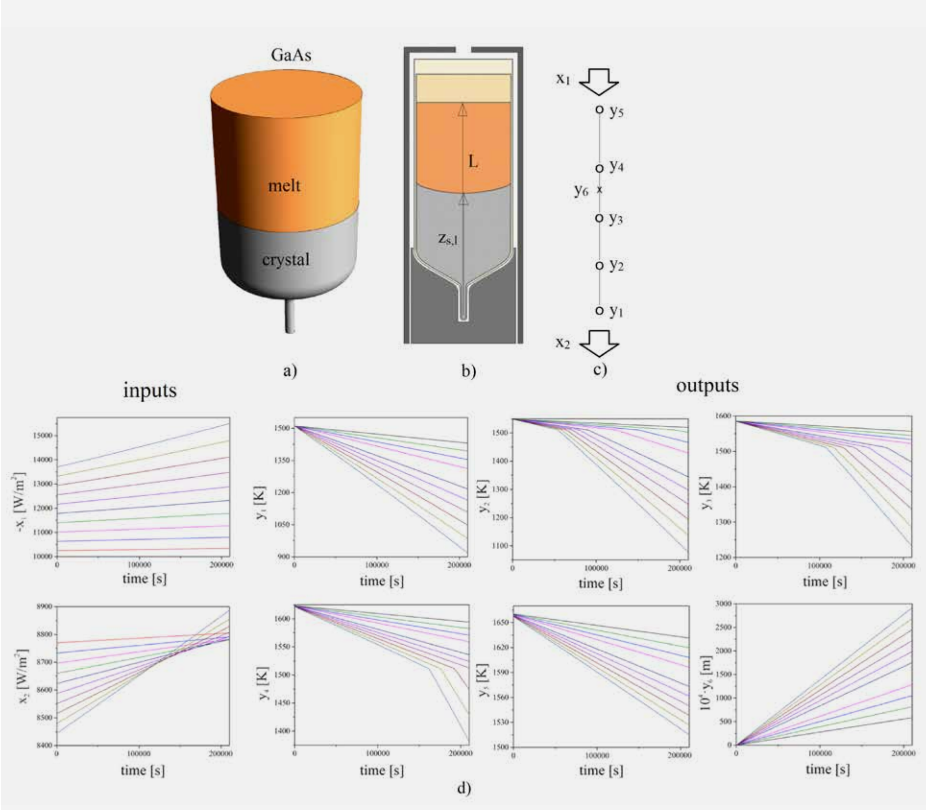


Fig. 1
VGF-GaAs geometry and growth recipe [2]: a) 3D model of melt and crystal, b) 2D model of a central part of a hot zone, c) 1D model of melt and crystal, d) temporal profiles of inputs x_1, x_2 (incoming and outgoing heat fluxes), b) temporal profiles of temperatures in characteristic points and of interface position in GaAs.

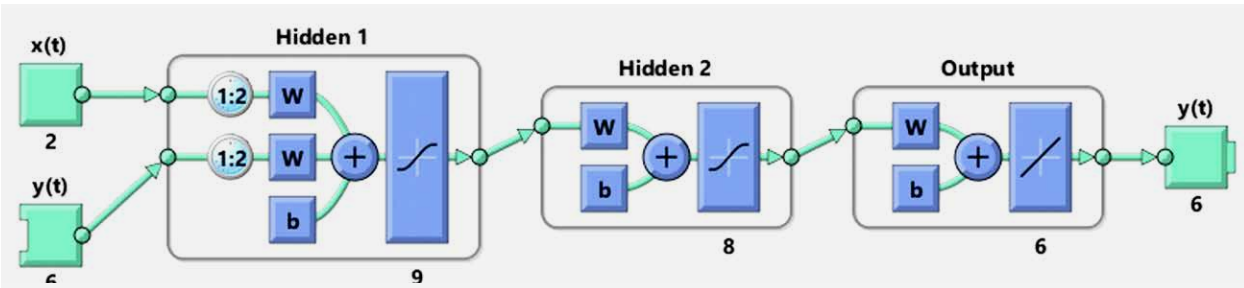


Fig. 2
Dynamic ANN architecture for fast forecasting of VGF-GaAs crystal growth [2].

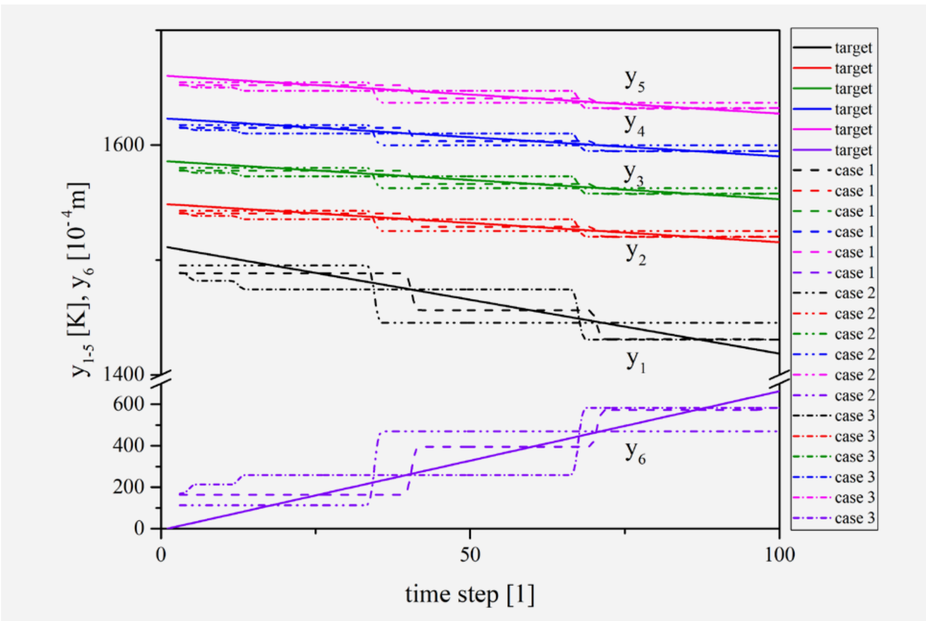


Fig. 3
Example of growth recipe forecasting i.e. predicted versus targeted temporal profiles of output variables y_1-y_6 using various ANNs with one and two hidden layers [2].

Classical Semiconductors

Float-zone growth of silicon crystals using large-area seeding

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[1]Leibniz-Institut für Kristallzüchtung, Berlin, Germany
[2]SolarWorld Innovations GmbH, Freiberg, Germany

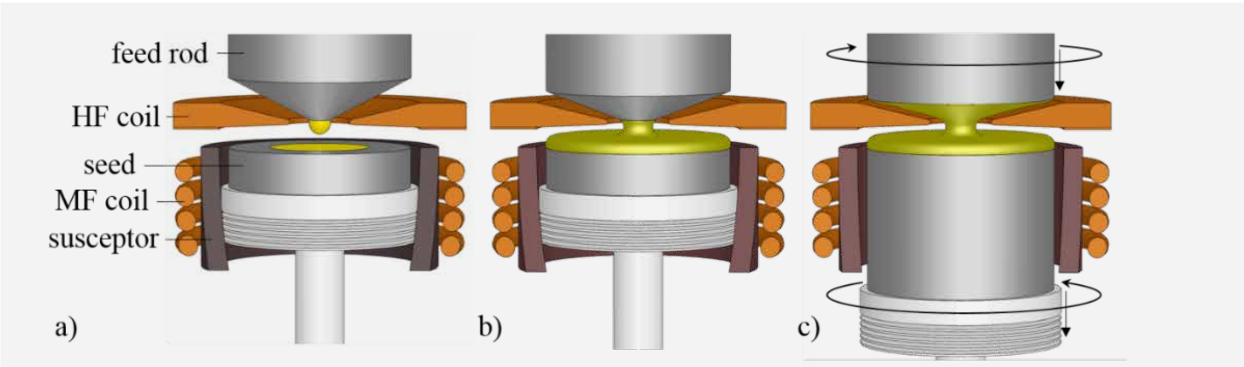

Fig. 1
FZ-like growth concept using large-area seeding.
a) melting of seed crystal surface and feed rod tip
b) generation of molten zone
c) crystallization by downward movement and counter rotation of feed rod and crystal

The crucible-free FZ method is used for production of silicon crystals with ultra-high purity and large diameter up to 8 inches. There is already a demand for FZ crystals with even larger diameter but there are tremendous technological barriers to increase the diameter beyond the currently achievable limit. A further improvement of the standard FZ technology does not seem sufficient for development of the next FZ wafer diameter generation. In particular the necessity to grow a small-diameter Dash-neck and thereafter a start cone, with smaller cross section than wafer size, is unfavorable with respect to crystal yield and design of suitable thermal conditions for all growth phases. The Dash-technique is commonly applied to eliminate dislocations introduced to the seed by the thermal shock when it is contacted to the source drop at the feed rod tip. The absence of dislocations is a precondition for monocrystalline FZ growth. If only a single dislocation is generated, the inherent large temperature gradients and thermal stresses in the large-diameter FZ crystal cause strong dislocation multiplication (EPD > 10^7 cm^{-2}) and evolution of grain boundaries. The classical FZ method with Dash-technique becomes less and less suitable for the production of larger FZ crystals and new approaches are worth investigating. In our recent work a modified FZ method without Dash-necking was investigated.

The new growth concept shown in Fig. 1 is similar to the classical FZ process, but the seeding method is adapted to the large-area seeding concept. Here, the seed diameter is equal to the crystal diameter. In contrast to FZ, no thermal shock with consequent dislocation generation is induced during seeding. By tuning the ratio of the high frequency (HF) coil power to medium frequency (MF) coil power, a temperature field with very small lateral gradients can be established. As in FZ, the continuous crystallization and melting starts by downward movement of crystal and feed rod.

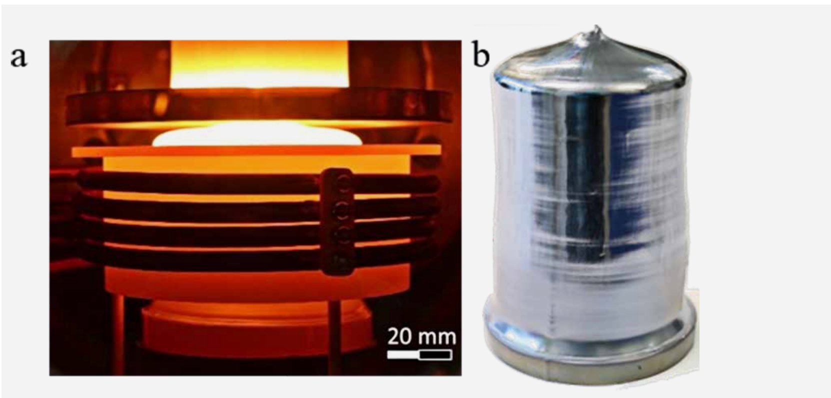

Fig. 2
a) Growth of a 4 inch crystal using the developed set-up for large-area seeding
b) As grown result.

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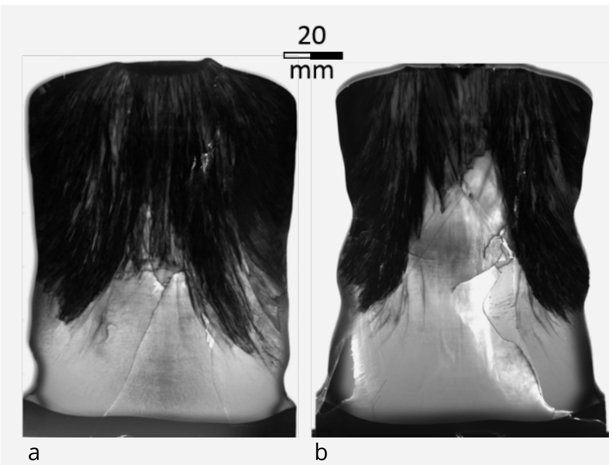
For experimental investigation of the large-area seeding concept, a standard FZ puller was modified to implement the growth set-up shown in Fig. 2a. The Fig. 2b shows an as grown crystal with a diameter of 4 inch and 120 mm length. In parameter studies the impact of the side heater power P_{MF} and pull rate v_p (0.8 – 3 mm/min) on the thermal stress level and defect structure in the crystal was examined. The main goal was a reduction of thermal stress during seeding and growth, to reduce the defect density.

For evaluation of the thermal stress state and its impact on the material quality, the von Mises equivalent stress was calculated and compared to values obtained for the classical FZ method [2]. A numerical model of the growth process was implemented in the finite element analysis software COMSOL Multiphysics. The thermal stress levels during classical FZ growth can reach more than 80 MPa and are the highest compared to any other established growth method for silicon bulk crystals. The thermal stress in the large-area seeding phase is much smaller. However, the thermal stress was calculated to be by a factor of 10 higher than the critical shear stress of 2 MPa in non-dislocation-free silicon near the melting point. The photoluminescence (PL) measurements in Fig.3 show a high dislocation density in the bulk of the seed. It must be concluded that dislocations from the seed surface were mobilized and gliding into the bulk of the seed before the actual start of the crystal growth. The seeds surface damage layer from sawing is a possible origin of these dislocations [2]. Since the dislocation-free state could not be preserved until this stage, dislocations were gliding into the growing crystal and no high stress levels as in FZ with Dash-seeding were acceptable for single-crystalline growth. Nevertheless, because of the reduced stress levels in the developed setup, the growth of at least partially monocrystalline crystals was possible. The PL measurements in Fig. 3 show a region of several centimeter height without grain boundaries. With increasing length of the crystal, evolution of small-angle grain boundaries and polycrystalline growth was observed.



The characterization results can be understood by the simulation results published in [2]. The calculated stress fields show the for FZ characteristic distribution with distinct maxima near the growth interface. An increasing interface deflection and thermal stress with progressing crystal length was found. An overall reduction of stress near the interface was calculated for growth at lower pull rate of v_p = 0.8 mm/min. In this case the calculated stress remained at about the same level as during seeding. The corresponding PL measurement in Fig. 3b shows a distinct increase of the monocrystalline region, especially in the center, but still a switch to polycrystalline growth in the top part of the crystal. A further reduction of the pull rate did not lead to a significant further reduction of stress below 20 MPa in the simulation and could not be realized in the experiments, due to difficulties related to the melting of the feed at low push rate. Hence, it must be concluded that further reduction of thermal stresses and extension of the monocrystalline region requires more fundamental modifications of the FZ-like growth set-up.

Acknowledgements

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Fig. 3
PL measurement on lateral cut of crystals grown at
a) v_p = 2.76 mm/min and
b) v_p = 0.8 mm/min.
The dark crystal regions have high defect density, whereas bright regions indicate monocrystalline growth with lower dislocation density.

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Development of High Purity Germanium Crystals for Radiation Detectors

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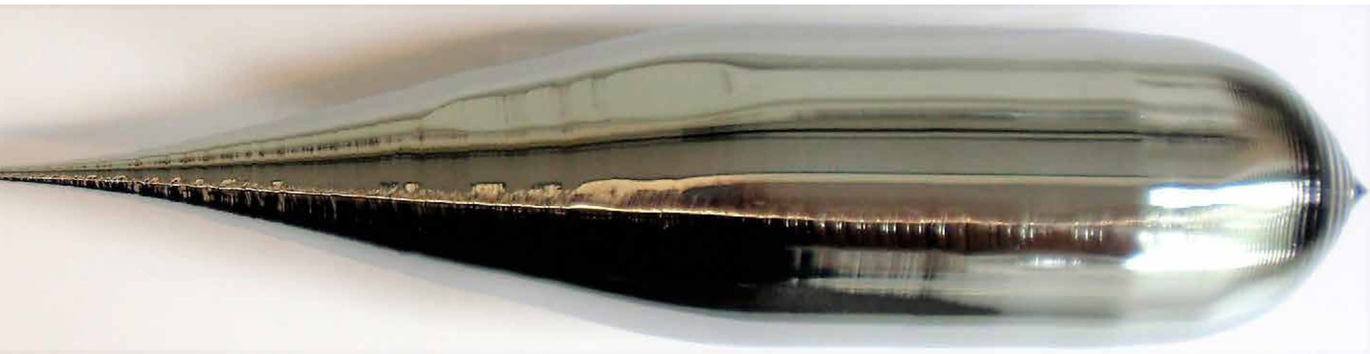

Fig. 1
A 2" HPGe crystal grown by Cz method

Radiation detectors made of High Purity Germanium (HPGe) are in the front line of fundamental research since their discovery. While mainly used as gamma ray detectors, they also play an important role in the field of nuclear physics and dark matter searches. Among its attractive detector applications, the major aim of our work is to use them in *Large Enriched Germanium for Neutrinoless double beta Decay* (LEGEND) experiments, an international collaboration initiative, built for the search of the neutrinoless double beta decay of ^{76}Ge isotope.

The recently formed LEGEND collaboration, with an active participation of IKZ, is aiming to deploy HPGe detectors made of germanium (Ge) single crystals from enriched ^{76}Ge isotope. The first phase of the experiment using 200 kg of HPGe detectors (LEGEND-200) is already in construction stage, while an upgrade to a total mass of 1 ton (LEGEND-1000) is in plan. Therefore, over the next few years an increased demand for HPGe crystals is expected.

Production of HPGe detectors from enriched material starts with the reduction of germanium oxide (GeO_2), followed by the zone refining process aiming at high purity starting material for crystal growth. The most challenging step is the subsequent Czochralski (Cz) growth of Ge single crystals in pure H_2 atmosphere. To implement the complete production chain of the enriched HPGe crystals, an oxide-reduction furnace has very recently been commissioned at our institute to process the GeO_2 powder for preparing poly-crystalline Ge bars for subsequent zone refining.

Zone refining or zone melting is the method of choice for purifying Ge beyond the standard electronic grade (6N) purity. Using our self-made zone refiner, we can simultaneously purify four Ge ingots. The Ge ingots are heated by a radio frequency (RF) coil to generate a melting zone that moves through the bar. Typical zone velocities are between 1 and 5 mm/min. The process requires the use of pure H_2 gas atmosphere to maintain the purity in the crystal as well. Zone refining of Ge is very challenging due to different segregation coefficients of various unintentional and unwanted impurity elements. We performed several experiments to tune the parameters for a maximum yield, and were able to obtain the high purity materials required for the crystal growth from our multiple zone-refining process. Furthermore, for HPGe detectors to be used in the experiments, rather large 3" diameter Ge single crystals are required with a net charge carrier density < 10^{10} cm^{-3} and a dislocation density between 5,000 – 10,000 cm^{-2}. In order to obtain ultra-high purity, the growth equipment has to be adapted specifically with an inductive heating set-up, which makes the control of the thermal field much more complicated as compared to resistive heating systems.

All internal parts of the furnace were designed and constructed at our institute. The construction was preceded by a detailed simulation of the heat transport, which takes place in the growth chamber. A realistic three-dimensional computer aided design (3D -CAD) model was used to define the geometry for computational fluid dynamics (CFD) simulation that has been carried out with a commercial ANSYS software.

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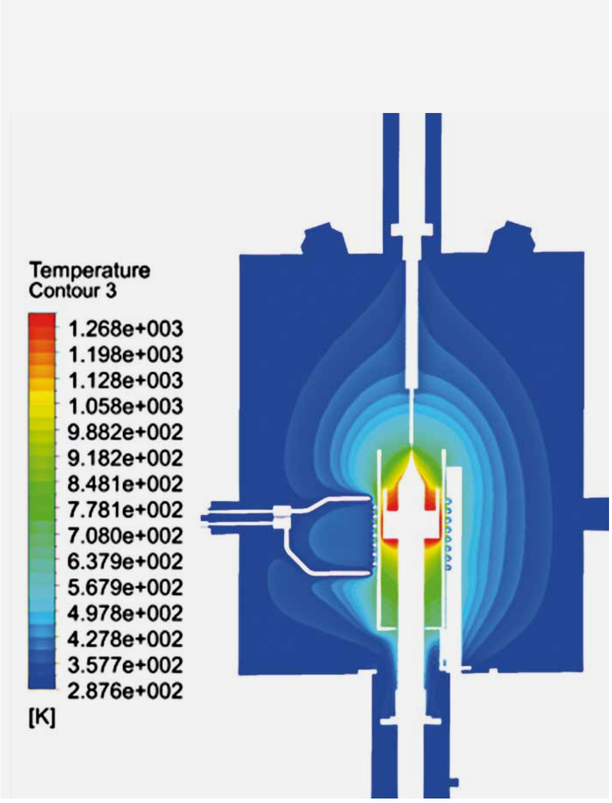

Fig. 2
Simulated temperature distribution for a typical Ge crystal growth process in our system

Fig. 2 shows a simulated temperature field in the furnace obtained by numerical calculation. The suitability of the constructed equipment is tested in a 2" growth setup, before an upgrade to 3" is implemented. 2" HPGe crystal growth has been carried out for process and technology development purposes.

The grown crystals were mainly analyzed by means of low temperature (77K) Hall-effect and Photo-Thermal Ionization Spectroscopy (PTIS) measurements to determine the electrical properties and for impurity investigation. Table 1 shows the results of the Hall-effect measurements performed on the samples prepared from one of the 2" crystals. Sample A was taken from the seed-end of the crystal, B from the middle and C from close to the tail portion.

Sample	ρ (Ω.cm)	n or p (cm^{-3})	μ (cm^2/V.s)
A	145	1.5×10^{12}	4.4×10^{4}
B	1608	1.3×10^{11}	4.7×10^{4}
C	154	1.5×10^{12}	3.3×10^{4}

Table 1
Results of the ***77K*** *Hall-effect measurements performed on three samples taken from one crystal (A-crystal cone, B-middle part, C- tail part)*

From the measured PTIS spectra of HPGe crystals, we have observed typical electrically active impurities like boron (B), aluminium (Al), gallium (Ga) and phosphorus (P). Further, different segregation coefficients of donors (P) and acceptors (B, Al, Ga) give raise to a p-n transition around the middle part of the crystal (i.e. around sample B). Both the Hall and PTIS results were used to reconstruct the impurity profile of the crystals, and as well to determine earlier the concentration of impurities in the starting material.

The dislocation density was estimated by the Etch Pit Density (EPD) method. The slices cut from the crystal undergo chemical mechanical polishing (CMP) after which they are etched to reveal the crystal defects. The etch pits in a selected area are counted under an optical microscope. The EPD measurements revealed that the number of dislocations in the grown crystals are in the required range (10^3 – 10^4 cm^{-2}) and with a slight radial dependency.

Some of the crystals were also characterized with Lateral Photovoltage Scanning (LPS) method to visualize the shape of the solid-melt interface during the growth process.

The quality of the crystals improves steadily which brings us closer to our intended goal to deliver detector material for the LEGEND experiment.

The project is supported by the BMBF under the grant number: 05A17BC1.

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Growth of dislocation-free, highly enriched ^{28}Si single crystals for redefinition of the kilogram mass unit

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On the 16th of November 2018, the General Conference on Weights and Measures in Paris passed a new definition of the kilogram, which has been successfully entered into force on the 20th of May 2019. The IKZ, namely the Silicon & Germanium group, played a decisive role in this process, because perfect crystals of almost isotope-pure ^{28}Si were of crucial importance for this purpose.

Measuring the characteristics of objects or processes is an essential part of daily life. There are seven fundamental units: meter, second, kilogram, ampere, candela, kelvin, and mole that are organized in International System of Units (SI). The main idea of metrology in the last decade has been to define these units in terms of fundamental natural constants, which involves redefining some of them. Of all units, the kilogram was the last one based on an artefact - the so-called prototype kilogram (Urkilogramm) in Sevre near Paris.

The IKZ has been involved in several projects aiming at a more precise determination of the Avogadro constant, which has been crucial for the new definition of the kilogram. It describes the number of atoms contained in a certain quantity of substance, i.e. in one mole. This precisely defined natural constant is used then for determining the Planck constant as the basis for the new definition of the kilogram standard.

Fig.1
Dislocation free ^{28}Si single crystal grown by the FZ technique

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These projects started with the international Avogadro project in 2004 and were then continued in the so-called "Kilogramm" projects under the initiative and management of the Physikalisch Technische Bundesanstalt (PTB; the German National Metrology Institute). The first highly perfect and isotopically pure ^{28}Si crystal of 4'' diameter was grown in IKZ in 2007, followed by several more since, like the one in Fig. 1, which was delivered to PTB in 2018. We used the float zone (FZ) growth technique as method of choice to achieve crystals with the highest perfection and purity. Precedent to the growth process, we had to conduct 10 FZ-runs that were carried out partly in vacuum for the purification of the polycrystalline starting material that was received from Russian partners of the projects. By this procedure impurities accumulate at the end of the crystal, which is then cut off. In addition, crystalline silicon is usually available as a mixture of the stable isotopes of mass numbers 28, 29 and 30. The technology of isotope enrichment with ultracentrifuges for civil applications is fortunately available with our co-operation partners in Russia. This technology was further developed to achieve record values of enrichment of more than 99.999% ^{28}Si. Due to this enrichment and the purification steps required, the value of the raw material was already about 1,000 times higher than for conventional silicon.

From the grown ^{28}Si crystals PTB prepared silicon spheres with less than 20 nm shape deviation at a diameter of approximately 93.6 mm and with a surface polished free of defects. These spheres are used for measurements to establish a connection between the volume and the number of atoms in the highly ordered crystalline structure.

In high-purity ^{28}Si crystals, almost all atoms have the same mass and are positioned in a regular three-dimensional crystal lattice, which makes it possible to determine the exact relationship between the mass of the crystal and the number of its atoms. From this relation, the value of the Avogadro constant can be deduced with unprecedented precision. This allows the Planck constant to be determined accordingly, which was defined as the basis for the determination of the kilogram.

Using the ^{28}Si single crystals grown at IKZ, the PTB was able to determine the Avogadro constant N_A with unprecedented precision as $N_A = 6.022\,140\,76 \times 10^{23}$ mol^{-1}

This relates to the number of ^{28}Si-atoms resulting in a crystal sphere of 1 kg total mass with the required uncertainty of less than 2×10^{-8}.

It amounts to: $2.152538397 \times 10^{25}$ atoms of ^{28}Si.

Silicon is a semiconductor material that has been widely studied over many decades and dominating today's microelectronics and communication technologies and thus almost all our daily life. IKZ will continue further to improve the material quality to enable highly demanding emerging applications like artificial intelligence and quantum technologies.

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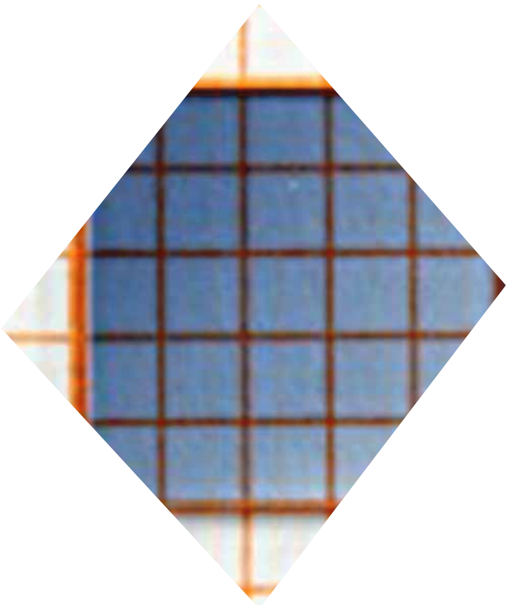

Dielectric & Wide Bandgap Materials

Dielectric & Wide Bandgap Materials

IKZ leads initiative for the development of UV light-emitting diodes

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In September 2018, a new joint project was launched, funded within the framework of the BMBF consortium “Advanced UV for Life” and coordinated by the IKZ. Over the next three years, the IKZ and its partners (Freiberger Compound Materials GmbH; CrysTec GmbH; Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik (FBH); TU Berlin) will establish and develop the whole value-added chain to enable the commercial production of UV light-emitting diodes (UV LEDs) with ultra-short wavelengths around 230 nm on AlN substrates. Such devices are important for new applications in gas and biochemical sensor technology, medical and environmental technology, water, surface and air disinfection, but are not yet available on the market. During 2018, first progress in the three major technical modules “crystalline quality” (dislocation density < 10^4 cm^{-2}), “UV transparency” (> 50% at 254 nm) and “surface quality” (Ra < 0.2 nm) was achieved.

The development of UV LEDs with a center wavelength in the range of 265-310 nm is in the focus of current activities in “Advanced UV for Life”. Based on a technology using epitaxially grown AlGaN layers on sapphire substrates, such devices are about to be launched on the market. However, devices with a wavelength below 265 nm require AlGaN layers with an Al content above 80%. Sapphire substrates are no longer suitable for these layers, and native, low-defect AlN substrates should be used.

At the very beginning of the value chain (Fig. 1) IKZ is developing a physical vapor transport (PVT) crystal growth technology and specific wafering processes for the production of AlN substrates with low defect density, diameters up to 25 mm, epi-ready surfaces and a sufficient optical transparency at the application wavelength in order to enable efficient extraction of the photons generated in the active layers.

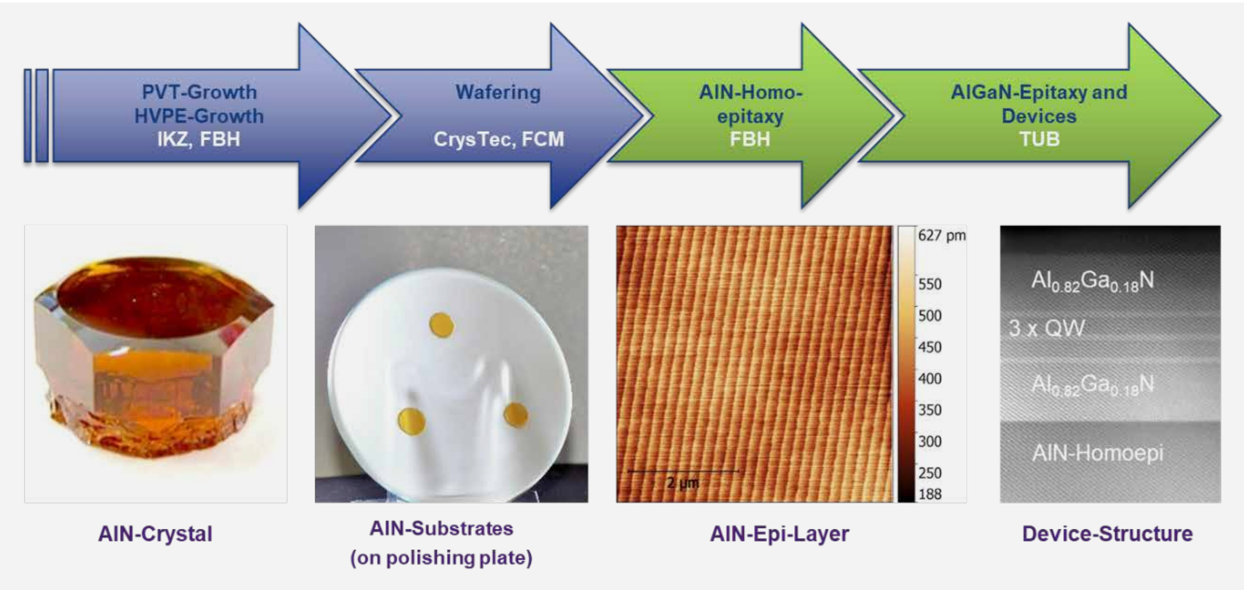

Fig. 1
Value chain in joint project “AlN 230nm” (photo: IKZ; C. Kuhn/TUB)

The Ferdinand-Braun-Institut (FBH) and the Technische Universität Berlin (TUB) will then use these substrates to optimize their epitaxy and device processes, respectively, and adjust the specification of the substrates if needed. In parallel, the applicability of crystal growth and wafering technologies for industrial demands will be assessed by the partners Freiberger Compound Materials (FCM) and CrysTec GmbH.

During 2018 IKZ installed and put into operation two additional sublimation growth reactors, thus doubling the existing equipment capacity, and intensified the activities on the central project topics crystalline quality, UV transparency and surface quality.

Crystalline Quality

To clarify the correlation of the T-field with growth rate and dislocation density, respectively, we performed an experimental series with different global temperature (T-seed) and T-difference between source and seed (ΔT). While special attention was paid on pyrometer calibration, the T-field was adjusted by controlling coil position and global power. The inner temperatures were extracted from the pyrometer measurements on top and bottom of the setup in combination with simulations by the commercially available software “Virtual reactor”. Fig. 2 shows a clear correlation of the growth rate with T-seed as well as with ΔT, which is in accordance with diffusion-based theoretical models (e. g. Noveski et al. [1]). The dislocation density is decreasing with increasing global temperature. Although the substrates prepared from the experiments still suffer from polycrystalline growth related defect clusters at the rim, a homogeneous, low dislocation density (< 10^4 cm^{-2}) in the central area was achieved (Fig. 3).

In the further course of the project, an efficient diameter enlargement technology will be developed as a precondition for enlarging crystals up to one inch, while maintaining the high quality that was demonstrated at small sizes.

UV Transparency

The optical properties of AlN crystals are mainly determined by the content of the impurities oxygen, carbon, silicon and their ratios. As silicon is mainly coming from the source material, which is available with Si contents below 1 ppm, this impurity typically plays a minor role in AlN growth. More attention has to be paid to oxygen, which is always present on the surface of the AlN source and can therefore not be completely avoided, and carbon, which is mainly coming from surrounding graphite and TaC setup parts.

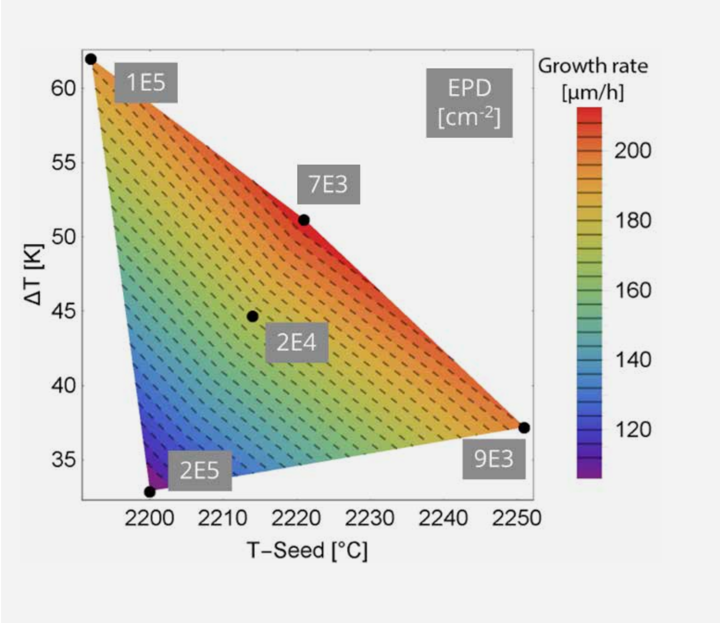

Fig. 2
Growth rate (xy plane) and dislocation density (bars) in crystals grown at different T-seed and ΔT(source-to-seed)

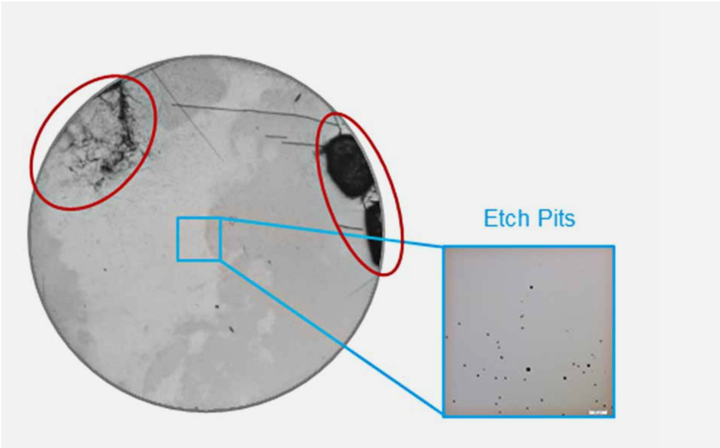

Fig. 3
AlN substrate (D = 5mm) after etching with poly-growth related defect clusters (red) at the rim and low dislocation density in the center (blue)

Investigations by Irmscher et al. [2] in particular revealed the importance of the O:C concentration ratio for the absorption at 4.7 eV explaining the strong quenching at high oxygen concentrations with a shift of the Fermi level and a correlated shift of the charge state of carbon related defects.

Growth experiments show that the O:C ratio, and with it the transparency at 254 nm, can be significantly influenced by the growth temperature. While the crystal shows a low oxygen concentration (SIMS: $5{\cdot}10^{18}$ cm^{-3}) and a low O:C ratio (≈1) at high temperatures and is therefore nontransparent in the deep-UV range, the oxygen concentration (SIMS: $1{\cdot}10^{19}$ cm^{-3}) and the O:C ratio (≈3) increase with decreasing temperature and the crystal becomes deep-UV transparent (transmission > 50% at 254 nm for the 80 µm thick wafer).

As the experiments with different temperature fields suggest that low-defect AlN should be grown at high temperatures, the next step will be to further reduce the carbon content by improving the shielding of graphite containing parts or by intentionally introducing oxygen to the growth process.

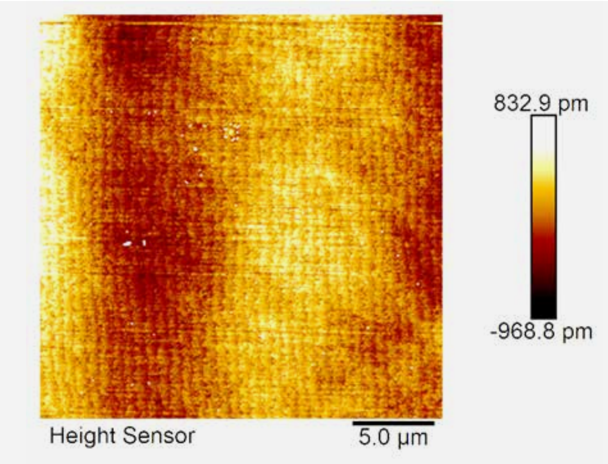

Fig. 4
AFM picture of the surface of an AlN substrate after chemo-mechanical polishing (CMP) showing a low value of Ra=0.2 nm

Surface Quality

Apart from the crystalline perfection of the bulk material, the quality of the epitaxial layers is mainly determined by the properties of the substrate surface after final polishing. During epitaxy, defects can be generated on structural surface defects like scratches, subsurface damage and residuals like silicon coming for example from the silicon oxide particles used during final chemo-mechanical polishing [3].

In particular the removal of the subsurface damage caused by the sawing process is crucial for the final surface quality. TEM investigations by the Electron Microscopy group at IKZ revealed a damage layer of only 2 µm thickness dominated by threading edge dislocations and an additional 5 µm zone with isolated basal plane dislocations. As a result, the damage layer removal by subsequent mechanical and chemo-mechanical polishing processes could be significantly reduced from 100 µm to 10 µm.

First substrates for epitaxy and device process optimization were polished and cleaned at the project partner CrysTec, based on polishing and cleaning processes developed at IKZ during the preceding project and later transferred to CrysTec. Random sampling AFM measurements (Fig. 4) show a homogeneous smooth surface with low Ra (>0.2 nm), no residuals and a step flow structure indicating good preconditions for epitaxy.

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Bulk $ZnGa_2O_4$ as a new ultra-wide bandgap conductive oxide

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A class of oxide materials that combines transparency in the visible / UV spectrum and semiconducting behaviour (transparent semiconducting oxides – TSOs) has intensively been studied at different levels: epitaxial growth, bulk crystal growth, fundamental properties, and devices. A particular attention is paid on ultra-wide bandgap materials that are suitable for deep UV optoelectronics and high power electronics that may have large contribution in energy saving policy, such as smaller power consumption, smaller size, low material usage for a device, high durability, etc. Currently, the most prominent TSO for such applications is β-Ga_2O_3, which we have been developing since a decade. In parallel, we conducted research on many other TSOs, searching for new materials. One of the promising candidates we found and that has very similar properties to that of β-Ga_2O_3 are bulk $ZnGa_2O_4$ single crystals obtained directly from the melt. This result is in contrast to thin films of $ZnGa_2O_4$ that are typically insulating or have very poor electrical properties, and therefore are not suitable for applications.

$ZnGa_2O_4$ is cubic ($Fd\bar{3}m$ space group) with a normal spinel structure, in which Zn^{2+} and Ga^{3+} cations are distributed in tetrahedral and octahedral lattice sites, respectively. The lattice parameter is 8.3336 Å. It has no cleavage planes, therefore wafer fabrication of different orientations is possible and easy, in contrast to β-Ga_2O_3. The bandgap of $ZnGa_2O_4$ is about 4.6 eV, similar to that β-Ga_2O_3. Bulk $ZnGa_2O_4$ single crystals obtained from the melt may reach a very high free carrier concentration (almost 10^{20} cm^{-3}) with high mobility (> 50 $cm^2V^{-1}s^{-1}$) that make this compound a very god candidate for vertical power devices. It is not possible to obtain such highly conducting bulk crystals of β-Ga_2O_3. Further, $ZnGa_2O_4$ shows an intensive cathodoluminescence emission and may act as luminescent material in devices.

Moreover, the lattice parameter of $ZnGa_2O_4$ well matches that of ferrite spinels (e.g. $NiFe_2O_4$), therefore it can be used as a lattice-matched substrate for epitaxial growth of such compounds.

We showed for the first time the growth of bulk $ZnGa_2O_4$ single crystals from the melt by the Vertical Gradient Freeze (VGF) method using an inductively heated iridium crucible [1]. Small crystals could be obtained by the Czochralski method as well. Both ZnO and Ga_2O_3 forming $ZnGa_2O_4$ are thermally unstable at high temperatures and tend to decompose even before solid state synthesis. As the result there is an incongruent evaporation of the most volatile species Zn(*g*) and Ga_2O(*g*) leading to a fast composition shift. Indeed, at measured melting point (1900±20°C) of $ZnGa_2O_4$ the ratio of partial pressures $p(Zn)/p(Ga_2O)$ exceeds 2000. The growth of bulk crystals requires a number of tools to stabilize $ZnGa_2O_4$ at high temperatures, by applying an incongruent starting composition, a suitable oxygen partial pressure in the growth atmosphere, overpressure, a proper furnace design and optimized growth parameters.

The crystallized material within a crucible typically consists of a few large single crystals with a total volume of about 8 cm^3. From such large single crystals, we could prepare 5x5 and 10x10 mm^2 wafers which showed a high structural quality (Fig. 1). The obtained material with 2 ≤ Ga/Zn ≤ 2.17 shows a single $ZnGa_2O_4$ phase. The FWHM of the rocking curve on the (100) face was typically below 50 arcsec. Annealing experiments (10 h) of the obtained crystals revealed their stability up to about 1100 and 700°C for oxidizing and reducing atmosphere, respectively. The thermal conductivity of $ZnGa_2O_4$ at room temperature is 22.1 $Wm^{-1}K^{-1}$, comparable to that of β-Ga_2O_3 along [001] axis (21 $Wm^{-1}K^{-1}$).

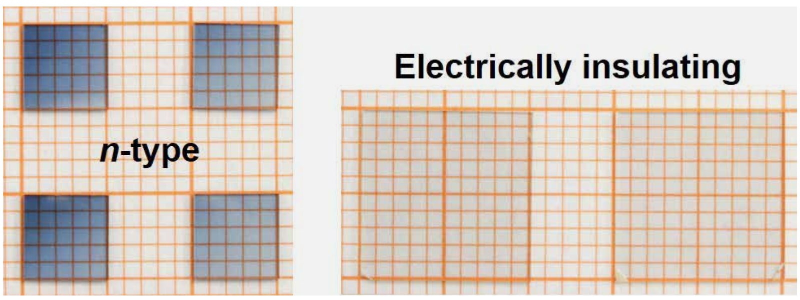

Fig. 1
Higly conducting (left) and electrically insulating (right) wafers prepared from bulk $ZnGa_2O_4$ single crystals obtained from the melt.

Dielectric & Wide Bandgap Materials

Nominally undoped $ZnGa_2O_4$ crystals were n-type semiconductors characterized by resistivities of 0.002 to 0.1 Ωcm, electron concentrations of $3x10^{18}$ – $9x10^{19}$ cm^{-3}, and electron mobilities of about 40–100 $cm^2V^{-1}s^{-1}$. It is worth to mention, that the highest electron mobility of about 100 $cm^2V^{-1}s^{-1}$ was measured at high electron concentrations of $1–2x10^{19}$ cm^{-3}. The electrical conductivity can be easily removed by annealing in oxidizing atmosphere (air or O_2) at 800-1400°C for 10 h. The electrical conductivity can be recovered (to some extend) by annealing $ZnGa_2O_4$ crystals in the presence of H_2 at or above 700°C for about 10 h or longer.

Transmittance spectra (Fig. 2a) show a sharp absorption edge originating at about 275 nm with substantially no absorption up to 2500 nm for electrically insulating crystals, and red / near infrared absorption for highly conducting crystals (free carrier absorption), respectively. The bandgap estimated from the absorption coefficient for the direct transition is 4.59±0.03 eV (Fig. 2b).

We demonstrated the possibility of obtaining bulk $ZnGa_2O_4$ single crystals directly from the melt, which enable us to fabricate 10x10 mm^2 wafers for epitaxial purposes. Very high free electron concentration and high mobility of the obtained crystals constitute a very promising material for high power electronics, in particular in vertical configurations. The fabrication of $ZnGa_2O_4$ based demonstrator devices will give us more insight in the suitability of this material for electronic applications. A comparison of basic features of both ultra-wide bandgap bulk β-Ga_2O_3 and $ZnGa_2O_4$ crystals is listed in Table 1.

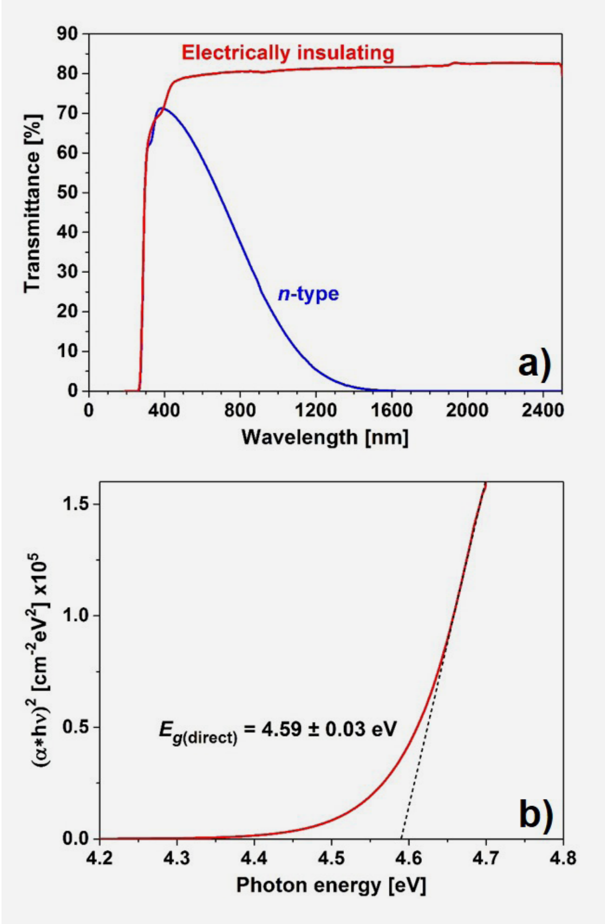

Fig. 2
Transmittance spectra (a) and absorption coefficient in power 2 versus photon energy that corresponds to direct transitions (b). Dashed black line in (b) indicates an extrapolation of the linear part of the curve.

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[1] Z. Galazka, S. Ganschow, R. Schewski, K. Irmscher, D. Klimm, A. Kwasniewski, M. Pietsch, A. Fiedler, I. Schulze-Jonack, M. Albrecht, T. Schröder, M. Bickermann; APL Mater. **7** (2019) 022512

Dielectric & Wide Bandgap Materials

	β-Ga_2O_3	$ZnGa_2O_4$
Status	Advanced development	First experiments
Melt growth method	Czochralski	VGF, Czochralski
Melting point [°C]	1800	1900
Max. volume of a single crystal in one run [cm^3]	160	8
Crystal system	Monoclinic	Cubic
Easy cleavage planes	{100} and {001}	None
Wafer fabrication (slicing, polishing)	Difficult	Easy
Pseudo-direct bandgap [eV]	4.56 || [001] 4.59 || [100] 4.85 || [010]	4.59
Basic electrical properties of undoped crystals	n = 5x10^{16}–2x10^{18} cm^{-3} μ = 100–150 $cm^2V^{-1}s^{-1}$ ρ = 1–0.04 Ωcm	n = 3·10^{18}–9·10^{19} cm^{-3} μ = 40–100$cm^2V^{-1}s^{-1}$ ρ = 0.1–0.002 Ωcm
Max. electron concentration [cm^{-3}]	10^{19} (by doping with Si or Sn)	~10^{20} (unintentionally doped)
Max. mobility at high electron concentration (≥ 10^{19} cm^{-3}) [$cm^2V^{-1}s^{-1}$]	50	107
Electrical insulator possible?	Yes	Yes
Thermal conductivity at room temperature [$Wm^{-1}K^{-1}$]	Along [100] = 11 Along [010] = 29 Along [001] = 21	22.1
Thermal stability of single crystals [°C] in oxidizing / reducing atmosphere	~1300 / ~600	~1100 / ~700

Table 1

Basic features of bulk single crystals of β-Ga_2O_3 and $ZnGa_2O_4$ grown from the melt.

Investigating the growth of delafossite single crystals

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Oxide electronics is a research field that attracts growing attention. It is based on transparent semiconducting oxide materials that show versatile properties useful for many different applications. A major challenge is to achieve p-type conductivity in oxides as a prerequisite for the fabrication of bipolar devices. As a breakthrough, in 1997 an exploitable p-type conductivity was discovered in $CuAlO_2$ by Hosono et al. [1]. $CuAlO_2$ has a delafossite structure, characterized by sheets of linearly coordinated singly changed cations (e.g. copper) stacked between edge-shared octahedral layers (e.g. AlO_6). Such a structure is also found in the cuprous high-Tc superconductors and enables high p-type conductivity and mobility. $CuAlO_2$ was subsequently studied by many research groups, but the electronic properties obtained from the typically sputtered polycrystalline thin films are adversely affected by scattering at grain boundaries. Single crystals do not have these limitations, but only very few reports show $CuAlO_2$ single crystal flakes. We thus investigated possible routes to provide $CuAlO_2$ single crystals, for use as a reference material or even as substrates for oxide epitaxy, within a research project funded by the DFG. While we were not able to achieve bulk single crystals of $CuAlO_2$, we could establish a corrected phase diagram and add important insights to the challenge of stabilizing compounds with intermediate oxidation states during growth.

It is well known that $CuAlO_2$ decomposes into Al_2O_3 and a copper-enriched oxide melt at temperatures around 1200°C. This is because the melting point of Al_2O_3 is much higher compared to Cu_2O. Under these circumstances, a Cu-rich flux must be used from which the delafossite phase gradually solidifies as the temperature decreases below the so-called peritectic (decomposition) point P. Thus, the Al_2O_3-Cu_2O-CuO phase diagram was explored to estimate the solubility and growth (solidification) rate of $CuAlO_2$. The phase diagram found in the literature [2] did not differentiate between Cu(I) and Cu(II), although compounds with ions in different charge states constitute different phases, and the control of the Cu charge state is essential to obtain $CuAlO_2$. If the oxygen partial pressure is too low, Cu_2O is reduced to elemental Cu, which alloys with virtually any crucible and destroys it. On the other hand, if Cu_2O is oxidized to CuO in the melt, $CuAl_2O_4$ spinel is formed instead of the delafossite. One cannot completely avoid either reaction, as copper ions of all charge states are present in the melt anyway, and redox reactions at the interface must be considered, too. Fortunate enough, air (0.21 bar O_2) is an adequate atmosphere to provide stable formation of $CuAlO_2$.

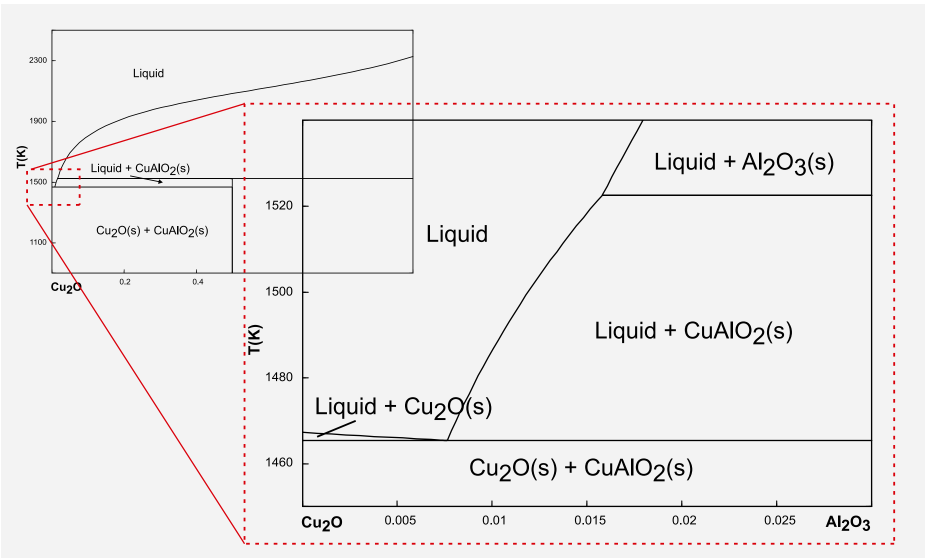

Fig. 1

Pseudo-binary Cu_2O-Al_2O_3-phase diagram for p_{O2} = 0.21 bar with enlarged $CuAlO_2$-liquidus area

Dielectric & Wide Bandgap Materials

The phase diagram was assessed by in-house experiments using our state-of-the-art differential thermal analysis and thermogravimetry (DTA/TG) equipment, and by solving the Gibbs free energy minimization problem using the thermochemical data and software FactSage. The result [3] shown in Fig. 1 is challenging, as the temperature range between P and the eutectic point E, where the remaining melt solidifies to form a solid fine-structured mixture of compounds, is only $\Delta T = 60$ K, and upon cooling a maximum of 1 mole per cent of the melt solidifies into $CuAlO_2$. In addition, the low Al concentration in the melt requires low cooling rates $dT/dt < 0.5$ K/h or low crystal growth pulling rates $R < 0.5$ mm/h, i.e. a growth run will last many hours even for small crystals. Subsequent growth experiments confirmed this and disproved the previous literature [2] that predicted a much more positive situation.

On the positive side, tiny crystallites of $CuAlO_2$ already formed in the small DTA/TG crucibles after rapid cooling (180 K/h). Further experiments carried out in the muffle furnace using Pt crucibles filled with a mixture of 98.5 mole % Cu_2O and 1.5 % Al_2O_3, heated to approx. 1250°C and subsequently cooled at a lower rate of 20 K/h yielded single crystalline $CuAlO_2$ platelets (see Fig. 2) of 5 x 5 mm^2 area [3]. These were larger than all previously published ones but showed clear crack formation caused by the different coefficients of expansion. Because longer growth runs always led to severe crucible damage by elemental Cu formation, further experiments were conducted using our new crucible-less Optical Float Zone (OFZ) furnace.

Fig. 2
$CuAlO_2$ single crystal as nucleated on the solidified melt solution in the Pt crucible

OFZ is quite challenging when growing from a flux that has to be kept in the molten zone, as the solidification temperature strongly depends on the composition of the flux. Even small differences in the Al_2O_3 concentration in the source rod and in the solution zone can quickly lead to large changes in the zone volume. If that volume gets too high, the zone just spills out. On the other hand, enhanced Cu_2O evaporation increases the melting temperature, eventually leading to a melting zone freeze that terminates the experiment and breaks the crystal. However, our attempts to grow single crystals finally failed because the density of the homemade sintered feed rods was insufficient to prevent infiltration of the melt zone, which was then "sucked" into the feed rod. The resulting compositional inhomogeneity in the rod led to solidification of a polycrystalline body composed of micrometer-sized $CuAlO_2$ crystallites in a Cu_2O matrix.

While the growth of $CuAlO_2$ was unsuccessful due to lack of suitably dense feeding rods, we found that another delafossite, $CuFeO_2$, would be more promising. Although it is also melting incongruently, it can be solidified at a lower temperature without the use of a solution zone pellet, i.e., by simply melting a stoichiometric Cu_2O-Fe_2O_3 feed rod. $CuFeO_2$ is interesting as a substrate material for epitaxy of other functional oxides with delafossite structure. So, while the original goal could not be reached, we were able to contribute novel insights regarding the $CuAlO_2$ phase diagram and growth stability, extended our studies to $CuAl_{1-x}Fe_xO_2$ mixed crystals [4] and recently obtained the first phase-pure $CuFeO_2$ bulk crystals by OFZ.

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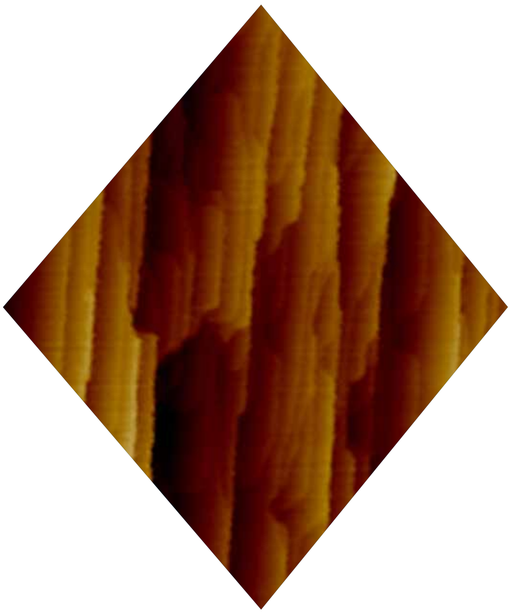

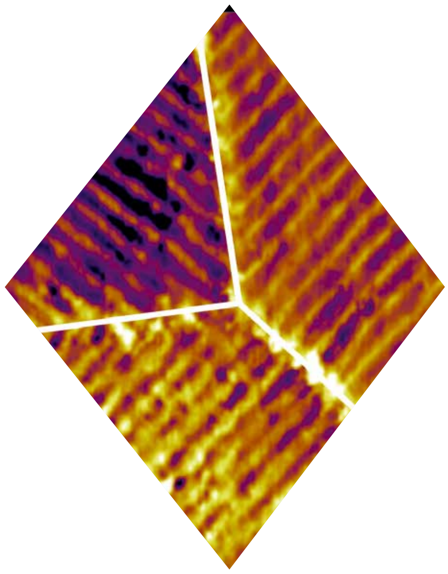

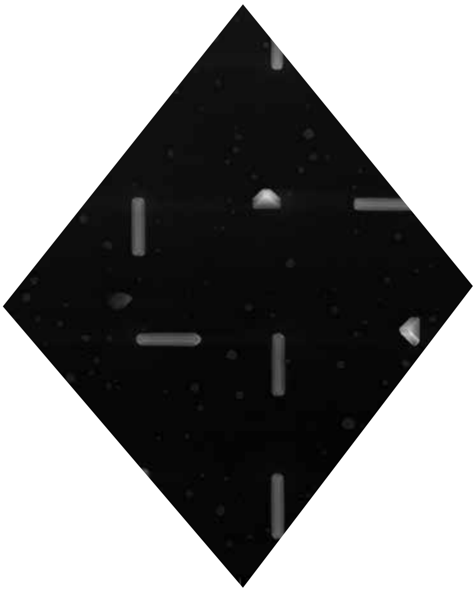

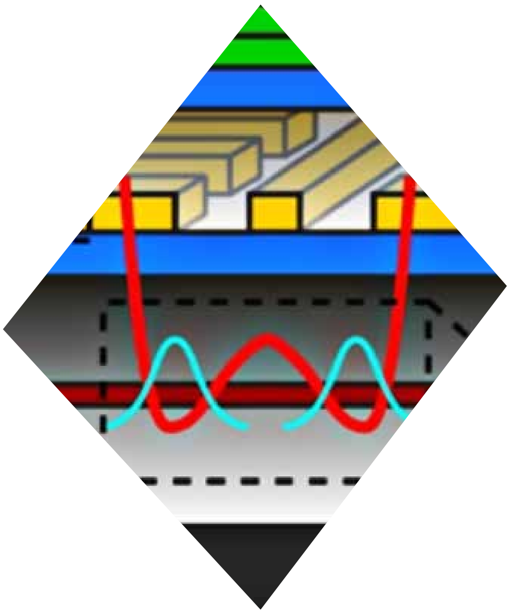

Layers & Nanostructures

MOVPE growth of homoepitaxial β-Ga_2O_3: Effect of substrate miscut angle on layer quality

A. Popp, S. Bin Anooz, R. Grüneberg, C. Wouters, R. Schewski, M. Schmidbauer, M. Albrecht, A. Fiedler, K. Irmscher, Z. Galazka and G. Wagner

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β-Ga_2O_3 belongs to the transparent semiconducting oxides. Compared to other semiconductors like SiC or GaN, β-Ga_2O_3 is characterized by its large band gap of about 4.7 - 4.9 eV. Thus, the transparent range extends into the deep ultraviolet prospectively leading to a high electrical break down field, which is estimated to 8 MV/cm, which is twice as high as SiC or GaN. Therefore, β-Ga_2O_3 has the potential to further increase the efficiency of high power converters. For such applications, high quality homoepitaxial β-Ga_2O_3 layers with superior structural and electrical properties are required, which could be achieved by epitaxy on native substrates. These are grown in-house by our group Oxides/Fluorides. In this work, our main focus was on optimizing the structural quality of the oxide layers, which can be attained by step flow growth.

Recently, we have found that at a growth rate of 1.6 nm/ min, substrates with a miscut angle of 6°, which corresponds to terrace width of about 5 nm, are necessary to achieve step flow growth mode and very smooth surfaces. Using (100) oriented substrates with a miscut angle below 6° – exhibiting terrace widths of more than 5 nm – leads to the nucleation of two dimensional islands with domains resulting in twin lamellae and a high defect density in the grown layers [1].

This result is explained by the fact that the effective diffusion length on the surface steps here is smaller than the terrace width. However, preparation of substrates with a miscut angle of 6° consumes a lot of material. Therefore, one of the most relevant objectives in the last year was the adjustment of the growth parameters to obtain step-flow growth on substrates with smaller miscut angle.

At first, due to the fact that β-Ga_2O_3 has a monoclinic crystal structure, we found that the direction of the miscut angle is crucial to achieve high quality layers. For the homoepitaxial growth of Si-doped films on β-Ga_2O_3 (100) substrates, which are off-oriented in [00-1] direction, step flow growth mode (Fig. 1a) with a surface roughness of 0.3 nm (rms) and low defect density (Fig. 2a) was achieved, while growth on β-Ga_2O_3 (100) vicinal surface with 6° miscut towards [001] direction led to island growth mode (Fig. 1b) and a high density of planar defects (Fig. 2b) [2]. Also the electrical properties of the layers grown on substrates with miscut angle towards [00-1] offered a better performance with a high electron mobility of about 90 $cm^2V^{-1}s^{-1}$ with an electron concentration of 2×10^{18} cm^{-3}. In contrast, layers grown under identical conditions and same doping concentrations but with 6° miscut toward the [001] direction exhibit low electron mobilities of around 10 $cm^2V^{-1}s^{-1}$.

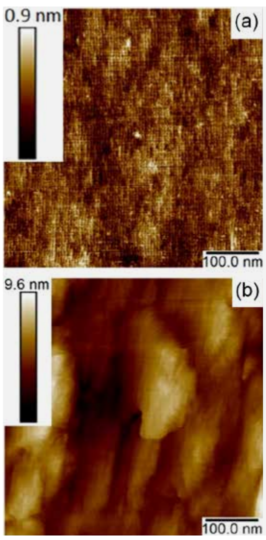

Fig. 1
Atomic force microscopy (AFM) images of a β-Ga_2O_3 layer grown on a substrate with a miscut angle 6° (a) towards [00-1] direction and (b) towards [001] direction.

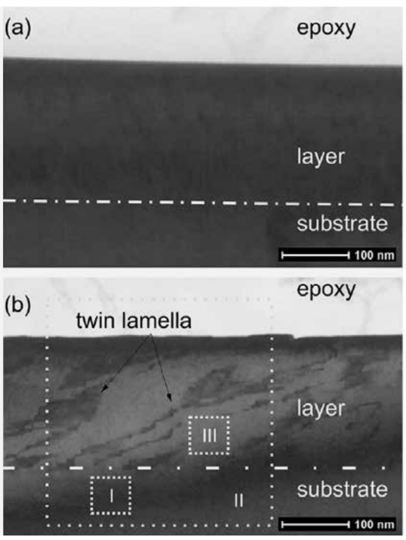

Fig. 2
Cross-sectional transmission electron microscopy (TEM) bright field image of a β-Ga_2O_3 layer grown on a substrate with a miscut direction
a) towards [00-1] and
b) towards [001]. The white dashed dotted lines correspond to the interface between the layer and the substrate.

Layers & Nanostructures

The motivation to reduce the miscut angle becomes evident by the following consideration: For the preparation of a 10x10 mm² large, 6° off oriented substrates with a substrate thickness of 500 µm approximately 60% of the material is lost during the polishing process. An increase of the growth rate results in an increase of the effective diffusion length of the gallium atoms. For adaptation of the higher effective diffusing lengths to the terrace width, a decrease of the miscut angle is possible and required. Therefore, the growth parameters were optimized to increase the growth rate and as a result as well the effective diffusion length. By the variation of chamber pressure, Ar push gas flow and Ga flux the growth rate has been increased to ~ 3.6 nm/min. As a result, we could achieve an increase of the effective diffusion length and the Hall mobility to 115 $cm^2V^{-1}s^{-1}$. However, at this growth conditions a morphology with step bunches was observed on the (100) oriented substrates with 6° miscut and the surface roughness increased from 0.3 nm (Fig. 3a) to about 1.3 nm (Fig. 3b). Step bunching occurred as a result of the increased effective diffusion length caused by the higher growth rate and/or the higher chamber pressure. The effective diffusion length is now larger than the terrace width, leading to a superimposing of on-growing steps. To overcome the step bunching, substrates with a miscut angle of 4° (terrace length ~ 8 nm) were used to adjust the terrace width to the higher effective diffusion length. Hereby, step flow growth mode was achieved, hence the surface roughness decreased to ~ 0.35 nm (Fig. 3c). Furthermore, the Hall mobility was enhanced to 131 $cm^2V^{-1}s^{-1}$ at a free charge carrier concentration of about $1x10^{17}$ cm^3. With these optimizations, we were not only able to increase the growth rate, but also to reduce the miscut angle of the substrates which provides lower material consumption. Simultaneously, the charge carrier mobility of the Si-doped Ga_2O_3 layers was significantly improved.

To summarize, in 2018, we have demonstrated, firstly, that in addition to the dimension of the substrate miscut angle the direction of the miscut is an important variable to achieve step flow growth mode. Secondly, we overcome the limitation of the miscut of 6° by the optimization of the growth conditions. Consequently, step flow growth mode with very smooth surfaces and improved electrical properties were achieved on substrates with 4° miscut angle.

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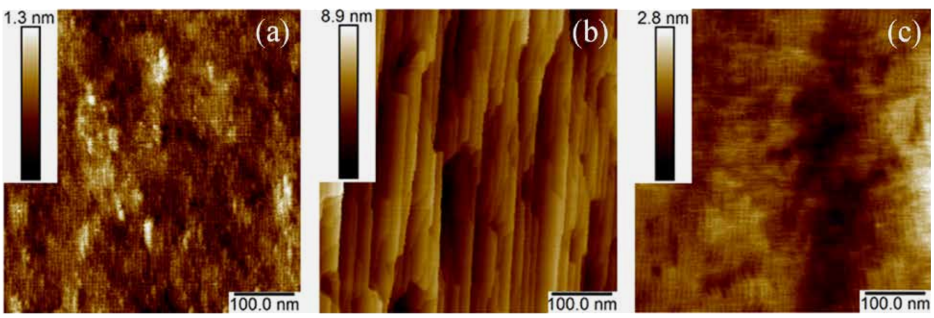

Fig. 3
AFM images of a β-Ga_2O_3 layer grown on a substrate with (a) a miscut angle of 6° and a growth rate of 1.6 nm/min, (b) a miscut angle of 6° and a growth rate of 3.6 nm/min and (c) a miscut angle of 4° and a growth rate 3.6 nm/min.

SiGe nanowires for electronic applications

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The investigation of the growth behavior of Si_xGe_{1-x} nanowires (NW) by molecular beam epitaxy (MBE) is one of the main tasks of the SiGe-Nano research group. Nanowires are very promising for future applications due to their small diameter up to several tens of nanometers and their potentially high crystalline quality. Due to their very good electrical properties, it is of particular interest to grow germanium nanowires on silicon or silicon oxide. FinFET transistors could be made from such NWs.

We apply the vapor-liquid-solid (VLS) method to grow NW in our MBE equipment. At a first step, gold is deposited on the substrate and coalesces to nanometer sized droplets which catalyzes the subsequent growth of NWs. In a first attempt, the growth of pure Ge NWs is investigated. The experiments are carried out on Si(001) nano-tip substrates [1] prepared by the Leibniz-Institut für innovative Mikroelektronik (IHP), Frankfurt (Oder). By varying the substrate temperature and the gold evaporation rate, the density of the gold droplets was brought into accordance with the Si tips [2]. The VLS grown Ge NWs on such Si nano-tips differ significantly from chemical vapor deposition (CVD) grown Ge islands [3] due to the shape-forming capability of the fluid gold droplet.

Moreover, the ultra-high vacuum of an MBE chamber leads to purer material since there are no chemically reacting agents in the vapor phase. The alignment into <110> direction is an inherent feature of VLS grown Ge NWs.

Analytical investigations have shown that gold monolayers are more stable on silicon than on silicon oxide. This leads to material transport from the oxide surface towards the Si tips during gold deposition. Consequently, a eutectic Au-Si droplet forms there. Depending on the substrate temperature this droplet solves as much Si as determined by the Au-Si phase diagram. Afterwards, when Ge impinges and the droplet supersaturates the solved Si and Ge will crystallize forming thereby a composition-graded SiGe pyramid with four inclined {111} side facets. In an early growth stage the droplet resides on the atomically rough (001) facet. But the tip area shrinks when the truncated pyramid evolves. Eventually, the gold droplet have to overcome one of the top edges towards a side facet. Small droplets fit well to such a single side facet. In this way the starting point and therefore the subsequent nanowire growth within <110> direction is predefined (see Fig. 1).

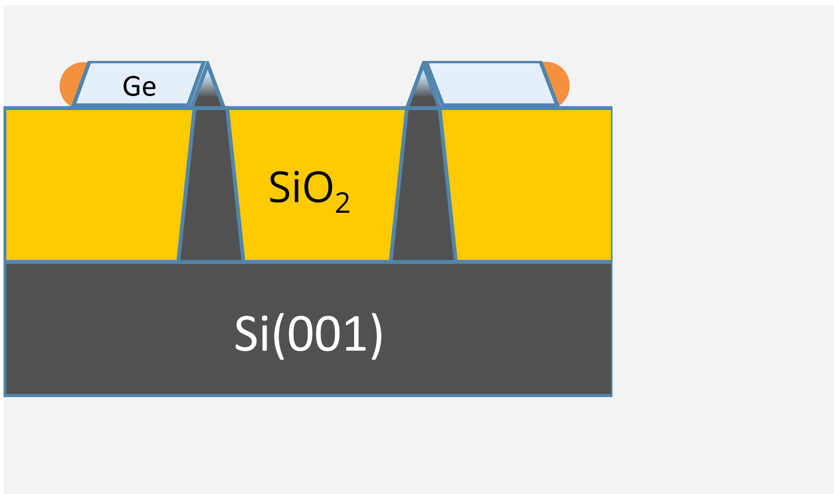

Fig. 1
Sketch of the VLS ELO process of Ge nanowires on nano-tip Si(001) substrates (left)
and top-view SEM image of grown Ge nanowires on a nano-tip Si(001) substrate with a pitch width of 1 µm.

Four equivalent <110> directions within the substrate plane in parallel to the base edges of the pyramid exist. The NW growth takes place by strictly straight epitaxial lateral overgrowth (ELO) on the oxide surface that surrounds the tip. Due to a certain attachment affinity of gold and germanium to the oxide the common rhombical cross section of the NW reduces to the half, i.e. to an isosceles triangle. The length of the strain-free NWs depend solely on growth time. Removing the oxide by wet etching allows the preparation of horizontally free standing Ge bars fixed only at the tips. The structural characterization of these NWs is ongoing.

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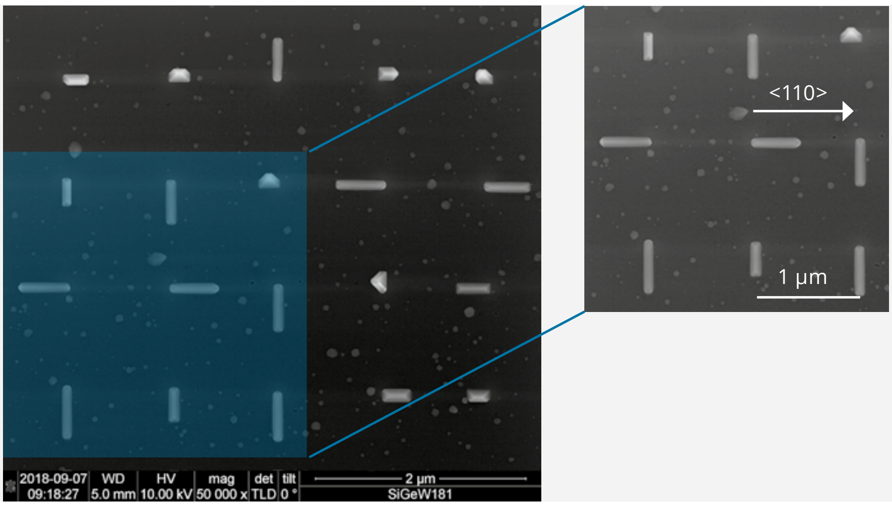

Tuning of the phase transition temperatures in ferroelectric $K_xNa_{1-x}NbO_3$ thin films by lattice strain

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Epitaxial growth of thin films offers the possibility to incorporate enormous lattice strains. Due to the highly ionic character of metal oxides there is a strong coupling between lattice deformations and physical properties. This can result not only in remarkably improved functional properties, rather also in a shift of phase transition temperatures of ferro-/piezoelectric compounds by several 100 K. Around such phase transition temperatures, properties, like dielectric permittivity or piezoelectric coefficient, are often significantly enhanced and can exceed the values of the corresponding bulk material by several times. Thus, the intentional shift of the phase transition temperature into the working regime of a ferroelectric device provides the option to exploit this enhanced functional properties.

Ferro-/piezoelectric thin films can be potentially employed for memory, sensor or microwave applications. One highly technologically interesting, but also challenging application is the use of thin films in surface acoustic wave (SAW) sensors. Here, it is expected that they provide an enhanced sensitivity compared to commonly used SAW sensors based on bulk materials. $K_xNa_{1-x}NbO_3$ represents a material system that exhibits not only high piezoelectric and electromechanical characteristics, which are indispensable for thin film SAW, but it is also a lead-free material. Since several years, our group Ferroelectric Oxide Layers is the only group worldwide, which has grown this material system epitaxially by liquid-delivery metal-organic vapor phase epitaxy (MOVPE). Recently, in cooperation with the work group of Roger Wördenweber at Forschungszentrum Jülich (FZJ), we have successfully demonstrated the propagation of surface acoustic waves in $K_{0.7}Na_{0.3}NbO_3$ thin films on $TbScO_3$ and $GdScO_3$ substrates, even for 30 nm thin films [1,2].

A possible approach to improve the performance of such SAW devices is offered by a shift of the phase transition to the specified temperature on the working regime by lattice strain incorporation. For that purpose, $K_xNa_{1-x}NbO_3$ thin films were prepared under different strain conditions. This was achieved in two different ways: First, the incorporated lattice strain was changed by the variation of the molar potassium content x between 0.54 and 0.77 in the films on the same substrate (e.g. $TbScO_3$). Second, films with the same chemical composition (e.g. $K_{0.7}Na_{0.3}NbO_3$) were grown on different rare-earth scandate substrates ($ReScO_3$ with Re = Dy, Tb, Gd, Sm). This series offers an increasing lattice parameter of the surface unit cell and thereby leads to a decreasing compressive in-plane strain in the films. These oxide substrates were provided by the work group Oxides & Fluorides at the IKZ. It has to be noted, that the rare-earth scandates as well as unstrained $K_xNa_{1-x}NbO_3$ exhibit an orthorhombic symmetry. Consequently, the films experience an anisotropic strain, i.e. the elastic strain states in perpendicular in-plane directions are different.

Different temperature dependent measurement techniques were applied to identify the phase transition temperature as a function of the incorporated lattice strain. The disappearance of the low temperature stripe domain pattern of the monoclinic M_C domains in piezoresponse force microscopy at the phase transition temperature is shown in Fig. 1a. In high resolution X-ray diffraction (HR-XRD) $\theta/2\theta$ scans, the phase transition is evaluated from the observed kink of the vertical lattice parameter (Fig. 1b) [3]. From temperature dependent dielectric permittivity measurements the phase transition temperature is determined by the application of the Curie-Weiss law in the high temperature range and which roughly coincide with the pronounced peak at 57°C for $K_{0.7}Na_{0.3}NbO_3$ film on $TbScO_3$ in Fig. 1c [2].

Layers & Nanostructures

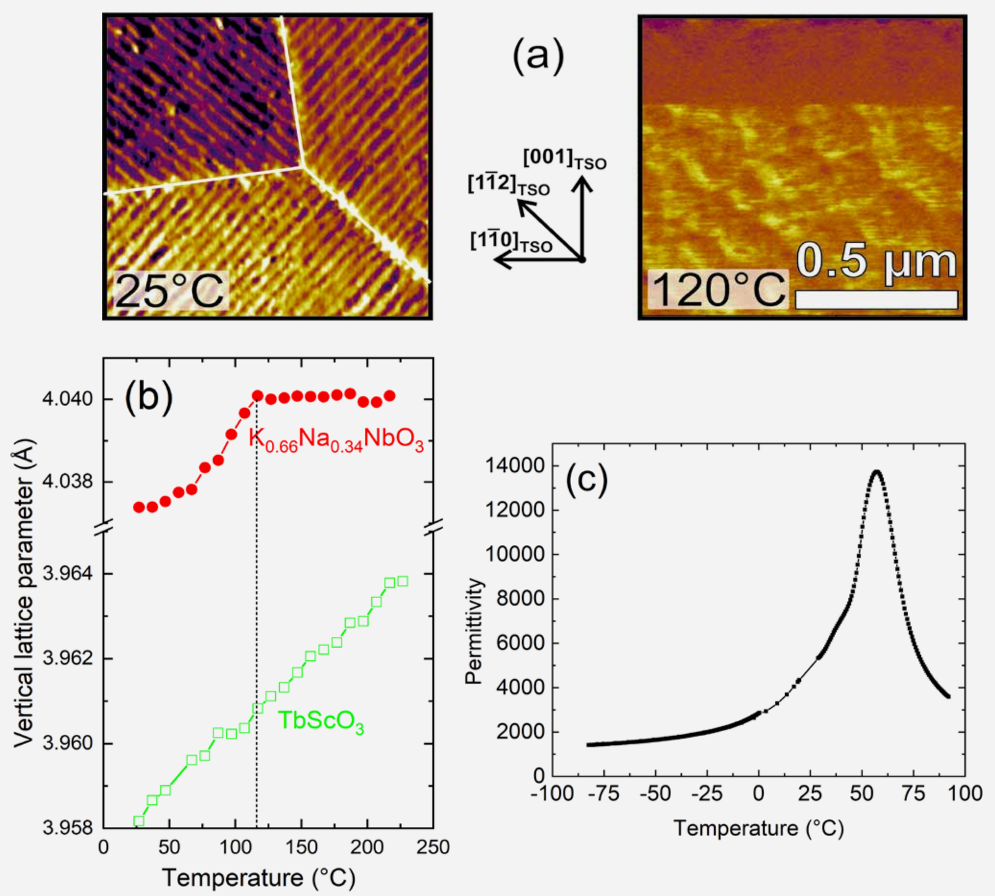


Fig. 1
a) Lateral piezoresponse force micrographs of a 42 nm $K_{0.66}Na_{0.34}NbO_3$ film on $TbScO_3$ revealing a periodic ferroelectric domain pattern below (measured at 25°C, left side) and an irregular domain pattern above (measured at 120°C, right side) the phase transition temperature.
b) Evolution of the vertical lattice parameter in dependency of the temperature for a 30 nm $K_{0.66}Na_{0.34}NbO_3$ film on $TbScO_3$ [3].
c) Dielectric permittivity as function of temperature of a 30 nm $K_{0.7}Na_{0.3}NbO_3$ film on $TbScO_3$ [2] (note the slightly different K content which results in a shift of phase transition to lower temperatures).

It has to be mentioned that the observed phase transition is a ferroelectric-ferroelectric phase transition from a monoclinic symmetry to an orthorhombic symmetry. The ferroelectric-paraelectric phase transition is expected to occur at still higher temperatures. The dependence of the ferroelectric-ferroelectric phase transition temperature on the compressive overall in-plane strain (here defined as the sum of the strain values along both in-plane unit cell directions) is presented in Fig. 2 [3]. It reveals a huge and apparently linear shift from -15 °C to 400 °C. The lowest phase transition temperature is found for the strongest compressive in-plane strain on $DyScO_3$, while the highest phase transition temperature is found on $SmScO_3$. Consequently, by the appropriate choice of the lattice mismatch between film and substrate material, the phase transition can be intentionally shifted to any temperature in the range of -15°C to 400°C.

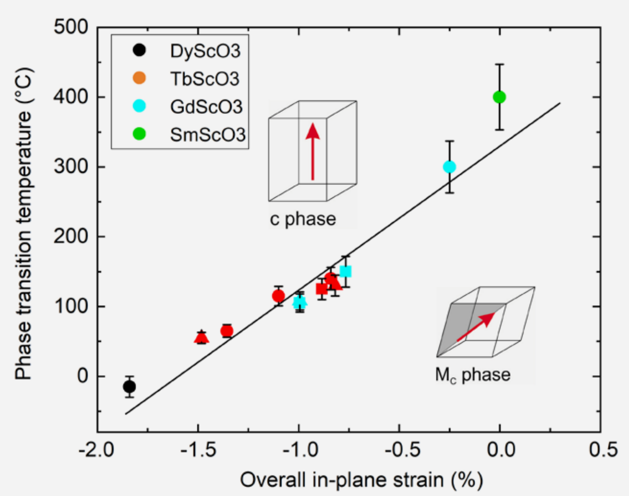


Fig. 2
Phase transition temperature from the monoclinic M_C phase to the orthorhombic c phase versus overall in-plane strain for $K_xNa_{1x}NbO_3$ films with x varying between 0.54 and 0.77 grown on different rare-earth scandate substrates [3]. Black, orange, cyan and green color indicate the use of $DyScO_3$, $TbScO_3$, $GdScO_3$, and $SmScO_3$ substrates, respectively.

With regard to SAW applications, it is worthwhile to follow up the SAW signal versus temperature. For 30 nm $K_{0.7}Na_{0.3}NbO_3$ films on $TbScO_3$ we observed an increase of the SAW signal from 3.6 dB at room temperature to 4.7 dB at the phase transition temperature of 330K (Fig. 3a), while the dielectric permittivity is enhanced by a factor of 2.5 (Fig. 1c). First attempts to use these SAW structures as sensors for biomolecules are currently being carried out in FZJ.

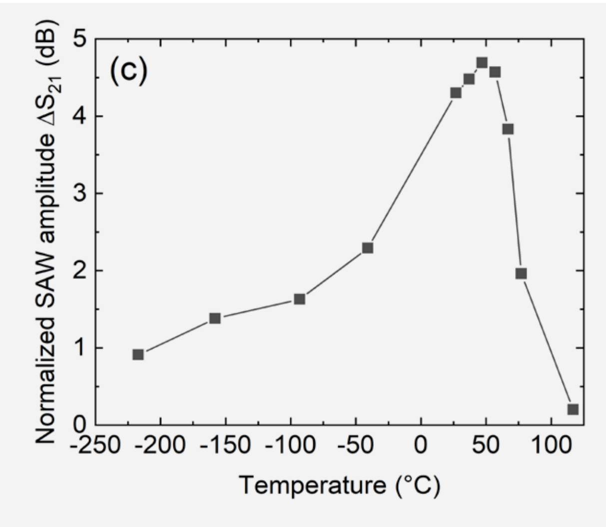


Fig. 3
Dependency of the SAW signal along the [1-10] direction of the $TbScO_3$ substrate on the temperature for a 30 nm $K_{0.7}Na_{0.3}NbO_3$ film on $TbScO_3$ [2].

Publications

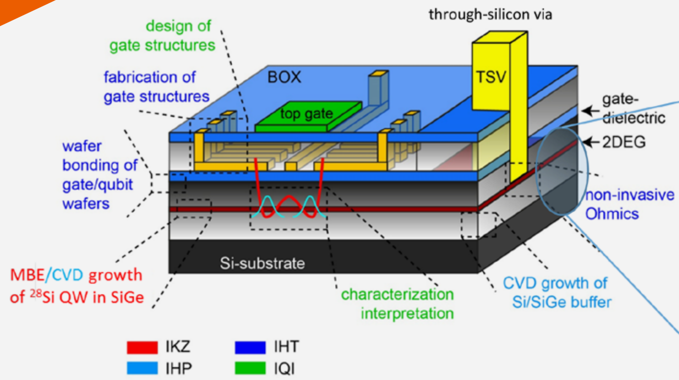
[1] L. von Helden, M. Schmidbauer, S. Liang, M. Hanke, R. Wördenweber, J. Schwarzkopf; Ferroelectric monoclinic phases in strained $K_{0.70}Na_{0.30}NbO_3$ thin films promoting selective surface acoustic wave propagation; Nanotechnology 29, 415704 (2019), https://doi.org/10.1088/1361-6528/aad485

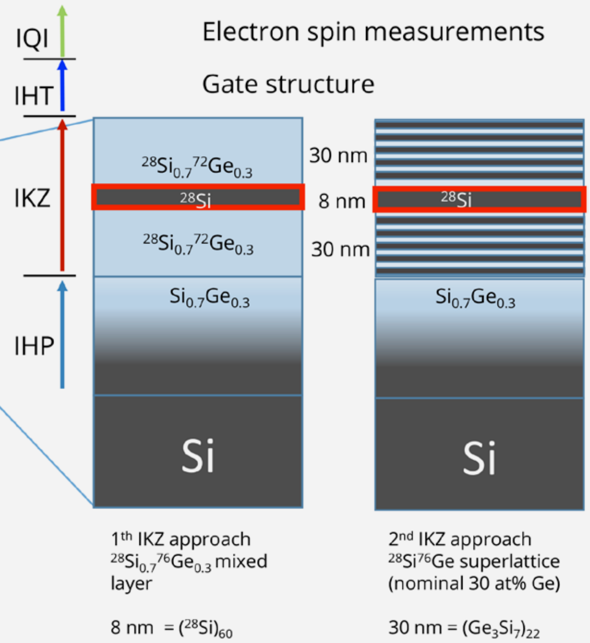
[2] S. Liang, Y. Dai, L. von Helden, J. Schwarzkopf, R. Wördenweber; Surface acoustic waves in strain-engineered $K_{0.7}Na_{0.3}NbO_3$ epitaxial films on (110) TbScO3, Appl. Phys. Lett 113, 052901 (2018), https://doi.org/10.1063/1.5035464

[3] L. von Helden, L. Bogula, P.-E. Janolin, M. Hanke, T. Breuer, M. Schmidbauer, S. Ganschow, J. Schwarzkopf; Huge impact of compressive strain on phase transition temperatures in epitaxial ferroelectric $K_xNa_{1x}NbO_3$ thin films; Appl. Phys. Lett. 114, 232905 (2019), https://doi.org/10.1063/1.5094405

Layers & Nanostructures

Outlook: Project SiGeQuant

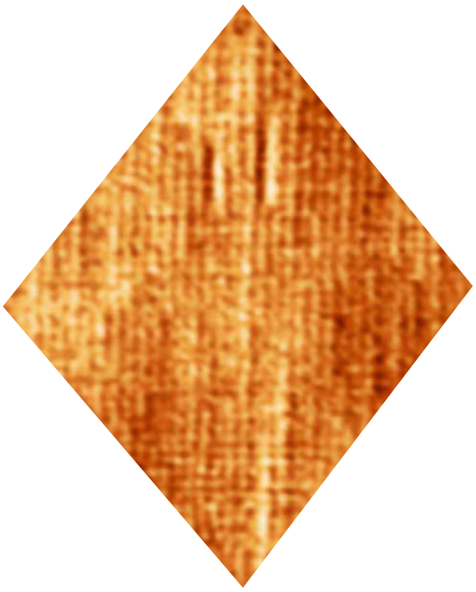


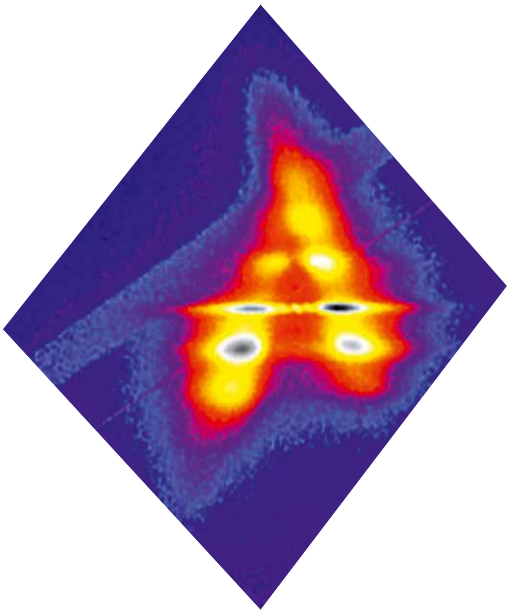


Schematic of a targeted Si/SiGe quantum well heterostructure equipped with gate-defined quantum dots that are realized with a non-invasive fabrication process. This device architecture facilitates an optimization of the materials growth with respect to qubit applications.
Sketch (left) by Lars Schreiber, IQI, RWTH Aachen.

The proposal „High-definition crystalline **Si**licon-**Ge**rmanium structures for **Quant**um circuits" (SiGeQuant) that was outlined at the beginning of the year won a three year funding by the Collaborative Excellence program in the frame of the Leibniz Competition. The project starts in 2019 and will be carried out in cooperation with the Leibniz-Institut für innovative Mikroelektronik (IHP), Frankfurt (Oder), the Institute of Semiconductor Electronics (IHT) of the RWTH Aachen University, and the JARA-Institute for Quantum Information (IQI), an alliance of the 2nd Institute of Physics of the RWTH Aachen university and the Peter-Grünberg Institute at Forschungszentrum Jülich. The IHP provides the so-called SiGe virtual substrate. This is a sophisticated layer stack on a convenient Si(100) wafer to realize a dislocation free, atomically flat SiGe surface ready for epitaxial growth. Our core task is molecular beam epitaxy (MBE) of a tensile strained, few nanometre thin layer of monoisotopic ^{28}Si, isomorphic grown in-between SiGe layers.

The high-purity ^{28}Si source material for evaporation will be prepared by the group-IV (Si & Ge) volume crystals research of the IKZ. The IHT is responsible for the non-invasive attachment of contacts on top of the epitaxial layers. With these contacts a two-dimensional electron gas that is injected into the ^{28}Si layer will be electrostatically formed within two nearby arranged quantum dots hosting therein single electrons. The IQI will manipulate and evaluate the quantum state of the electrons by electron spin resonance measurements within a $^3He/^4He$ dilution refrigerator at 10 mK. The project SiGeQuant is intended to develop a CMOS compatible technology for a Si based quantum computer circuit. A one-purpose MBE chamber exclusively intended for the evaporation of small amounts of the expensive ^{28}Si and ^{72}Ge isotopes will be designed and ordered next year to be in line with the purity requirements of such a ^{28}Si layer with regard to electrically active foreign atoms (< 10^{14} cm³) and magnetically parasitic ^{29}Si and ^{73}Ge isotopes (~ 10^{17} cm³).





Simulation & Characterization

Faceting and step flow growth in the homoepitaxy of β-Ga_2O_3

R. Schewski[1], K. Lion[2], A. Fiedler[1], C. Wouters[1], A. Popp[1], S. V. Levchenko[3,4], T. Schulz[1], M. Schmidbauer[1], S. Bin Anooz[1], R. Grüneberg[1], Z. Galazka[1], G. Wagner[1], K. Irmscher[1], M. Scheffler[3], C. Draxl[2] and M. Albrecht[1]

[1]Leibniz-Institut für Kristallzüchtung, Berlin, Germany
[2]Humboldt-Universität zu Berlin, Institut für Physik und IRIS, Berlin, Germany
[3]Fritz-Haber-Institut der Max-Planck-Gesellschaft, Berlin, Germany
[4]Skolkovo Institute of Science and Technology, Moscow, Russia

An important advantage of β-Ga_2O_3 in contrast to other wide band gap semiconductors (e.g. SiC and GaN) is the availability of bulk single crystals that can be grown with high structural perfection from the melt. Homoepitaxial growth is therefore the natural choice to obtain high quality, functional layers as required for power electronics. In the last years impressive results on homoepitaxial growth have been obtained by different growth techniques (e.g. metalorganic chemical vapor deposition (MOVPE), molecular beam epitaxy (MBE) and halide vapor phase epitaxy (HVPE) on a variety of possible substrate orientations (among them (100), (010), (001), ($\bar{2}$01)). The substrate orientation has been chosen for pragmatic reasons, i.e. considering the achievable growth rates for the respective growth method and the available substrate size or a combination of them. Commercially available wafer sizes today range from 2 inch for ($\bar{2}$01) and (001) orientations (Novel Crystal Technology Inc.) over 1 inch for (010) (Kyma Technologies Inc.) to sizes of 10x15 mm^2 and 10 x 10 mm^2 available for all other orientations. In MBE the growth rate on (010) is reportedly an order of magnitude higher than that on (100) substrates, while it is widely independent on substrate orientation in MOVPE.

An aspect that has been drawn little attention up to know is how the growth mode is influenced by the substrate orientation and growth conditions. The step flow growth mode, highly desirable to achieve homogeneous incorporation of dopants and atomically abrupt interfaces of heterostructures, e.g. in field effect transistors, has up to now exclusively been observed on the (100) surface for MBE and MOVPE, while all other orientations resulted in faceted or macroscopically rough surfaces.

Density functional calculations show a high anisotropy of the surface energies for β-Ga_2O, with the (100) surface having by far the lowest surface energy (Fig.1). All surfaces show a substantial reduction in energy upon surface relaxation which, however, differs significantly between the different surfaces and may even change the order of their surface energies. While the surface energy of the (100)-B surface is only reduced by 0.2 Jm^{-2} (32% reduction in energy), the biggest reduction can be found for the ($\bar{2}$01). This strong effect of relaxation on the surface energy is caused by the sixfold and fourfold coordination environment of the Ga atoms in β-Ga_2O_3.

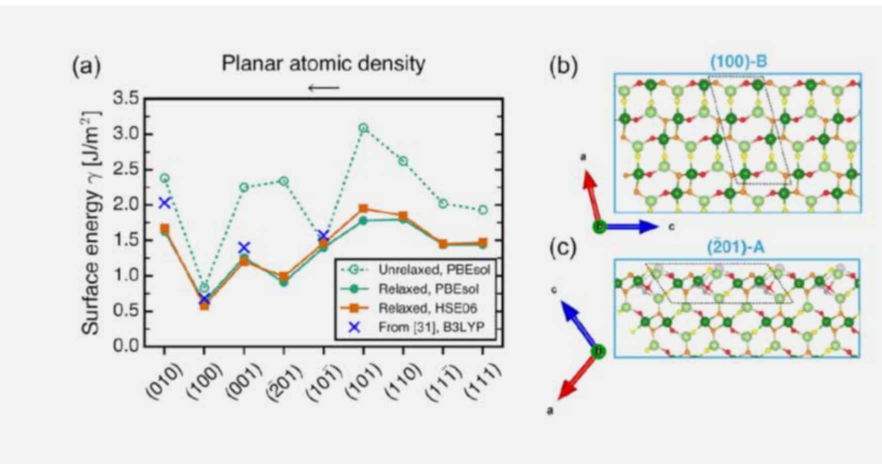


Fig. 1
(a) Calculated energies of different β-Ga_2O_3 surfaces. The surface terminations are ordered from left to right on the x-axis according to decreasing planar atomic density. If more than one surface termination is available for a given Miller plane, only the termination with the lowest surface energy is shown. [(b) and (c)] Side view of the two surface terminations with the lowest surface energies. Two terminations (A and B) can be found for both the (100) and the ($\bar{2}$01) surfaces. Here, we only show the most stable termination for both Miller planes. The relaxed slab (colored spheres) is superimposed with the unrelaxed slab (light gray spheres). The dashed parallelograms indicate the surface unit cell.

Simulation & Characterization

These findings by theory are in excellent agreement with our experimental findings that all surfaces except the (100) surface tend to form lower energy surface facets as described in the classical work by G. Wulff in 1901 (Zeitschrift für Kristallographie). It clearly shows that surface faceting in β-Ga_2O_3 is governed by thermodynamics. These findings by theory also explain a striking experimental finding in growth on the stable (100) surface with different miscut directions. Due to the monoclinic symmetry miscuts toward [001] and [00$\bar{1}$] are not equivalent. While substrate surfaces with miscuts toward [$\bar{1}$00] exhibit monolayer surface steps terminated by (($\bar{2}$01) facets, their counterparts on surfaces with miscut angles towards [001] exhibit a mixture of monolayer and bilayer steps bound by (001) facets (Fig. 2). Since the latter have higher energy, these (001) facets undergo a transformation to low energy facets by twinning of the complete layer. The twinning of the layer causes stacking mismatch boundaries that are electrically active, i.e act as acceptors that reduce the concentration of free charge carriers and as scattering centers that reduce their mobility. The Hall effect measurements of series of samples grown on substrates with optimum miscut angles of 6° toward [00$\bar{1}$] and [001] shown in Fig. 3 prove that those grown with the miscut toward [00$\bar{1}$] have reproducibly high mobilities that are in the range of the best values published in the literature, while those grown with miscuts toward [001] have extremely low values.

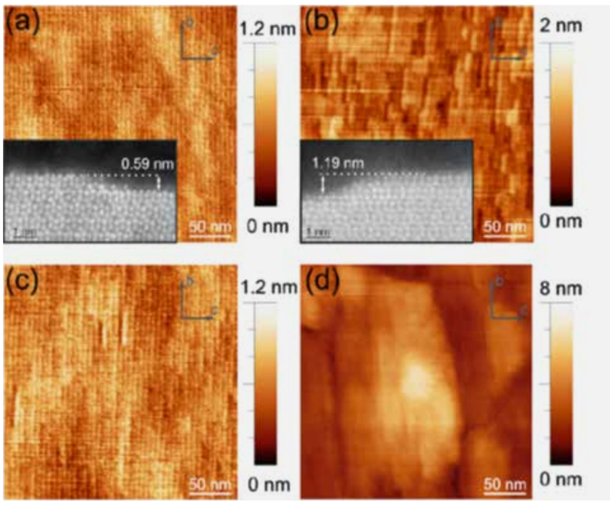


Fig. 2
AFM images of annealed β-Ga_2O_3 (100) substrates with a miscut of 6° toward (a) the [00-1] and (b) the [001] directions. The insets show atomically resolved cross-sectional STEM images (Ga atoms appear as bright dots) recorded along the [010] projection direction, of the layer grown on the substrates shown in (a) and (b), respectively. The step in (a) is a monolayer step of half a unit cell thickness; the step in (b) is a bilayer step of a unit cell height; [(c) and (d)] AFM images of the surface of the layer grown on substrates shown in (a) and (b), respectively. Step-flow growth is observed in (c), and three-dimensional growth is observed in (d).

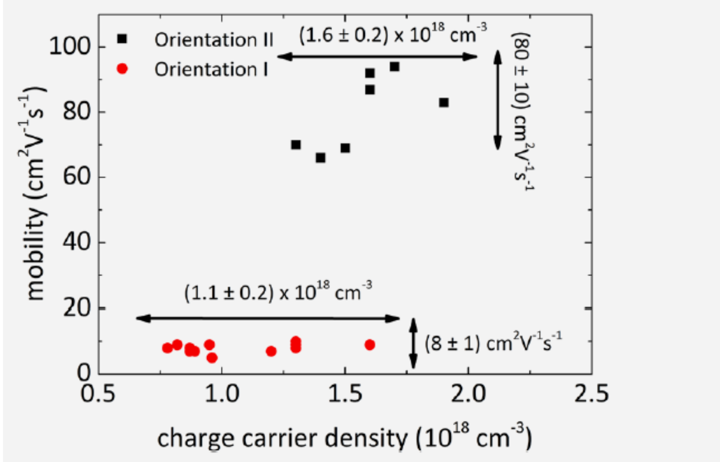


Fig. 3
Electron Hall mobility as a function of the electron Hall concentration at room temperature for β-Ga_2O_3 layers homoepitaxially grown by MOVPE on (100) oriented substrates with a predefined miscut of 6°, either along [001] (red dots) or [00$\bar{1}$] (black squares)

Publications

R. Schewski , K. Lion , A. Fiedler, C. Wouters , A. Popp, S. V. Levchenko, T. Schulz , M. Schmidbauer, S. Bin Anooz, R. Grüneberg, Z. Galazka , G. Wagner, K. Irmscher , M. Scheffler, C. Draxl, and M. Albrecht; *Step-flow growth in homoepitaxy of β-Ga_2O_3 (100) – The influence of the miscut direction and faceting,* APL Mater. **7**, 022515 (2019).

P. Mazzolini, P. Vogt, R. Schewski, C. Wouters, M. Albrecht, and O. Bierwagen, *Faceting and metal-exchange catalysis in (010) β-Ga2O3 thin films homo-epitaxially grown by plasma-assisted molecular beam epitaxy*, APL Materials, APL Mater. **7**, 022511 (2019).

In situ grazing-incidence X-ray diffraction –

A versatile tool for the investigation of ferroelectric phase transitions in $K_xNa_{1-x}NbO_3$ strained epitaxial layers

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X-ray diffraction is an established and powerful tool for the structural characterization of matter. One of the main benefits is the high angular resolution, which makes X-rays sensitive to small lattice strains and to periodic structures at the mesoscopic length scale up to about one micrometer. In addition, there are specific advantages in the investigation of thin layers and multilayered structures since the penetration depth of the X-rays can be tuned from a few nanometers up to a couple of micrometers.

Here, we report on the investigation of thermally induced phase transitions in epitaxially strained ferroelectric thin films. *In situ* X-ray diffraction is well suited for this purpose since information can be obtained both about the atomic structure of the epitaxial layer and about its periodic ferroelectric domain formation. Ferroelectric domains form to relax epitaxial strain in the layer. Their formation is governed by the energy balance of electrostatic, elastic and interfacial contributions, and they are often arranged in a periodic order. In the corresponding X-ray diffraction pattern this leads to a characteristic peak splitting and accompanying satellite reflections caused by the periodic arrangement of the domains and domain walls. Therefore, temperature dependent *in situ* X-ray diffraction is an effective and elegant way to identify and characterize ferroelectric phase transitions in epitaxial layers.

These investigations require a rapid and effective data acquisition. In order to get the full information about the three-dimensional (3D) arrangement of the domains, the scattered intensity distribution has to be measured in all three dimensions of the reciprocal space. For this purpose, we employ an area detector, which allows a 3D mapping of the reciprocal space with a single scan of the sample. In order to further reduce the data acquisition time and at the same time obtain good counting statistics, we have used highly brilliant synchrotron radiation. For a fixed sample temperature a single 3D mapping takes about 10-30 minutes so that a temperature series can be performed in a reasonable period of time.

We performed X-ray diffraction experiments in various complementary scattering geometries including grazing incidence X-ray diffraction (GIXD). This technique is particularly sensitive to in-plane strains and in-plane domain morphology (domains size and periodic arrangement). On the other hand, the limited penetration depth makes GIXD particularly sensitive to the thin film. Out-of-plane high-resolution X-ray diffraction has been also applied. This yields complementary information about out-of-plane strains and the overall 3D arrangement of the domains and domain walls.

The investigated material system $(K,Na)NbO_3$ is a promising candidate for the replacement of lead-containing ferro-/piezoelectrics in technological devices. Ongoing research in close cooperation with the group 'Ferroelectric Oxide Layers' investigates strain engineering of $(K,Na)NbO_3$ epitaxial layers, grown by metal organic vapor phase epitaxy (MOVPE) on various rare earth scandate substrates, such as $NdScO_3$, $GdScO_3$, $TbScO_3$, or $DyScO_3$ (for an overview of these activities see [1]). In particular, monoclinic ferroelectric phases can be induced by the built-in lattice distortions caused by the (anisotropic) lattice mismatch between substrate and layer. In these monoclinic phases, the electrical polarization vector is not constrained to highly symmetrical crystallographic directions – as in rhombohedral, orthorhombic or tetragonal phases – but has the degree of freedom to rotate within certain mirror planes of the monoclinic unit cell. This leads to huge piezoelectric coefficients, making monoclinic ferroelectric phases very attractive for piezoelectric and ferroelectric technological applications.

An alternative approach to achieve improved functional properties is to involve phase transitions. This is interesting with regard to two aspects: Firstly, technologically important parameters such as dielectric permittivity or piezoelectric coefficients are often greatly increased in the immediate vicinity of phase transitions.

Simulation & Characterization

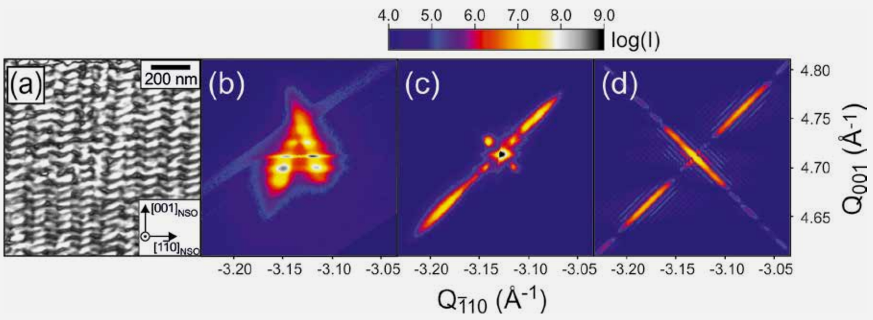


Fig. 1
(a) Lateral piezoresponse force microscopy (LPFM) amplitude image of a 38 nm $K_{0.9}Na_{0.1}NbO_3$ ferroelectric film grown on (110) $NdScO_3$. GIXD in-plane intensity distribution around the $(2\text{-}26)_{NSO}$ substrate Bragg reflection measured at (b) 25°C, and (c) 300°C, (d) corresponding simulation for 300°C.

Secondly, the phase transition temperatures can be intentionally changed by the specific implementation of epitaxial strains and thus be adapted to possible technological requirements. This so-called 'strain engineering' of phase transitions therefore plays a very important role and is investigated in more detail in the department Layers & Nanostructures.

Here we report on $K_{0.9}Na_{0.1}NbO_3$ epitaxial layers grown on $NdScO_3$ (NSO) substrates by MOVPE in the thickness range of 14 to 52 nm. The room temperature structure shows a characteristic herringbone-like domain arrangement which is caused by the coexistence of two differently oriented monoclinic phases. A typical domain pattern is presented in Fig. 1a for a 38 nm film along with the corresponding room temperature GIXD intensity distribution (Fig.1b). The room temperature structure is discussed in detail in [2] and in the annual reports of 2015 & 2017.

At about T = 200°C we observe a ferroelectric-ferroelectric phase transition for all films and the corresponding GIXD diffraction patterns significantly change. This is exemplarily shown in Fig. 1c for the 38 nm film measured at T = 300°C. We have performed a detailed analysis of the high temperature phase. Due to the complexity of the domain pattern and corresponding X-ray diffraction intensity distributions, we have investigated a large number of nonequivalent Bragg reflections. Only in this way it is possible to unambiguously disentangle the impact of lattice strains/tilts and the periodic arrangement of the domain pattern on the diffraction pattern. Accompanying theoretical simulations of the experimental X-ray diffraction pattern were carried out. Our analysis proves that a high temperatures an orthorhombic ferroelectric phase is present at sufficiently small layer thicknesses (≈ 14 nm). Here the electrical polarization vector is aligned in the plane and rotates alternately by ± 90° between adjacent domains. This leads to a so-called a_1/a_2 domain structure, with a corresponding stripe domain pattern.

With increasing film thickness, we observe a small elastic lattice distortion (≤1°) along the in-plane diagonal of the orthorhombic unit cell, which – eventually – leads to the formation of a distorted orthorhombic unit cell with monoclinic symmetry (Fig.2).

In our simulations we have taken this lattice distortion into account and found the presence of a characteristic peak splitting along the $[11\text{-}2]_{NSO}$ directions of the $NdScO_3$ substrate. We obtained a very good qualitative agreement between experiment (Fig.1c) and simulation (Fig.1d). For the sake of clarity we only show the results obtained in the vicinity of the $(2\text{-}26)_{NSO}$ substrate Bragg reflection, but we would like to stress at this point that this agreement has been achieved for a very large number of different Bragg reflections.

Our results demonstrate that *in situ* x-ray diffraction is a versatile, nondestructive tool to identify and structurally characterize phase transitions in ferroelectric epitaxial layers. We thank ESRF, PETRA III, DIAMOND and BESSY staff for technical support during the measurements.

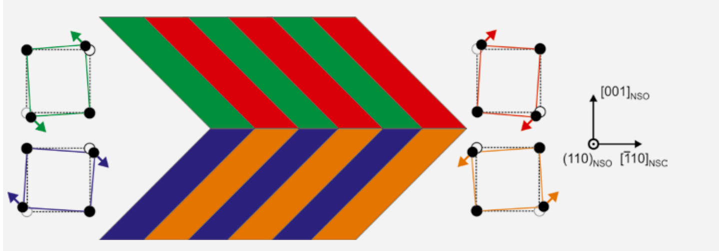
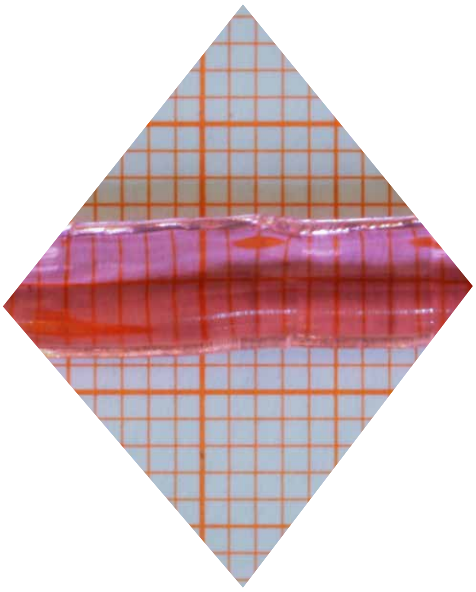


Fig. 2
Schematic view of the stripe domain pattern exhibiting a distorted a_1/a_2 orthorhombic crystal structure proposed for high temperatures. The different domain types are color coded with respective distorted in-plane unit cell.

Publications

[1] J. Schwarzkopf, D. Braun, M. Hanke, R. Uecker, M. Schmidbauer; Strain Engineering of Ferroelectric Domains in $K_xNa_{1-x}NbO_3$ Epitaxial Layers; Front. Mater. **4**, 26 (2017); https://doi.org/10.3389/fmats.2017.00026

[2] M. Schmidbauer, D. Braun, T. Markurt, M. Hanke, J. Schwarzkopf; Strain Engineering of Monoclinic Domains in $K_{0.9}Na_{0.1}NbO_3$ Epitaxial Layers: A Pathway to Enhanced Piezoelectric Properties; Nanotechnology **28,** 24LT02 (2017); https://doi.org/10.1088/1361-6528/aa715a



Center for Laser Materials

Growth of high-melting cubic sesquioxide crystals by the optical floating zone method

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The cubic sesquioxide laser crystals lutetia (Lu_2O_3) and scandia (Sc_2O_3) have been shown to be excellent host materials for rare-earth-doped laser gain media. They possess a high thermal conductivity and a strong crystal field strength, which ensures a good heat management in high-power lasers and yields broad emission spectra and/or emission at unusual wavelengths, respectively. Moreover, sesquioxides exhibit comparably low phonon energies, making them highly suitable host materials for mid-infrared lasers, e.g. when doped with erbium (Er^{3+}).

Unfortunately, both crystals exhibit very high melting points of more than 2400 °C, which imposes great challenges on their growth. In the past, the heat exchanger method (HEM) has been applied for the growth of these crystals in rhenium crucibles. Rhenium is the only crucible material known to be chemically inert to the melt even at the required high temperatures. Nevertheless, rhenium crucibles are very expensive and require a very precise control of the oxygen partial pressure during the growth to avoid corrosion.

To overcome these difficulties, researchers from the Center for Laser Materials (ZLM) and the Oxide and Fluoride group at the IKZ suggested to utilize the optical floating zone (OFZ) method for the growth of sesquioxide laser crystals. This research was funded within the BMBF project "EQuiLa" (FKZ 13N14192). In the OFZ method schematically displayed in Fig. 1, rods made from pressed and sintered crystal growth starting materials mixed according to the desired composition of the crystal are fed with velocities of several millimeters per hour through the focus of a strong xenon arc lamp, where they melt up to maintain a molten zone between the feed end and the growing crystal. The liquid zone is held by surface tension and solidifies in a crystalline phase after exiting the lamp focus. The crystals grown at several millimeters per hour can be several centimeters in length with a diameter of millimeters or even up to the centimeter scale, sufficient for many laser applications. The OFZ method does not require any crystal growth crucibles or insulation, which enables a substantial reduction of the production cost. Moreover, the growth atmosphere can be freely chosen, ensuring optimized crystal quality.

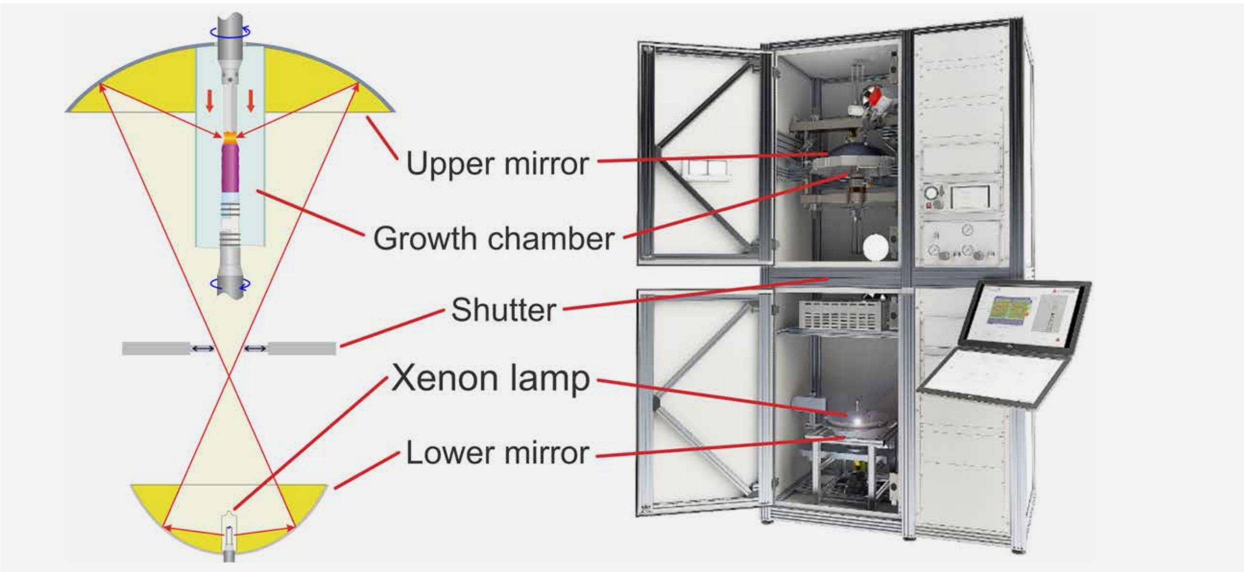

Fig. 1
Schematic setup and photography of the optical floating zone crystal growth furnace (Photo courtesy of SciDre).

Center for Laser Materials

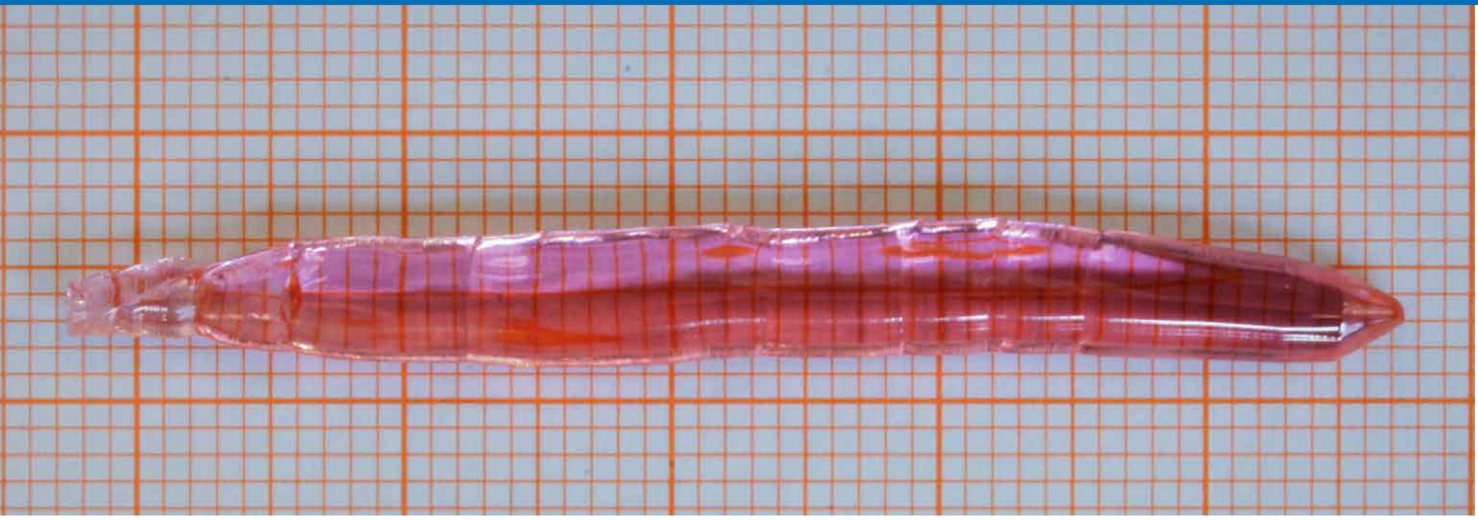

Fig. 2
OFZ-grown Er^{3+}(7at.%):Lu_2O_3 crystal

In numerous growth experiments different growth parameters such as lamp power, growth atmosphere and pressure, as well as translation and rotation velocity of the feed and the growing crystal were varied. As a result of this study, rare-earth doped sesquioxide crystals with more than 4 cm length and a diameter of ca. 4 mm were successfully grown for the first time (see Fig. 2). The facetted crystals showed a high transparency and were free of color centers, cracks or any other visible structural defects.

Due to the absence of an afterheater and the resulting very strong thermal gradients, up to now the as-grown crystals exhibit stress induced birefringence which is revealed by inspection between crossed polarizers. It can, however, be expected that this stress will be significantly reduced after the installation of an afterheater scheduled for the second half of 2019.

Even the samples fabricated with the current setup enabled preliminary spectroscopic investigations. These revealed a high uniformity of the doping ion distribution in the crystal. Moreover, the lifetime of the excited state of Er^{3+}(7at.%):Lu_2O_3 was found to be nearly twice as high as that of crystals of the same composition grown by the conventional heat exchanger method. The latter is attributed to the absence of impurities caused by the crucible or the insulation materials. This is of particular importance for the efficiency of the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition of the Er^{3+} ion, which enables efficient laser operation in the mid-infrared at 2.85 µm in Er:Lu_2O_3. Due to the strong absorption of water in this wavelength range, such lasers are highly demanded e.g. in medicine where they find application in laser scalpels.

Therefore, excellent laser performance can be expected from OFZ grown sesquioxide laser crystals as soon as the installation of the afterheater completes the commissioning of the new high temperature OFZ furnace at IKZ.

These results give rise also to the growth of sesquioxide crystals doped with other rare earth ions. In particular ytterbium (Yb^{3+}) doped sesquioxide crystals have been shown to exhibit outstanding properties for the generation of ultrashort pulses at wavelengths around 1 µm and the geometry of the samples grown by OFZ is well suited for modern “crystal-fiber” amplifier systems which rely on very long and thin crystals for efficient heat removal from the active element. Also for lasers in the 2 µm spectral range there is a strong demand for holmium (Ho^{3+}) and thulium (Tm^{3+}) doped sesquioxide crystals.

Center for Laser Materials

Efficient direct yellow laser emission from Tb^{3+}-doped fluoride crystals

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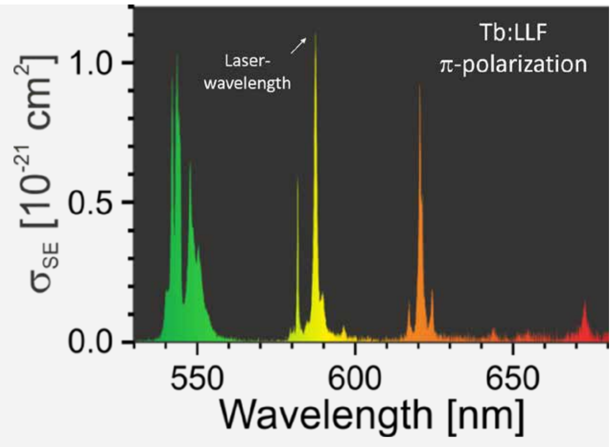
Laser emission in the visible range is often not straightforward to achieve. The well-known "green gap" in the emission of semiconductor materials hinders the development of semiconductor-based sources emitting in the green to orange spectral range. For this reason, even well-established visible lasers such as green laser pointers, though compact, are quite complicated diode-pumped frequency doubled solid-state lasers. They utilize a GaAlAs-based laser diode emitting at 808 nm pumping an Nd^{3+}-doped laser crystal emitting at 1064 nm, which itself is converted into green light at 532 nm in a nonlinear frequency conversion process in a KTP crystal.

Fluoride crystals doped with the trivalent rare earth element praseodymium (Pr^{3+}) can simplify the generation of visible laser emission. Modern InGaN-based laser diodes emitting in the blue at wavelengths around 450 nm can serve as efficient pump sources for these Pr^{3+}-doped diode-pumped solid-state lasers, which directly generate visible laser emission. Pr^{3+}-doped crystals enable highly efficient laser operation in the red, green and orange spectral range at efficiencies comparable to the aforementioned Nd^{3+}-lasers at 1064 nm, but as no further wavelength conversion is required, the total system efficiency is much higher.



However, Pr^{3+} does not enable laser operation in the yellow spectral range between 570 nm and 590 nm. Therefore, recently crystals doped with trivalent terbium (Tb^{3+}) were suggested as laser active materials. Tb^{3+} is known and well-established as a brilliant lemon-yellow phosphor in fluorescent lamps and color TV tubes. Indeed, as shown in Fig. 1 it exhibits strong emission lines in the green, yellow and orange spectral range. Still, for a long time it was not considered a suitable candidate for laser operation. This is due to its low absorption and emission cross sections caused by the relevant transitions being spin-forbidden. Moreover, while the laser transitions occur within the 4*f*-shell, the low energetic position of the higher 5*d*-shell-states imposes the risk of detrimental excited state absorption from the upper laser level. This absorption would be parity allowed and thus very strong and was believed to hinder the laser process.

Researchers of the Center for Laser Materials (ZLM) at the IKZ successfully circumvented these limitations by using highly Tb^{3+} doped lithium lutetium fluoride ($LiLuF_4$ or LLF) as the gain material. The low crystal field strength of fluoride crystals strongly diminishes the detrimental excited state absorption and the high concentration of Tb^{3+}-ions in this material compensates for the low absorption and emission cross sections.

By this approach, a 28% Tb^{3+}-doped LLF crystal pumped by an optically pumped frequency doubled semiconductor laser at 488 nm delivered a record high output power of 0.5 W at a laser wavelength of 588 nm well within the yellow spectral range (see Fig. 2).

Fig. 1
Stimulated emission cross-section for light polarized parallel to the optical axis of Tb:LLF.

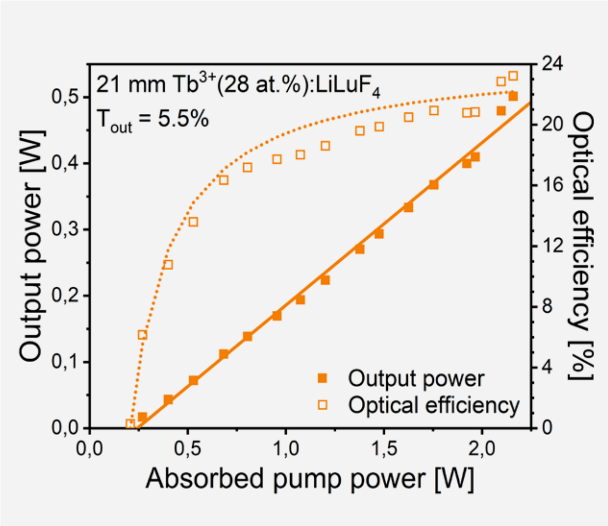


Fig. 2
Laser characteristics at 588 nm for a 21 mm long LLF crystal doped with 28 at.% of Tb^{3+} at the best output coupler transmission of 5.5%.

The slope efficiency of this system amounts to 25%, which makes this laser the most efficient directly yellow emitting solid-state lasers.

Besides the outstanding performance in the yellow Tb:LLF allows for even higher efficiencies in excess of 50% when operated at the green transition around 545 nm, where already more than 1 watt of output power was demonstrated.

The output power of Tb^{3+} lasers is currently only limited by the pump power of the frequency doubled semiconductor pump source used in these proof-of-principle experiments. The prospects for future diode pumping are excellent since laser diodes at the required pump wavelength of 488 nm are becoming available. Further increase of their output power will also enable power scaling, since LLF is a well-established host crystal known to withstand high powers when doped with other laser ions.

Since the emission wavelength of this Tb^{3+}-laser is very close to the sodium (Na) absorption D-lines at 589 nm, it may find applications in fields that require sodium detection such as microscopy or astronomical optics, where, e.g., laser guide stars are produced by exciting sodium in higher atmospheric layers. In addition, the high absorption of hemoglobin at yellow wavelengths allows for very selective treatments in skin and eye surgery. The complexity of the current yellow lasers utilized in this applications could drastically decrease by the implementation of these simple and cost-efficient Tb^{3+}-based lasers.

Publication

E. Castellano-Hernández, P. W. Metz, M. Demesh, and C. Kränkel, *Efficient directly emitting high-power Tb^{3+}:$LiLuF_4$ laser operating at 587.5 nm in the yellow range,* Opt. Lett. **43** (19), 4791 (2018)

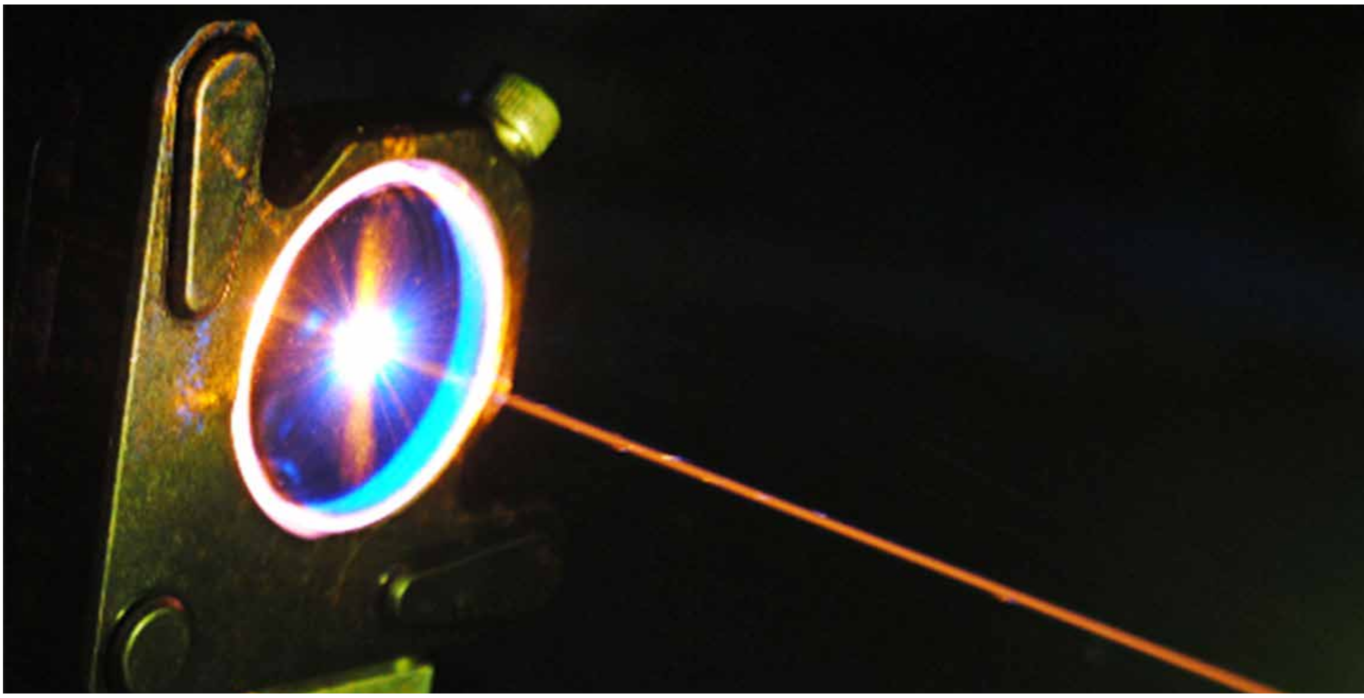


Fig. 3
Detail photography of the yellow emitting Tb:LLF laser resonator.

Appendix

Publications

Articles in international peer-revieved journals

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Monography

K. Eylers; *Entwicklung eines Verfahrens zur Züchtung von örtlich definierten $Cu(In,Ga)Se_2$ Absorbern für Mikrokonzentrator-Solarzellen*; Verlag Dr. Hut GmbH; 115 pp

Other publications (non-reviewed)

N. Dropka, C. Frank-Rotsch, F. M. Kiessling, P. Rudolph; *Intensification of bulk crystal growth by magnetic fields: from lab-scale to commercial size equipment*; Proc. 55th Meeting of the Serbian Chamical Society

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Talks and Posters

Invited talks at national and international conferences

N. V. Abrosimov; Monoisotopic silicon: *Technological peculiarities related to the growth, properties and application*; Silicon-2018, Chernogolovka, Russia

M. Albrecht; R. Schewski, D. Meiling, M. Baldini, K. Irmscher, T. Markurt, B. Neuschulz T. Remmele, T. Schulz, G. Wagner; *Elementary processes in homoepitaxial growth of Ga_2O_3 studied by transmission electron microscopy*; Photonics West 2018, San Francisco, USA

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M. Albrecht; R. Schewski, A. Fielder, M. Baldini, A. Popp, S. Bin Anooz, G. Wagner, Z. Galazka, K. Irmscher; *Ga_2O_3 from materials to devices;* 20th Workshop on Dielectrics in Microelectronics, Berlin, Germany

M. Albrecht; M. Anikeeva, T. Schulz, L. Lymperakis, C. Freysoldt, Z. Chen, X. Zheng, C. Cheze, R. Calarco, J. W. Tomm, F. Mahler, P. Wolny, M. Sawicka, Marcin Siekacz, C. Skierbiszewski, G.Schmidt, F. Bertram, J. Christen, X. Q. Wang, J. Neugebauer; *InGaN Still to be discovered*; International Symposium on Growth of III-Nitrides ISGN-7, Warsaw, Poland

M. Bickermann; Z. Galazka, S. Ganschow, D. Klimm, R. Uecker; *Crystals and Substrates for Semiconducting Oxide Applications*; Deutsch-Französischer Oxidkristall-/Dielektrika-/Laserkristall-Workshop 2018 (DGKK-Oxide 2018) Idar-Oberstein, Germany

M. Bickermann; C. Hartmann, J. Wollweber, A. Dittmar, I. Gamov, K. Irmscher; *On the preparation of AlN single crystals and substrates for AlGaN devices*; Internationalen Workshop on Nitride Semiconductors (IWN 2018), Kanazawa, Japan

N. Dropka; Ch. Frank-Rotsch, F.M. Kiessling, P. Rudolph; *Intensification of bulk crystal growth by magnetic fields: from lab-scale to commercial size equipment*; 55. Meeting of Serbian chemical society, Novi Sad, Serbia

N. Dropka; M. Holena, S. Ecklebe, Ch. Frank-Rotsch, J. Winkler; *Towards optimization of bulk crystal growth recipe by dynamic neural networks*; IWMCG-9, Kona, USA

S. Ecklebe; J. Winkler, F. Woittennek, Ch. Frank-Rotsch, N. Dropka; *Control of the VGF Process I: Feedforward Control and Flatness Based State Feedback*; ECCG-6, Varna, Bulgaria

Ch. Frank-Rotsch; *Semiconductor single crystal growth with reduced defect formation by optimized process parameters*; 26th Annual Meeting of the German Crystallographic Society (DGK), Duisburg/Essen, Germany

Z. Galazka; *Progress in bulk growth of β-Ga_2O_3*; German-Austrian Conference on Crystal Growth GACCG/DKT 2018; Vienna, Austria

Z. Galazka; *Defects in ultrawide-bandgap oxide semiconductor β-Ga_2O_3*; Europhysical Conference on Defects in Insulating Materials (EURODIM 2018), Bydgoszcz, Poland

Z. Galazka; *New methods for growing thermally unstable oxide single crystals from their melts*; 6th European Conference on Crystal Growth (ECCG6), Varna, Bulgaria

S. Ganschow; D. Klimm; *Challenges in melt growth of high melting point oxide single crystals*; Materials Science and Engineering, Darmstadt, Germany

K. Irmscher; A. Fiedler, Z. Galazka, M. Baldini, A. Popp, G. Wagner, R. Schewski, and M. Albrecht; *Doping and Defects in β-Ga_2O_3*; Gordon Research Conference on Defects in Semiconductors, New London, USA.

K. Irmscher; A. Fiedler, Z. Galazka, A. Popp, G. Wagner, R. Schewski, and M. Albrecht; *Doping and Defects in β-Ga_2O_3*; International CECAM-Workshop "Reliable and quantitative prediction of defect properties in Ga-based semiconductors", Bremen, Germany

K. Irmscher; A. Fiedler, Z. Galazka, A. Popp, S. Bin Anooz, G. Wagner, R. Schewski, and M. Albrecht; *Doping and Defects in β-Ga_2O_3*; MRS Fall Meeting, Boston, USA

D. Klimm; *Single-Crystal Growth Supported by Means of TGA-DTA-MS Skimmer Coupling*; 7th Coupling Days on Thermal Analysis Coupled to Evolved Gas Analysis, Selb, Germany

C. Kränkel; E. Castellano-Hernández, A. Uvarova, P. von Brunn, C. Paradis, N. Modsching, V. J. Wittwer, T. Südmeyer, and A. Heuer; *Advanced materials for multi-wavelength, high power and short pulse solid state lasers;* OPTIQUE Toulouse 2018, Toulouse, France

Talks and Posters

C. Kränkel; E. Castellano-Hernández, and A. M. Heuer; *Tailored crystals for solid-state lasers;* 18th International Conference Laser Optics (ICLO2018), St. Petersburg, Russia

C. Kränkel; *Fabrication of advanced MIR Gain Media – Status and Overview (HECMIR);* Photonic-Tage Berlin-Brandenburg, Workshop on High Energy Class Mid Infrared Lasers, Berlin, Germany

C. Kränkel; *Novel crystalline laser materials for lasers from the visible to the mid-infrared spectral region;* 29th International SAOT Workshop on Lasers - Simulation and Design of Advanced Solid-State Lasers, FAU Erlangen-Nürnberg, Erlangen, Germany

C. Kränkel; *Novel solid-state materials*; Conference on Lasers and Electro-Optics (CLEO2018), San Jose, USA

W. Miller, A. Popescu, X. Qi; Numerical investigations on grain evolution during direct solidification of silicon; 10th International Workshop on Crystalline Silicon for Solar Cells (CSSC-10); Sendai, Japan

A. Popp, S. Bin Anooz, R. Grüneberg, A. Fiedler, Z. Galazka, C. Wouters, R. Schewski, M. Albrecht, K. Irmscher and G. Wagner; *The challenge to grow delta-doped ß-Ga_2O_3 layers by MOVPE*; 2018 Program Review of Aerospace Materials for Extreme Environments, Niceville, USA

A. Popp; S. Bin Anooz, R. Grüneberg, A. Fiedler, Z. Galazka, C. Wouters, R. Schewski, M. Albrecht, K. Irmscher and G. Wagner; *Realizing of homoepitaxial ß-Ga_2O_3 layers by MOVPE to generate Si-delta doped structures*; E-MRS 2018 Fall Meeting, Warsaw, Poland

A. Popp; G. Wagner, S. Bin Anooz, M. Albrecht, C. Wouters, A. Fiedler, Z. Galazka, K. Irmscher, R. Schewski, M. Schmidbauer; *Influence of the substrate orientation on structural and electrical properties of homoepitaxial β-Ga_2O_3 layers grown by MOVPE* ; US Workshop on Gallium Oxide, Columbus, USA

H. Tanaka; E. Castellano-Hernández, C. Kränkel, S. Fujita, and F. Kannari; *Chromium and cobalt doped saturable absorbers for passively Q-switched visible lasers;* 13th Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR) 2018, Hong Kong, China

M. Tokurakawa; E. Fujita, A. Suzuki, and C. Kränkel; *Sub-120 fs Kerr-lens mode-locked Tm:Sc_2O_3 laser at 2.1 µm wavelength range;* 18th International Conference on Laser Optics (ICLO2018), St. Petersburg, Russia

G. Wagner; A. Popp, M. Albrecht, A. Fiedler, Z. Galazka, K. Irmscher, R. Schewski, M. Schmidbauer; *Influence of the substrate orientation on the properties of β-Ga_2O_3 layers deposited by MOVPE*; ICMOVPE XIX, Nara, Japan

Invited talks at national and international institutions

M. Bickermann; *Status and Challenges of AlN Bulk Crystal Growth for Use as Substrates in Deep-UV Applications*; Colloquium of the Fraunhofer IISB, Erlangen, Germany

M. Bickermann; *Kristalle und Substrate aus Aluminiumnitrid für optoelektronische Bauelemente im tiefen UV*; Seminar at the Fraunhofer THM, Freiberg, Germany

M. Bickermann; *Volumenkristallzüchtung für die (Opto-) Elektronik der Zukunft: Herausforderungen bei der Herstellung von SiC-, AlN- und Ga_2O_3-Substraten*; Seminar on the 80th birthday of Klaus-Werner Benz at the FMF, Freiburg, Germany

M. Bickermann; *Crystal growth of oxides and fluorides for novel applications*; Seminar "Optical Single Crystals", National Institute for Materials Science (NIMS) in Tsukuba, Japan

K. Dadzis; *Measurement systems in crystal growth: from process control to material characterization*; Seminar"Measurement Systems", TU Dresden, Dresden, Germany

A. Fiedler, R. Schewski, A. Popp, S. Bin Anooz, M. Baldini, Z. Galazka, G. Wagner, M. Albrecht; K. Irmscher; ß-Ga_2O_3 – Challenge to achieve device grade material for power electronics; Ohio State University, Columbus, USA

D. Klimm; *Seltenerd-Scandiumoxid-Systeme: Phasendiagramme und Kristallzüchtung*; Max-Planck-Institut für Chemische Physik fester Stoffe, Dresden, Germany

C. Kränkel; *Tailored laser crystals for solid state lasers*; Common Meeting of the Laboratories for Attosecond Physics, Max Planck Institut für Quantenoptik/LMU München/TU München, München, Germany

C. Kränkel; *Novel crystals for tailored solid state lasers*; Laser Colloquium, Photonics and Ultrafast Laser Science, Ruhr Uni Bochum, Bochum, Germany

T. Markurt; *Point defect formation and clustering in $SrTiO_3$ crystals*; Institut-Neel, Grenoble, France

T. Markurt; *In-situ Gas Cell TEM for crystallization and phase stability experiments;* In-situ Electron Microscopy Workshop, Karlsruhe Institute of Technology, Karlsruhe, Germany

Talks and Posters

A. Popp; G. Wagner, S. Bin Anooz, M. Albrecht, C. Wouters, A. Fiedler, Z. Galazka, K. Irmscher, R. Schewski, M. Schmidbauer*; Influence of the substrate orientation on structural and electrical properties of homoepitaxial β-Ga_2O_3 layers grown by MOVPE & The growth of delta doped layers*; Air Force Research Laboratory, USA

T. Teubner, N.V. Abrosimov; *SiGe MBE and ^{28}Si at IKZ;* Infineon-Workshop "Process concepts for a Si-based quantum chip", Dresden, Germany

J. Wollweber; A. Dittmar, C. Harmann, M. Bickermann; *Growth of ScN-AlN mixed crystals by PVT*; Institut für Angewandte Physik, TU Braunschweig, Germany

Oral contributions at national and international conferences

S. Bin Anooz, A. Popp, R. Grüneberg, M. Schmidbauer, C. Wouters, A. Fiedler, A. Kwasniewski, M. Ramsteiner, R. Schewski, M. Albrecht, K. Irmscher, G. Wagner; Indium incorporation in ß-Ga_2O_3 thin films grown by metal organic vapor phase epitaxy; E-MRS Fall Meeting, Warsaw, Poland

L. Bogula; T. Markurt, M. Albrecht, J. Schwarzkopf; *Defect and interface formation in $SrTiO_3$ homoepitaxial thin film growth;* DPG Spring Meeting, Berlin, Germany

J. Boschker; S. Bin Anooz, B. Kalas, T. Markurt, S.V. Pettersen, M. Ramsteiner, J.K. Grepstad, P. Petrik, M. Albrecht and Jutta Schwarzkopf; *Epitaxial stabilization of NbO_2 on TiO_2 (110)*; DPG Spring Meeting; Berlin, Germany

J. Boschker; S. Bin Anooz, B. Kalas, T. Markurt, S.V. Pettersen, M. Ramsteiner, J.K. Grepstad, P. Petrik, M. Albrecht and Jutta Schwarzkopf; *Epitaxial Stabilization of Single Crystalline Semiconducting and Metallic NbO_2;* CIMTEC 2018 im Perugia, Italy

J. Boschker; B. Kalas, T. Markurt, S.V. Pettersen, M. Ramsteiner, J.K. Grepstad, P. Petrik, M. Albrecht and Jutta Schwarzkopf; *Progress in the epitaxial growth of Nb_2O_5 and NbO_2*; 14th meeting of the working group "Materials for Nonvolatile Memories", Halle, Germany

J. Boschker; *Introduction to the Leibniz-Institut für Kristallzüchtung (IKZ)*; MADMAX Autumn meeting; Zaragoza, Spain.

E. Castellano-Hernández; M. Demesh, H. Tanaka, C. Kränkel; Efficient *High Power Yellow Tb^{3+}:$LiLuF_4$ Laser*; CLEO Conference 2018; San José, California, USA

E. Castellano-Hernández; A. Uvarova, M. Demesh, H. Tanaka, C. Kränkel; *Tb^{3+}-doped materials for efficient lasing at 588 nm*; 8th EPS-QEOD Europhoton 2018; Barcelona, Spain

S.Y. Choi; T. Calmano, F. Rotermund, C. Saraceno, and C. Kränkel; *Multi-GHz mode-lokced Yb:YAG channel waveguide laser using SESAM and carbon nanotube saturable absorbers;* 13th Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR) 2018, Hong Kong, China

K. Dadzis; R. Menzel, H. Riemann, N.V. Abrosimov; *Development of the granulate crucible method for growth of large silicon crystals;* 10th International Workshop on Crystalline Silicon for Solar Cells, Sendai, Japan

K. Dadzis; R. Menzel, H. Riemann, N.V. Abrosimov; *Modeling of phase boundaries in floating zone growth using COMSOL;* 1st German-Austrian Conference on Crystal Growth (GACCG/ DKT2018), Vienna, Austria

M.P. Demesh; E. Castellano-Hernández, V. E. Kisel, A. S. Yasukevich, V. I. Dashkevich, V. A. Orlovich, C. Kränkel, and N. V. Kuleshov; *Spectroscopy and laser operation of Eu^{3+}:$LiYF_4$;* 18th International Conference on Laser Optics (ICLO2018), St. Petersburg, Russia

A. Dittmar; C. Hartmann, A. Kwasniewski, M. Schmidbauer, D. Klimm, J. Wollweber, M. Bickermann; *PVT growth of bulk $Al_{1-x}Sc_xN$ as lattice matched substrate for AlGaN UV-LEDs;* DKT 2018, Vienna, Austria

N. Dropka; A.G. Ostrogorsky; *CZT growth in vertical Bridgman configuration with the rotating baffle;* IWMCG-9, Kona, USA

A. Fiedler, M. Ramsteiner, Z. Galazka, K. Irmscher; *Electronic Raman scattering in ß-Ga_2O_3;* DPG Spring Meeting, Berlin, Germany

A. Fiedler, M. Ramsteiner, Z. Galazka, K. Irmscher; *Electronic Raman scattering in ß-Ga_2O_3;* Compound Semiconductor Week, Boston, USA

A. Fiedler, M. Ramsteiner, Z. Galazka, K. Irmscher; *Electronic Raman scattering in ß-Ga2O3*; E-MRS Fall Meeting, Warsaw, Poland

Talks and Posters

M. Gaponenko; F. Labaye, P. Brochard, N. Modsching, K. Gürel, V. Wittwer, C. Paradis, C. Kränkel, S. Schilt, and T. Südmeyer; *CEO frequency stabilization of a thin disk laser with intra-cavity high harmonic generation;* 8th EPS-QEOD Europhoton Conference 2018, Barcelona, Spain

F.M. Kiessling; Nikolay Abrosimov, Matthias Czupalla, Natasha Dropka, Jörg Fischer, Oleksii Gybin, Klaus Irmscher, József Janicskó-Csáthy, Uta Juda, Stefan Kayser, Wolfram Miller, Mike Pietsch; *Technology Development of High-Purity Germanium Crystals for Detectors to Be Used in GERDA and LEGEND*; ECCG-6, Varna, Bulgaria

F. Labaye; M. Gaponenko, V. Wittwer, A. Diebold, C. Paradis, N. Modsching, L. Merceron, F. Emaury, I. Graumann, C. Phillips, C. Saraceno, C. Kränkel, U. Keller, and T. Südmeyer; *Extreme ultraviolet light source by high-harmonic generation inside an ultrafast thin-disk laser*; Advanced Photonics 2018 Congress, Zurich, Switzerland

F. Lange; *Si & Ge nanowires growth by MBE*; Winter School 2018 / Compact Course: Characterization of micro- and nano-materials; Cottbus, Germany

T. Markurt; C. Guguschev, D. Kok, M. Niu, K. Irmscher, F. Kamutzki, and M. Albrecht; *Analysis of point defect formation, diffusion and clustering in $SrTiO_3$;* EMRS Fall Meeting, Warsaw, Poland
T. Markurt; *High resolution transmission electron microscopy for nano-characterization of solids;* Winterschool Characterization of micro- and nano-materials, BTU Cottbus-Senftenberg, Cottbus, Germany

T. Markurt; L. Bogula, J. E. Boschker, J. Schwarzkopf, J. Stöver, K. Irmscher, and M. Albrecht; *Analysis of point defects in oxide films grown by pulsed laser deposition;* EMRS Fall Meeting, Warsaw, Poland

T. Markurt; C. Wouters, P. Vogt, O. Bierwagen, C. Sutton, and M. Albrecht; *Studying crystallization and phase formation of $(In_xGa_{1-x})_2O_3$;* CISCEM, Saarbrücken, Germany

N. Modsching; C. Paradis, P. Brochard, N. Jornod, K. Gurel, C. Kränkel, S. Schilt, V. Wittwer, and T. Südmeyer; *Frequency comb stabilization of a 4 W, 50-fs thin-disk laser oscillator;* 32nd European Frequency and Time Forum, Torino, Italy

N. Modsching; C. Paradis, P. Brochard, N. Jornod, K. Gurel, C. Kränkel, S. Schilt, V. Wittwer, and T. Südmeyer; *Frequency comb stabilization of a 50-fs thin-disk laser oscillator operating in a strongly SPM-broadened regime;* Conference on Lasers and Electro-Optics (CLEO2018), San Jose, USA

C. Paradis; N. Modsching, O. Razskazovskaya, J. Drs, F. Meyer, C. Kränkel, C. J. Saraceno, V. J. Wittwer, and T. Südmeyer; *Thin-disk laser oscillator driven broadband THz source;* 43rd International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW – THz), Nagoya, Japan

C. Paradis; N. Modsching, O. Razskazovskaya, J. Drs, F. Meyer, C. Kränkel, C. J. Saraceno, V. J. Wittwer, and T. Südmeyer; *50-fs thin-disk laser oscillator generating broadband THz pulses;* Europhoton Conference 2018, Barcelona, Spain

C. Paradis, N. Modsching, O. Razskazovskaya, J. Drs, F. Meyer, C. Kränkel, C. J. Saraceno, V. J. Wittwer, and T. Südmeyer; *Thin-disk laser oscillator driving THz generation up to 6 THz;* 43rd International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW – THz), Nagoya, Japan

A. Popp; S. Bin Anooz, R. Grüneberg, A. Fiedler, Z. Galazka, C. Wouters, R. Schewski, M. Albrecht, K. Irmscher and G. Wagner; Realizing of homoepitaxial ß-Ga_2O_3 layers by MOVPE to generate Si-delta doped structures; EMRS Fall Meeting, Warsaw, Poland

R. Schewski; A.Fiedler, K. Irmscher, K. Lion, S. Levchenko, M. Scheffler, C. Draxl, T.Schulz, M. Schmidbauer, A. Popp, M. Baldini, G. Wagner, Z. Galazka, M. Albrecht; *Homoepitaxial growth on the (100) plane of β-Ga_2O_3 by MOVPE - the influence of the miscut direction;* EMRS Fall Meeting, Warsaw, Poland

J. Schwarzkopf; L. von Helden, S. Liang, R. Wördenweber, M. Schmidbauer; *Piezoelectric properties of monoclinic ferroelectric phases in anisotropically strained $K_{0.7}Na_{0.3}NbO_3$ thin films*; EMRS Fall Meeting Warsaw, Poland

J. Stöver; L. Bogula, T. Markurt, J. Boschker, J. Schwarzkopf, M. Albrecht, K. Irmscher; *The electric field dependence of the permittivity of $SrTiO_3$*; Deutsche Physikalische Gesellschaft – DPG Spring Meeting , Berlin, Germany

J. Stöver; L. Bogula, T. Markurt, J. Boschker, J. Schwarzkopf, M. Albrecht, K. Irmscher; *Permittivity of $SrTiO_3$ in high electric fields and its temperature dependence*; EMRS 2018, Warsaw, Poland

Talks and Posters

H. Tanaka; E. Castellano-Hernández, C. Kränkel, and F. Kannari; *Transition-metal-doped solid-state saturable absorbers for passively Q-switched visible Pr:YLF lasers*; Conference on Lasers and Electro-Optics Pacific Rim (CLEO-PR 2018), San Jose, USA

H. Tanaka; E. Castellano-Hernández, C. Kränkel, and F. Kannari; *Characterization of transition-metal-doped saturable absorbers for passive Q-switching of visible lasers*; 7th Advanced Lasers and Photon Sources Conference ALPS'18, Yokohama, Japan

M. Tokurakawa; E. Fujita, and C. Kränkel; *Sub-120 fs Kerr-lens mode-locked Tm:Sc_2O_3 laser in-band pumped by an Er;Yb fiber MOPA;* Conference on Lasers and Electro-Optics (CLEO2018), San Jose, USA

D. Uebel; R. Bansen, C. Ehlers, Th. Teubner, T. Boeck; *Surface preparation by laser treatment for liquid phase epitaxy*; DPG-Frühjahrstagung der Sektion Kondensierte Materie gemeinsam mit der EPS; Berlin, Germany

L. von Helden; M. Schmidbauer, L. Bogula, M. Hanke, P.E. Janolin, S. Liang, R. Wördenweber, J. Schwarzkopf; *Tuning the Curie-Temperature of ferroelectric, monoclinic domains in $K_xNa_{1-x}NbO_3$ thin films by different strain conditions;* DPG Spring Meeting, Berlin, Germany

L. von Helden; M. Schmidbauer, L. Bogula, M. Hanke, P.E. Janolin, S. Liang, R. Wördenweber, J. Schwarzkopf; *Tuning the Curie-Temperature of ferroelectric, monoclinic domains in $K_xNa_{1-x}NbO_3$ thin films by different strain conditions;* ISAF-FMA-AMF-AMEC-PFM, Hiroshima, Japan

C. Wouters; Toni Markurt, Robert Schewski, Christopher Sutton, Holger Von Wenckstern, Oliver Bierwagen, Patrick Vogt, Martin Albrecht; *Exploring phase stability in $(In_xGa_{1-x})_2O_3$ alloys by TEM investigations;* E-MRS 2018 Fall Meeting, Warsaw, Poland

Poster presentations at national and international conferences

N. Abrosimov, M. Czupalla, N. Dropka, J. Fischer, O. Gybin, K. Irmscher, J. Janicskó-Csáthy, U. Juda, S. Kayser, W. Miller, M. Pietsch, F.- M. Kiessling; *Technology Development for High-Purity Germanium Crystals for Detectors to Be Used in GERDA and LEGEND*; Sixth European Conference on Crystal Growth, ECCG-6, Varna, Bulgaria

N. Abrosimov, M. Czupalla, N. Dropka, J. Fischer, O. Gybin, K. Irmscher, J. Janicskó-Csáthy, U. Juda, S. Kayser, W. Miller, M. Pietsch, F. M. Kiessling; *Status of Technology Development of High-Purity Germanium Crystals at IKZ*; LEGEND workshop, Knoxville, Tennessee, USA

J. Boschker, T. Markurt, M. Albrecht, J. Schwarzkopf; *Effect of symmetry mismatch on the heteroepitaxial growth of T-Nb_2O_5 on $SrTiO_3$*; 25th International Workshop on Oxide Electronics, Les Diablerets, Switzerland

N. Dropka, C. Frank-Rotsch, F.-M. Kiessling, P. Rudolph; *Intensification of bulk crystal growth by magnetic fields: from lab-scale to commercial size equipment;* 55. Meeting of the Serbian Chemical Society; Novi Sad, Serbia

O. Ernst, K. Eylers, F. Ringleb, Th. Teubner, B. Heidmann, M. Schmid, T. Boeck; *Local Growth and Insulation of CIGSe islands for micro concentrator solar cells*; E-MRS 2018 Spring Meeting; Strasbourg, France

C. Hartmann, J. Wollweber, A. Dittmar, K. Irmscher, M. Bickermann; *Strongly improved UV transparency of bulk AlN crystals grown by PVT*, IUVA-AUVL Joint International Conference UV LED Technologies & Applications 2018 (ICULTA 2018); Berlin, Germany

F. Lange, R. Bansen, Th. Teubner, T. Boeck; *Preparation of nucleation centres for the growth of Si/Ge nanowires*; 1st Joint ISTDM/ICSI 2018 Conference; Potsdam, Germany

R. Menzel, H.-J. Rost, F. M. Kießling, L. Sylla, T. Richter; *Crucible-free growth of mono-Si using large-area seeding*; Ninth International Workshop on Modeling in Crystal Growth, IWMCG-9, Kona, USA

J. Stöver, L. Bogula, T. Markurt, J. Boschker, J. Schwarzkopf, M. Albrecht, K. Irmscher; *Temperature dependence of the permittivity of $SrTiO_3$ in high electric fields;* WODIM 2018, 20th Workshop on Dielectrics in Microelectronics, Berlin, Germany

D. Uebel, C. Ehlers, R. Bansen, Th. Teubner, T. Boeck; *Growth of Thin Film Silicon on Low-cost Substrates for Solar Cells;* 1st German-Austrian Conference on Crystal Growth (GACCG/DKT2018); Wien, Austria

N. Wolff, D. Klimm, D. Siche; *Thermodynamic investigations on the growth of $CuAlO_2$ delafossite crystals – a potential transparent p-type oxidic semiconductor;* German-Austrian Conference on Crystal Growth, Vienna, Austria

A. Wiciak, F. Lange, T. Boeck; *Elimination of the ripening process during the preparation of nucleation centers for the growth of Si Nanowires*; 18th International Conference of Physics Students (ICPS 2018); Helsinki, Finland; August 08-14, 2018

Patents

Patents

S. Ganschow, R. Bertram, D. Klimm, P. Reiche, R. Uecker
Verfahren und Anordnung zur Herstellung von ZnO-Einkristallen
DE 10 2004 003 596.2

Ch. Frank-Rotsch, P. Rudolph, R.-P. Lange, O. Klein, B. Nacke
Vorrichtung und Verfahren zur Herstellung von Kristallen aus elektrisch leitenden Schmelzen
DE 10 2007 028 548.7
08784553.3 (DK, ES, FR, NO)
KRIST*MAG*®

R.-P. Lange, M. Ziem, D. Jockel, P. Rudolph, F. Kießling, Ch. Frank-Rotsch, M. Czupalla, B. Nacke, H. Kasjanow
Vorrichtung zur Herstellung von Kristallen aus elektrisch leitenden Schmelzen
DE 10 2007 028 547.9
08784554.1 (DK, ES, FR, NO)
KRIST*MAG*®

Ch. Frank-Rotsch, P. Rudolph, R.-P. Lange, D. Jockel
Vorrichtung und Verfahren zur Herstellung von Kristallen aus elektrisch leitenden Schmelzen
DE 10 2007 046 409.8
KRIST*MAG*®

P. Rudolph, M. Ziem, R.-P. Lange
Vorrichtung zum Züchten von Einkristallen aus elektrisch leitfähigen Schmelzen
DE 10 2007 020 239.5
KRIST*MAG*®

R. Fornari, S. Ganschow, D. Klimm, M. Neubert, Schulz
Verfahren und Vorrichtung zur Herstellung von Zinkoxid-Einkristallen aus einer Schmelze
DE 10 2007 006 731.5

P. Rudolph, M. Ziem, R.-P. Lange, D. Jockel
Vorrichtung zur Herstellung von Kristallen aus elektrisch leitenden Schmelzen
DE 10 2008 035 439.2

F. Büllesfeld, U. Sahr, W. Miller, P. Rudolph, U. Rehse, N. Dropka
Verfahren zum Erstarren einer Nichtmetall-Schmelze
DE 10 2008 059 521.7
09 749 132.8 (DK, ES, IT, NO, R, GB)

P. Rudolph, R.-P. Lange, M. Ziem
Vorrichtung zur Herstellung von Sililziumblöcken
DE 10 2009 045 680.5

N. Dropka, P. Rudolph, U. Rehse
Verfahren und Anordnung zur Herstelllung von Kristallblöcken von hoher Reinheit und dazugehörige Kristallisationsanlage
DE 10 2010 028 173.5

H. Riemann, N. Abrosimov, J. Fischer, M. Renner
Verfahren und Vorrichtung zur Herstellung von Einkristallen aus Halbleitermaterial
EP 2 504 470 (NO, ES, NL, FR, DK, GB, BE, IT)

N. Dropka, Ch. Frank-Rotsch, M. Ziem, P. Lange
Verfahren und Vorrichtung zur gerichteten Kristallisation von Kristallen aus elektrisch leitenden Schmelzen
DE 10 2012 204 313.6

N. Dropka, Ch. Frank-Rotsch, P. Rudolph, R.-P. Lange, U. Rehse
Kristallisationsanlage und Kristallisationsverfahren zur Herstellung eines Blocks aus einem Material, dessen Schmelze elektrisch leitend ist
DE 10 2010 041 061.6

O. Klein, F. Kießling, M. Czupalla, P. Rudolph, R.-P. Lange, B. Lux, W. Miller, M. Ziem, F. Kirscht
Verfahren und Vorrichtung zur Züchtung von Kristallen aus elektrisch leitenden Schmelzen, die in der Diamant- oder Zinkblendestruktur kristallisieren
DE 10 2009 027 436.7

H. Riemann, N. Abrosimov, J. Fischer, M. Renner
Verfahren und Vorrichtung zur Herstellung von Einkristallen aus Halbleitermaterial
DE 10 2010 052 522.7
10801372.3 (EP), 13/511,751 (US), 2012-540285 (JP)

F. Kießling, Ch. Frank-Rotsch, N. Dropka, P. Rudolph
Verfahren zur gerichteten Kristallisation von Ingots
DE 10 2011 076 860.2

M. Wünscher, H. Riemann
Vorrichtung für das tiegelfreie Zonenziehen von Kristallstäben
DE 10 2012 022 958.8
PCT/DE2013/000627

Patents

Z. Galazka, R. Uecker, R. Fornari
Method and apparatus for growing indium oxide (In2O3) single crystals and indium oxide (In2O3) single crystal
EP2841630B1 (DE, BE, FR, GB, IT), JP2018501184

A. Dittmar, C. Hartmann, J. Wollweber, M. Bickermann
(Sc, Y): Einkristalle für Gitter-angepasste AlGaN Systeme
DE 10 2015 116 068.4, PCT/EP2016/070539

Z. Galazka, R. Uecker, D. Klimm, M. Bickermann
Method for growing beta phase of gallium oxide (ß-Ga_2O_3) single crystals from the melt contained within a metal crucible
EP 15150582.3, PCT/EP2015/079938

Pending

U. Rehse, P. Rudolph, W. Miller, N. Dropka, F. Büllesfeld, U. Sahr
Method for the solidification of a non-metal melt
WO002012060802A3 (CN, US, TW)

T. Boeck, R. Fornari, R. Heimburger, G. Schadow, J. Schmidtbauer, H.-P. Schramm, T. Teubner
Kristallisationsverfahren zur Erzeugung kristalliner Halbleiterschichten
DE 10 2010 044 014.0

N. Dropka, Ch. Frank-Rotsch, P. Lange, P. Krause
Kristallisationsanlage und Kristallisationsverfahren zur Kristallisation aus elektrisch leitenden Schmelzen sowie über das Verfahren erhältliche Ingots
DE 10 2013 211 769.8

A. Dittmar, C. Hartmann, J. Wollweber, U. Degenhardt, F. Stegner
Keimhalter einer Einkristallzüchtungsvorrichtung, Einkristallzüchtungsvorrichtung und Kompositwerkstoff
DE 10 2014 017 021.7

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Teaching and Education

Teaching and education

Prof. Dr. Matthias Bickermann

- *Kristallzüchtung II: Methoden und Anwendungen;* Technische Universität Berlin, Institut für Chemie, WS 2017/2018, WS 2018/2019
- *Kristallzüchtung I: Grundlagen und Methoden;* Technische Universität Berlin, Institut für Chemie; SS 2018
- Forschungspraktikum: Betreuung vom Studienenden am IKZ; Technische Universität Berlin, Institut für Chemie

Dr. habil. Christian Kränkel

- *Applied Photonics;* Humboldt-Universität zu Berlin, Institut für Physik, WS 2018/2019

PD Dr. habil. Detlef Klimm

- *Phasendiagramme;* Humboldt-Universität zu Berlin, Institut für Chemie, WS 2017/18, WS 2018/2019
- Versuch *„Phasendiagramme"* im Fortgeschritttenen-Praktikum der Physik; Humboldt-Universität zu Berlin; WS 2017/2018, WS 2018/2019

apl. Prof. Dr. Dietmar Siche

- *Wachstum einkristalliner Materialien und ausgewählte Anwendungen;* Brandenburgische Technische Universität Cottbus-Senftenberg, Blockveranstaltung; SS 2018

PD Dr. habil. Martin Schmidbauer

- *Röntgenstreuung: Grundlagen und Anwendungen in der Materialwissenschaft;* Humboldt-Universität zu Berlin, Institut für Physik, WS 2017/18, WS 2018/2019

Doctoral theses (ongoing)

Mariia Anikeeva
Transmission Electron Microscopy of Short Period Superlattices for Rational (In,Ga)N

Aykut Baki
MOCVD of perovskite oxide films

Laura Bogula
Untersuchung von ferroelektrischen Domänen in verspannten dünnen Schichten mittels moderner Röntgenbeugungsverfahren

Leonardo Cancellara
TEM-Untersuchungen an AlN/AlGaN – Struktiren für LEDs

Elena Castellano Hernandéz
Spektroskopische Charakterisierung und Laser-Experimente an Tb^{3+} -dotierten Kristallen

Christian Ehlers
Wachstum und Charakterisierung von Silizium aus Zinn Lösungen für die Photovoltaik

Owen Ernst
Wachstum und Charakterisierung von CIGSe-Absorberinseln für Mikrokonzentrator Solarzellen

Andreas Fiedler
Electrical and Optical Characterization of the Transparent Semiconducting Oxide beta-Ga_2O_3

Ivan Gamov
Point defects and their impact on temperature-dependent properties in AlN bulk crystals

Kevin Peter Gradwohl
Entwicklung von Kristallisationsverfahren zur Herstellung von hochreinen Germaniumeinkristallen für Strahlungsdetektoren

Leonard von Helden
Characterization of Domain Structures in Strained Ferroelectric $Ka_{1-x}Na_xNbO_3$ Thin Films

Stefan Kayser
Charakterisierung mono- und multikristalliner Halbleiter wie SiGe, Si, Ge und GaAs mit LPS- und SPL-Methoden

Felix Lange
Functional Materials and Film Systems for Efficient Energy Conversion (FuSion)

Lucinda Matiwe
Generation und Evolution von Strukturdefekten bei der AlN-Kristallzüchtung, der AlN-Substratpräparation und der AlN/AlGaN-Epitaxi

Angelina Nikiforova
Entwicklung eines Eigentiegelverfahrens zur Herstellung von einkristallinem Silizium

Daniel Pfützenreuter
Wachstum und Optimierung von verspannten ferroelektrischen Kalium-Niobat-Schichten

Julian Stöver
Physics and control of defects in oxide films for adaptive electronics

Teaching and Education

David Uebel
Wachstum und Charakterisierung von Silizium auf kostengünstigen Subtraten

Anastasiia Uvarova
Züchtung und Lasercharakterisierung von Er^{3+}-dotierten Sesquioxiden

Nora Wolff
Züchtung von Delafossit-Substratkristallen

Charlotte Wouters
Transmission Electron Microscopy Studies on Phase Formation in Group III-Sesquioxides

Martina Zupancic
Transmission electron microscopy studies on barium stanate based heterostructures for electronic applica-tions

Doctoral theses (completed)

Katharina Eylers
Wachstum und Charakterisierung von Cu(In,Ga)Se_2 Absorbern für Mikrokonzentratorsolarzellen

Robert Schewski
Transmission electron microscopic investigation of the growth of group III sequioxides Ga_2O_3

Diploma, Master and Bachelor theses (completed)

Julia Hidde
Thermoanalytische Untersuchungen und Eink-ristallzüchtung von dotiertem Niob(V)-Oxid

Nicole Suss
AFM-Messungen an AlN-Wachstumsfacetten

Wolfram Troeder
Tuning the electrical and optical properties of NbO_2 thin films using strain

Professional education at IKZ (completed)

Sebastian Schermer
Cutting machine operator

Membership in Committees

Committees

M. Bickermann
- IGAFA e.V. – the scientific network of the non-university research institutions located in Berlin-Adlershof e.V.; member of the board

Ch. Frank-Rotsch
- Deutsche Gesellschaft für Kristallzüchtung und Kristallwachstum (DGKK), secretary
- International Organization for Crystal Growth (IOCG) member of the council
- European Network of Crystal Growth (ENCG), member of the council

W. Miller
- Deutsche Gesellschaft für Kristallzüchtung und Kristallwachstum (DGKK), chairman
- International Organization for Crystal Growth (IOCG) member of the council
- European Network of Crystal Growth (ENCG), coordinator

T. Schröder
- DESY Photon Science Council , member
- microSPIRE (FET project council Uni Milano); member of the advisory committee
- BMBF Quantentechnologie – Grundlagen und Anwendung (QuTeGa); member of the adivsory committee

Conference committees

M. Bickermann
- European Materials Research Society Fall Meeting 2018 (Symposium P) (EMRS Fall 2018), Conference chair and chief organizer Symposium P: Epitaxial Oxide Films for Electronic Applications
- International Workshop on Nitride Semiconductors 2018 (IWN 2018) Kanazawa (Japan), Member of the Program Committee, of the Topical Committee for Session A (Bulk Growth), and Session Chair

C. Guguschev
- ICCGE-19/OMVPE-19 Program Committee, member

K. Irmscher
- International CECAM Workshop; Reliable and quantitative prediction of defect properties in Ga-based semiconductors, Co-organizer

D. Klimm
- Commission on Crystal Growth and Characterization of Materials der IUCr (International Union of Crystallography), consultants

C. Kränkel
- Advanced Solid State Lasers Conference 2018, member of materials committee

W. Miller
- 6th European Conference on Crystal Growth (ECCG-6); member of scientific committee
- 9th International Workshop on Modeling in Crystal Growth (IWMCG-9), member of advisory committee

T. Schröder
- Workshop on Dielectrics in Microelectronics (WoDiM), Scientific Advisory Council
- Joint International SiGe Technology and Device Meeting (ISTDM) & International Conference on Silicon Epitaxy and Heterostructures (ICSI), Scientific Advisory Council

Editoral committees

M. Bickermann
- Progress in Crystal Growth and Characterization of Materials, Elsevier, associate editor

C. Kränkel
- Optics Express, associate editor

W. Miller
- Crystals, member of editorial board

Other committees

M. Bickermann
- Dissertationspreis Adlershof, member of the jury

T. Schröder
- Humboldt Universität Berlin: Director Paul Drude Institut; member of the appointment committee Brandenburgisch Technische Universität Cottbus – Senftenberg: wireless systems; member of the appointment committee
- Leibniz project group on gender Equality ; joint chairmanship with Prof. C. Spiess (DIW Berlin)
- Brandenburgisch Technische Universität Cottbus Senftenberg / BTU-CS: Professorship System Design; member of the appointment committee

Guest Scientists

Guest scientists

Prof. Kookrin Char
20.08. - 19.09.2018
29.10. - 23.11.2018
Seoul National University
South Korea

Michael Makowski
29.01. - 23.02.2018
Nicolaus Copernicus University, Torun
Poland

Oleg Medvedev
02.11. - 30.11.2018
St. Petersburg State University
Russia

Prof. Gang Niu
20.11. - 29.11.2018
University of Xi'an
China

Ewelina Nowak
08.01. - 08.03.2018
Poznan University of Technology
Poland

Dr. Daniel Rytz
26.03. - 11.04.2018
Forschungsinstitut für mineralische und metallische Werkstoffe, Edelmetalle/Edelsteine GmbH
Deutschland

Prof. Petr. G. Sennikov
12. - 22.11.2018
Russian Academy of Sciences
Russia

Bartosz Szcefaowics
09.07. - 09.10.2018
Poznan University of Technology
Poland

Hiroki Tanaka
07.08.2017 - 01.02.2018
Keio University, Yokohama
Japan

Dr. Philip Weiser
03.12. - 07.12.2018
University of Oslo
Norway

Agnieszka Wiciak
29.01. - 30.09.2018
Poznan University of Technology
Poland

Colloquia at the IKZ

Colloquia

Dr. Neil Curson
"Fabrication and characterisation of nanoscale donor devices towards silicon quantum information processing"
London Centre for Nanotechnology and Dept. Electronic & Electrical Engineering, University College London, UK
January 15, 2018

M. Sc. Nora Wolff
"Untersuchungen zur Züchtung von $CuAlO_2$-Einkristallen"
IKZ, AG Oxide/Fluoride
January 29, 2018

Dr. Andreas Fuhrer
"From Transistors to Qubits"
Quantum Technology group at IBM Research - Zürich
February 26, 2018

Dr. Carsten Richter
"Characterization of atomic displacements in crystals using resonant x-ray diffraction techniques"
The European Synchrotron, X-ray Nanoprobe Group
March 2, 2018

Prof. Dr. Silvana Botti
"Discovery and characterization of new materials using supercomputers: crystal structure prediction and theoretical spectroscopy"
AG Festkörpertheorie, Institut für Festkörpertheorie und Optik (IFTO) der FSU Jena March 12, 2018

Dr. Hugo Schlich
"Kristallzüchtung bei MaTecK"
Fa. MaTecK (Material-Technologie & Kristalle GmbH)
March 15, 2018

Prof. Dr. Andreas Danilewsky
"Diffraction imaging: More than nice pictures"
Kristallographie, Institut für Geo- und Umweltnaturwissenschaften
Albert-Ludwigs-Universität, Freiburg
March 19, 2018

Prof. Dr. Kookrin Char
"Progress in $BaSnO_3$-based Materials and Devices"
Institute of Applied Physics, Dept. of Physics and Astronomy, Seoul National University
April 9, 2018

M. Sc. Charlotte Wouters
"TEM investigations on phase formation in $(Ga_{1-x}Inx)_2 0_3$"
April 16, 2018

Dr. Amol Choudhary
"Miniature femtosecond laser sources"
ARC DECRA Fellow in the School of Physics
University of Sydney
May 3, 2018

Dr. Stefan Schmult
"Functional GaN/AlGaN heterostructures grown on bulk GaN by MBE"
TU Dresden, Electrical & Computer Engineering
Inst. of Semiconductors and Microsystems,
Nanoelectronics Materials Laboratory (NaMLab)
May 14, 2018

Prof. Dr. Winicjusz Drozdowski
"Advanced Techniques in Research on Scintillator Material"
Scintillator and Phosphor Materials Spectroscopy Group
Optoelectronics, Institute of Physics
Nicolaus Copernicus University, Torun, Poland
May 18, 2018

Prof. Dr. Jörg Schäfer
"Novel Nanoscale Quantum Materials – From Design to Spectroscopy"
Experimentelle Physik IV, Universität Würzburg
June 18, 2018

Dr. Linus Pithan
"Enabling tailored molecular thin film growth through in-situ x-ray diffraction"
ESRF - The European Synchrotron
Experiments Division, ID03 Beamline, Grenoble
June 19, 2018

Kuan-Kan HU und Lu-Chung CHUANG
"Moving direction of grain boundary during directional solidification of mc-Si" und "Interaction between grain boundaries at the crystal/melt interface of mc-Si"
Tohoku University Sendai, Japan
June 20, 2018

Prof. Dr. Roman Schnabel
"Gravitational-wave detection and the role of 100kg-sized crystalline-silicon mirrors"
Institut für Laserphysik und Zentrum für Optische Quantentechnologien, Universität Hamburg
June 25, 2018

Colloquia at the IKZ

Prof. Dr. Brice Gautier
"Nanoscale measurement of the electrical properties of ferroelectric thin films and crystals for the control and the engineering of domains and domain walls"
INSA, Lyon
July 3, 2018

Dr. Peter Gaal
"Photoacoustic in synchrotron-based material science"
Institut für Nanostruktur- und Festkörperphysik, Universität Hamburg
July 4, 2018

Prof. Dr. Dr. h.c. Ullrich Pietsch
"Probing Structure to property relations of single semiconductor nanowires"
Festkörperphysik, Department Physik, Universität Siegen
August 13, 2018

Herr Dr. Frank Zobel
"Float-Zone Kristalle aus vorgezogenen Vorratsstäben für Anwendungen in der Photovoltaik"
Fraunhofer-Center für Silizium Photovoltaik CSP
September 3, 2018

Dr. Bela Majorovits
"MADMAX: searching for Axion Dark Matter with a dielectric haloscope"
Max-Planck-Institut für Physik, Werner-Heiseberg-Institut (MPP), TU München
September 4, 2018

Prof. Dr. Jan Ingo Flege
"In situ microscopy of oxide growth and transformation in reactive environments"
Chair Applied Physics and Semiconductor Spectroscopy, BTU Cottbus-Senftenberg
September 10, 2018

M. Sc. Christian Riha
"Quantum transport investigations of low-dimensional electron gases in AlxGa1-xAs/GaAs- and Bi2Se3- based materials"
AG Neue Materialien, HU Berlin
September 17, 2018

Prof. Dr. André Strittmatter
"Epitaxy of III/V-semiconductors at Otto-von-Guericke Universität Magdeburg"
Abteilung Halbleiterepitaxie, Institut für Experimentelle Physik, Universität Magdeburg
October 15, 2018

Dr.-Ing. Nazmul Islam
"Single crystal growth of some complex oxides in an optical floating zone machine"
Head of the Crystal Growth Laboratory Department of Quantum Phenomena in Novel Materials, Helmholtz-Zentrum Berlin für Materialien und Energie
October 16, 2018

Dr. Roger Loo
"Epitaxial growth schemes for fin and Gate All Around devices"
Principal Member of Technical Staff at IMEC, Leuven, Belgium
November 5, 2018

M. Sc. & M. Sc. Eng. Paul-Antoine Douissard
"X-ray area detectors and scintillating screens for synchrotron applications"
Instrumentation Services and Development Division Detectors & Electronics, ESRF - The European Synchrotron
November 19, 2018

Prof. Dr. Inga Fischer
"Group-IV semiconductor nanostructures for optoelectronic device applications"
Chair Experimental Physics and Functional Materials at Brandenburg Technical University, Cottbus-Senftenberg
December 3, 2018

Dr. Andreas Grimm
„Compound semiconductors in the Research Fab Microelectronics Germany, Research Fab Microelectronics Germany (FMD);
Fraunhofer Gesellschaft, Berlin
December 4, 2018

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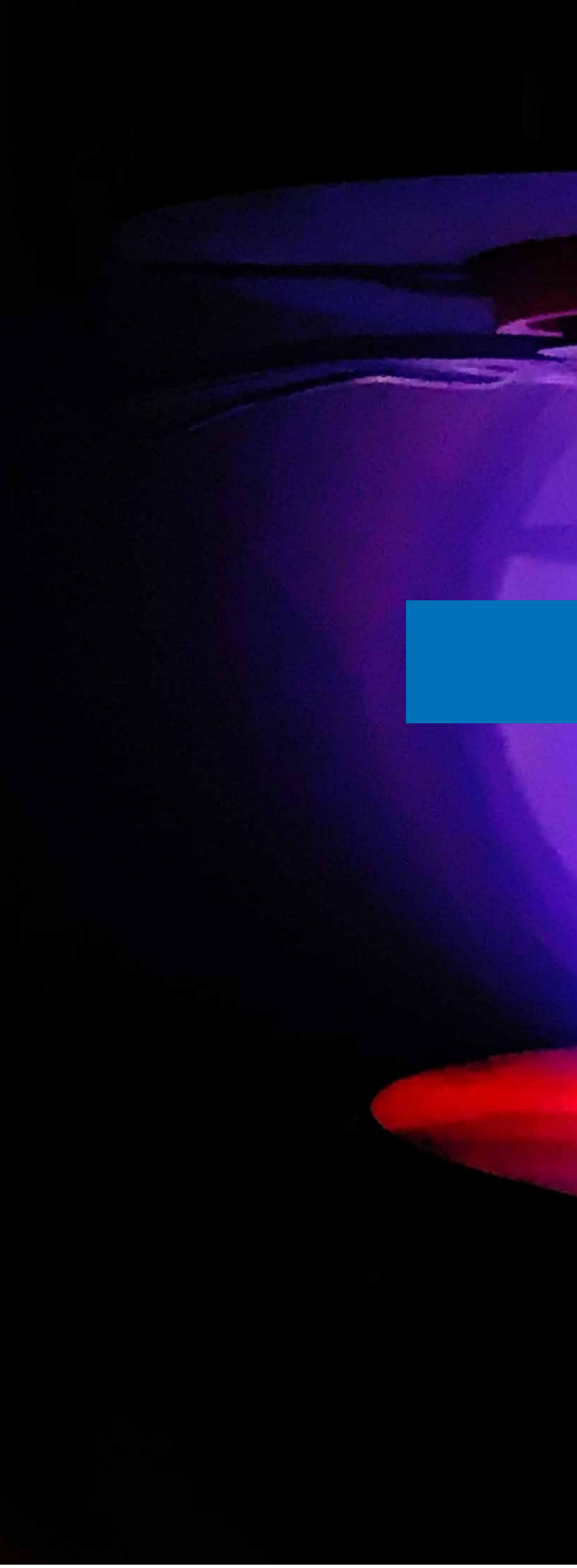
“Plasmaschwaden in einer Pulsed Laser Deposition (PLD) -
Anlage / Plasma plume in a pulsed laser deposition (PLD) system”
Daniel Pfützenreuter

Berlin, September 2019



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