LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG

GALLIUM OXIDE – THE NEXT HIGH PERFORMANCE MATERIAL FOR HIGH POWER DEVICES

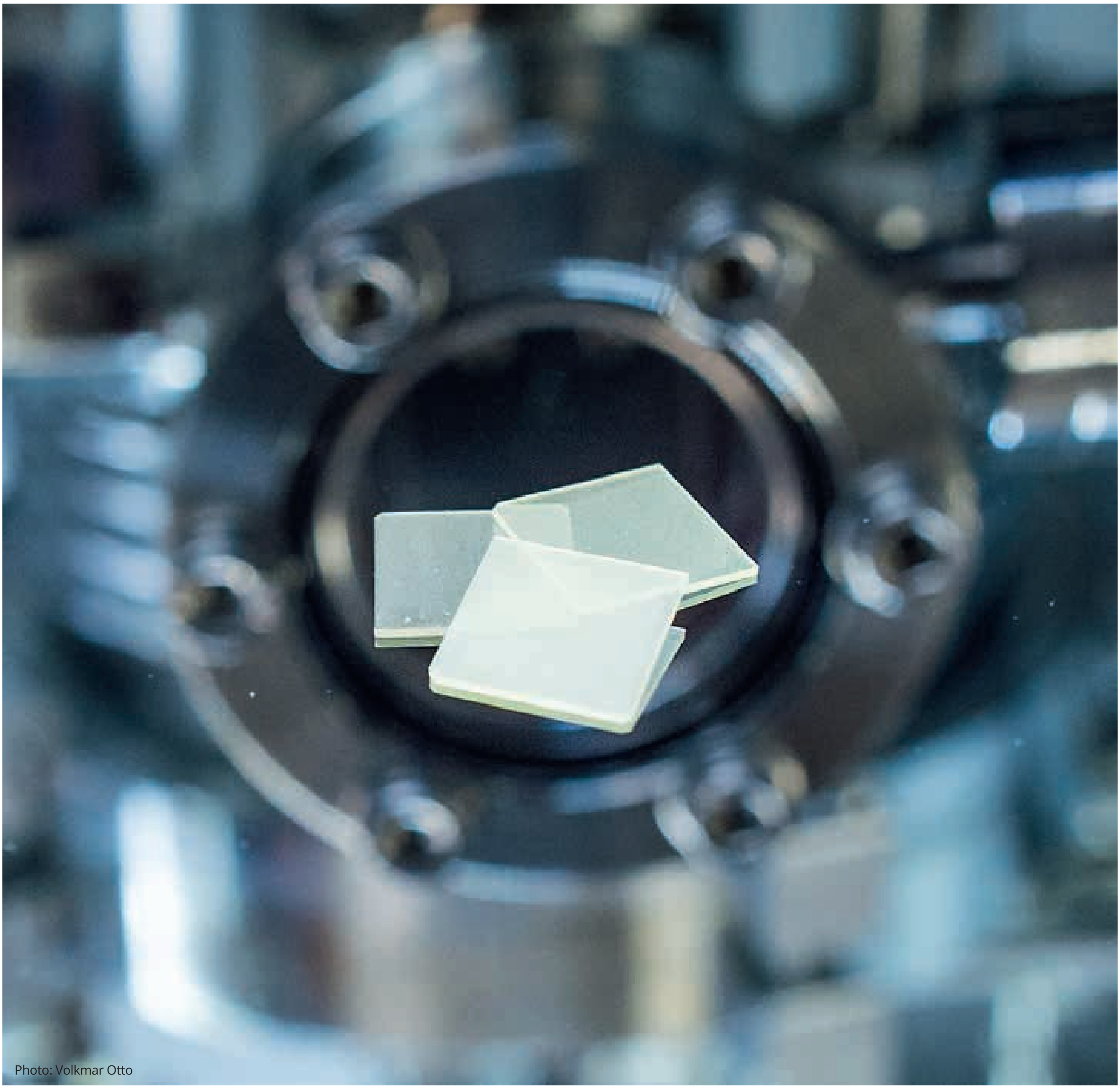
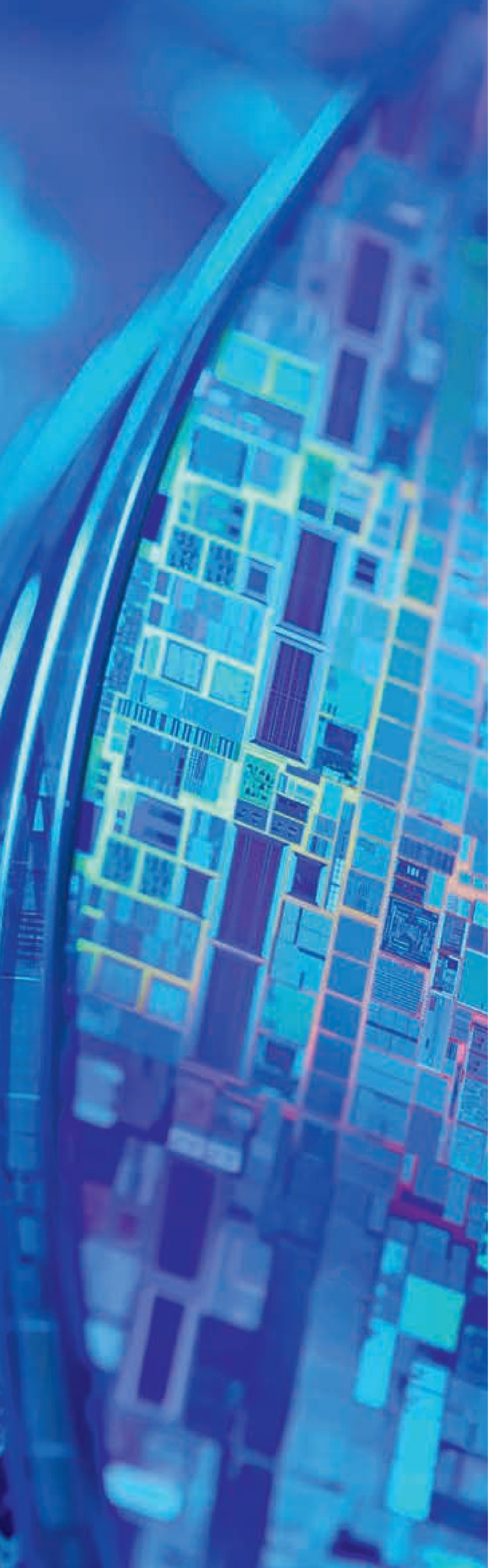


Photo: Volkmar Otto



GALLIUM OXIDE

Energy efficiency is one of society's most important challenges along with the energy transition. Energy conversion plays a key role in both electromobility and electric grids, and research is focused on developing materials that enhance efficiency and mitigate energy losses in these critical processes. For the above purpose, β-gallium oxide (β-Ga_2O_3) has emerged as a key player in pursuing more efficient power conversion systems and electricity-driven technology. Despite its relatively lower thermal conductivity, gallium oxide has an impressive wide bandgap (~4.8 eV), high breakdown field (8 MV/cm), excellent electrical properties, and potentially lower manufacturing cost (compared with SiC and GaN), making it well-suited for high-power and high-voltage applications. These unique properties enable the design of power electronics with enhanced efficiency, reduced losses, and improved performance. Gallium oxide-based devices have the potential to revolutionize various technology sectors, including electric vehicles, renewable energy systems, and power grids.

Research groups at the Leibniz-Institut für Kristallzüchtung (IKZ) have devoted the past 15 years to developing bulk growth, epitaxy technology, and characterization routines for gallium oxide technology.

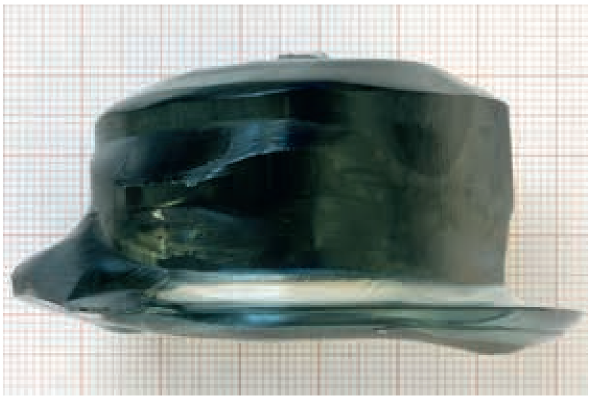
IKZ aims to contribute to the widespread adoption of more efficient and sustainable β-Ga_2O_3 technology with a commitment to further refine and optimize the gallium oxide crystal growth and epitaxy process, ensuring scalability, reliability, and cost-effectiveness. Our expertise supports your path to the next generation of power electronic applications.

Renewable energy and electric car

Industrial engines

High-speed train

CRYSTAL GROWTH



Semi-insulating (Mg-doped, right) and conducting (Si-doped, left) β-Ga_2O_3 single crystals of 2 in. diameter grown by the Czochralski method.

Photo: Moritz Thau

The IKZ has a long-term experience in research on gallium oxide crystal growth. Using the Czochralski method, we have developed and patented a proprietary technology for the growth of bulk β-Ga_2O_3 single crystals up to 2 inches in diameter. This method ensures a very high structural quality of the obtained crystals with fewer dislocations, no low-angle grain boundaries, and no nanopipes commonly present in β-Ga_2O_3 grown by other melt methods.

Wafers obtained from such crystals, in particular (100) oriented with a dedicated offcut, enable deposition of thick films in the µm range with high structural quality and excellent electrical properties. Bulk crystals can be electrical insulators by doping with Mg, Co, and Ni, normal semiconductors, or degenerate semiconductors by doping with Si or Sn.

The impact of other dopants on growth stability and physical properties is also part of our research activities. The free electron concentration in semiconducting crystals ranges from 10^{16} to 10^{19} cm^{-3} with a maximum electron mobility of 160 $cm^2V^{-1}s^{-1}$. In addition to excellent electrical properties, β-Ga_2O_3 crystals grown by the Czochralski method revealed good scintillation properties under gamma excitation. Work on β-Ga_2O_3 crystals has been extended to β-$(Al_xGa_{1-x})_2O_3$, aiming to increase the bandgap and critical electric field. The Al content in the crystals can be as high as 40 mol.%, offering unique wafers for quasi-homoepitaxial growth of β-$(Al_xGa_{1-x})_2O_3$ layers.

For further information,

please visit our website or contact us via galliumoxid-substrates@ikz-berlin.de

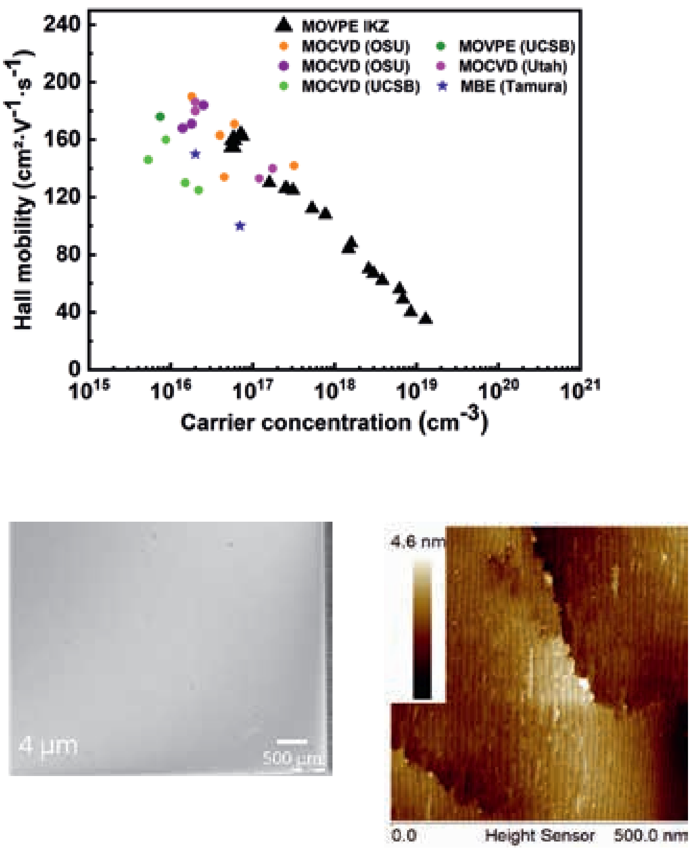
An overview can be found here:

Zbigniew Galazka: *Growth of bulk β-Ga_2O_3 single crystals by the Czochralski method;* J. Appl. Phys. 131, 031103 (2022) https://doi.org/10.1063/5.0076962, and Zbigniew Galazka, et al.: *Bulk single crystals and physical properties of β-$(Al_xGa_{1-x})_2O_3$ (x = 0–0.35) grown by the Czochralski method;* J. Appl. Phys. 133, 035702 (2023) https://doi.org/10.1063/5.0076962.

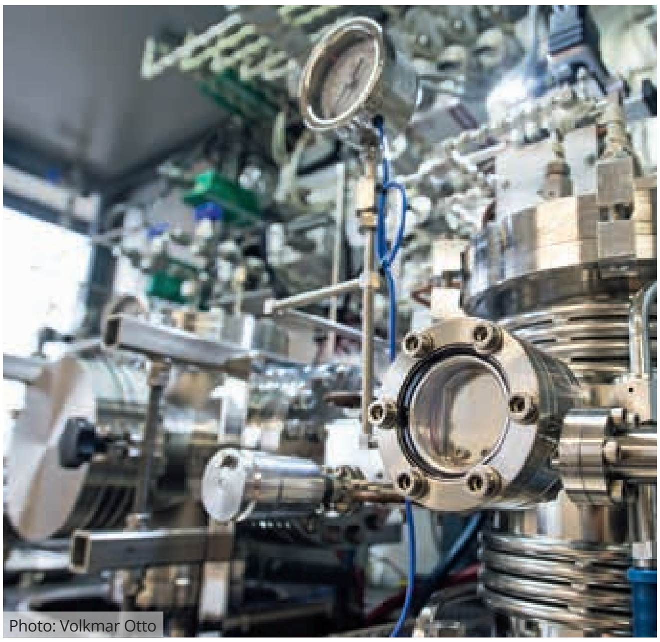
HIGH-QUALITY β-Ga_2O_3 LAYERS

Since 2013, homoepitaxial β-Ga_2O_3 thin films via metalorganic vapor phase epitaxy (MOVPE) have been the focus of the IKZ initiated by the in-house development of high-quality Czochralski-grown crystals. To achieve the application potential of β-Ga_2O_3 in power electronics, the MOVPE process has been optimized for both lateral and vertical device structure on (100) β-Ga_2O_3 with intentional 4° offcut. High-quality β-Ga_2O_3 films with a smooth step-flow morphology, clean surface, and excellent electrical properties compared to bulk (carrier mobility above 160 cm^2/Vs) have been reported on the (100) planes in a wide variety of thicknesses (50 nm to µm-level) and doping concentrations (10^{16} cm^{-3} to 10^{19} cm^{-3}). They form the basis for the application of β-Ga_2O_3 as an electric active layer in various electronic devices, especially in high-power applications such as power-switching transistors and diodes. The precise control of film thickness and doping concentration achieved by MOVPE enables the tailoring of material properties to meet specific device requirements for improved performance and efficiency.

In addition, data-driven approaches, such as machine learning are used, to accelerate the development of our epitaxy processes and reveal their hidden physics. To pave the way for the future industrialization of β-Ga_2O_3 technology, IKZ and industry partners plan to develop in-situ monitoring solutions on the β-Ga_2O_3 MOVPE process by implementing commercial reflectance spectroscopy. Employing cutting-edge electron microscopy techniques and various electrical characterization methods, IKZ characterization experts are providing a link between the fundamental structural influences and the material's electrical properties under varying growth conditions. Notably, IKZ's findings confirm the exceptional quality of both crystal and epilayer, unveiling the crucial role of specific substrate offcuts on (100) β-Ga_2O_3, as identified through transmission electron microscopy (TEM). This discovery led to the development of an effective strategy to adapt the offcut of the substrates specifically to the epitaxial growth in order to attain the desired surface morphology and minimize structural defect density in the grown films. Simultaneously, comprehensive characterization via current transport and capacitive measurements such as conductivity and Hall effect measurements (20-1100 K), deep-level transient spectroscopy (20-800 K), and photo-thermal ionization spectroscopy are performed to precisely key parameters. These efforts aim to determine the concentration and mobility of free charge carriers, dopant levels, and the presence of compensating impurities or defects in both bulk crystal and epilayer.



High-quality MOVPE-grown β-Ga_2O_3 film up to 4 µm thickness with high carrier mobilities within a wide doping concentration of 10^{16} cm^{-3} to 10^{19} cm^{-3}. Particle-free surface and step-flow morphology are characterized by light microscopy and atomic force microscopy (T.-S. Chou et al., Jpn. J. Appl. Phys. 62, SF1004 (2023) https://doi.org/10.35848/1347-4065/acb360).



MOVPE reactor and loadlock

For further information,

please visit our website or contact us (galliumoxide-substrats@ikz-berlin.de).

A good overview can be found here: Jana Rehm, Ta-Shun Chou, Saud Bin Anooz, Palvan Seyidov, Andreas Fiedler, Zbigniew Galazka, Andreas Popp: *Perspectives on MOVPE-grown (100) β-Ga_2O_3 thin films and its Al-alloy for power electronics application;* Appl. Phys. Lett. 121, 240503 (2022) https://doi.org/10.1063/5.0122886

OUR SERVICES

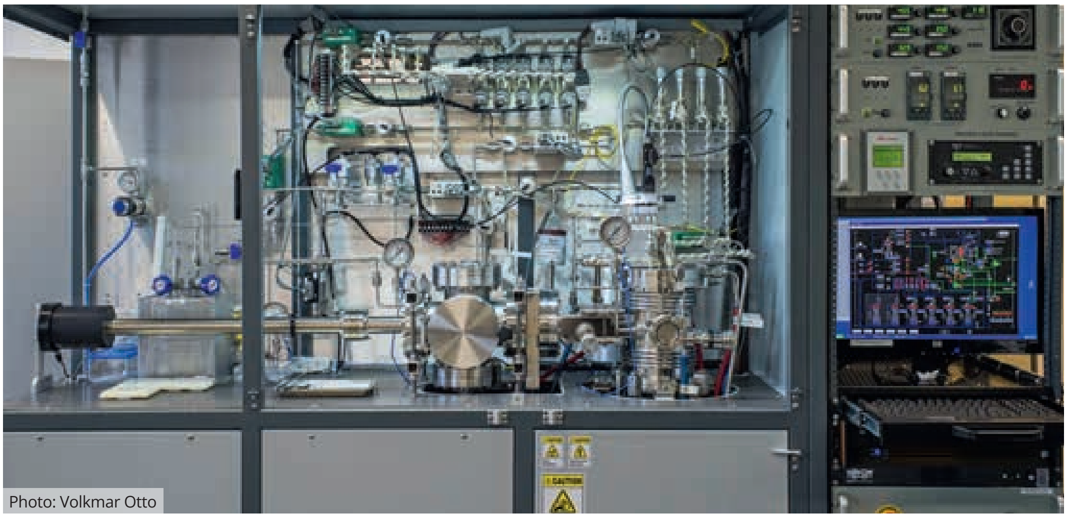


Photo: Volkmar Otto

Front view of MOVPE reactor and control unit

Going beyond the basic research level, IKZ is dedicated to promote gallium oxide technology for the next-generation power electronics complementary to SiC and GaN. With more than 15 years of experience and a diverse patent portfolio, IKZ offers high-quality Czochralski-grown (100) β-Ga_2O_3 substrates (commercially available via our partner CrysTec GmbH) and MOVPE-grown β-Ga_2O_3 epilayers.

Further details, as well as the specifications of our crystals and epilayers, can be found here: https://www.ikz-berlin.de/en/offer/gallium-oxide. We are open to research collaborations and joint projects. If you have any questions or inquiries, please contact us.

CZOCHRALSKI-GROWN SEMI-INSULATING (100) β-Ga_2O_3 SUBSTRATES

A key prerequisite for the development of gallium oxide based technologies is the availability of high-quality single crystalline substrates. Here at IKZ, we have developed proprietary technology for the growth of bulk gallium oxide (β-Ga_2O_3) single crystals with a diameter of 2 inches using the Czochralski method. The crystals can be semi-insulating, semiconducting, and highly conducting (degenerate semiconductors). For example, semi-insulating (100) β-Ga_2O_3 substrates, including offcut, can be obtained from our partner CrysTec GmbH via the service website above.

EPITAXY

In parallel with bulk crystal growth, we have made significant advances in epitaxy technologies to grow device-level β-Ga_2O_3 layers with low defect density, high mobility, and high surface quality via MOVPE (Metal Organic Vapor Phase Epitaxy).

High-quality epilayers are available from IKZ with a wide-range of thickness and doping concentration as specified. Our epitaxy process is compatible with different β-Ga_2O_3 crystalline orientations (100) (4° offcut) and (010) and has the potential for heteroepitaxy on foreign substrates, including sapphire, Si, SiC, GaN... etc. Homo- and hetero-epitaxial layers can be customized based on the requests. Please contact us via the service website above.

CHARACTERIZATION

IKZ offers a comprehensive suite of tools for material analysis, covering structural, optical, electrical, and thermo-analytical techniques across all length scales. Our methods include x-ray diffraction and imaging, electron microscopy, deep-level transient spectroscopy, Hall measurements, and optical spectroscopy. These services are also available to partners or customers on request. Please find an overview of our equipment and techniques at https://www.ikz-berlin.de/en/transfer-service/special-equipment.

CONSULTING AND TECHNOLOGY TRANSFER

We also offer our expertise for consultations or joint collaborations. We have several patents filed in the field of gallium oxide growth technology. You will find a complete list under https://www.ikz-berlin.de/en/transfer-service/patents-licenses.

Patents include, among others:

Z. Galazka, R. Uecker, D. Klimm, M. Bickermann
Method for growing beta phase of gallium oxide (β-Ga_2O_3) single crystals from the melt contained within a metal crucible; EP 3242965 B1, US 11028501 B2, JP 7046117 B2, KR 101979130 B1

Z. Galazka, S. Ganschow, M. Bickermann, T. Schröder, W. Häckl
Method and apparatus for producing electrically conducting bulk β-Ga_2O_3 single crystals and electrically conducting bulk β-Ga_2O_3 single crystal; PCT/EP2023/051212

Z. Galazka, S. Ganschow, M. Bickermann, T. Schröder
Melt-grown bulk ß-$(Al_xGa_{1-x})_2O_3$ single crystals and method for producing bulk ß-$(Al_xGa_{1-x})_2O_3$ single crystals; PCT/EP2022/078252

T. Chou, A. Popp, W. Häckl
Method for producing a gallium oxide layer on a substrate
EP 21187231.2

Photo: Sebastian Rost

THE LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG IKZ

The Leibniz-Institut für Kristallzüchtung (IKZ) in Berlin-Adlershof is an international state-of-the-art competence center for science & technology as well as service & transfer for innovations in and by crystalline materials. The R&D spectrum ranges from basic applied research activities to pre-industrial research tasks.

Crystalline materials are key technology enabling components to provide electronic and photonic solutions to today's and future challenges in society, such as artificial intelligence (communication, mobility, etc.), energy (renewable energies, power conversion, etc.), and health (medical diagnosis, modern surgical instruments, etc.).

The IKZ provides innovations in crystalline materials based on in-house expertise in plant engineering, numerical simulation, and crystal growth, to achieve novel compounds with high structural quality, tailored properties, and novel applications.

Nanostructures, thin films, and bulk crystals are a subject of research and development, the latter being the unique selling point of the institute. Cutting-edge theoretical and experimental materials science know-how is a strong asset of IKZ's R&D activities.

Together with partners from institutes, with technology platforms as well as industry companies, the institute is also driving innovation by crystalline materials, namely the reliable evaluation and benchmarking of innovative crystalline prototype materials for disruptive technology approaches in electronics and photonics.

---

ikz LEIBNIZ-INSTITUT FÜR KRISTALLZÜCHTUNG

Max-Born-Str. 2
12489 Berlin
Germany

Phone +49 30 6392 3001
E-Mail cryst@ikz-berlin.de

www.ikz-berlin.de