BULK SINGLE CRYSTALS OF TRANSPARENT SEMICONDUCTING OXIDES

Z. Galazka[a], S. Ganschow, K. Irmscher, D. Klimm, R. Schewski, M. Albrecht, A. Dittmar, T. Schulz, M. Pietsch, A. Kwasniewski, I. M. Hanke, M. Sündermann, T. Schröder, M. Bickermann[b]

Leibniz-Institut für Kristallzüchtung (IKZ), Max-Born-Str. 2, 12489 Berlin, Germany
[a] *E-mail:* zbgniew.galazka@ikz-berlin.de
[b] also at Technische Universität Berlin, Institute of Chemistry, Straße des 17. Juni 115, 10623 Berlin, Germany
E-mail: matthias.bickermann@ikz-berlin.de

Transparent semiconducting oxides (TSOs) constitute one of the fastest growing areas in materials science and technology. Unique electrical, optical, and sensing properties place the TSOs in the frontline of future applications. The TSOs offer an opportunity for developing novel devices in electronics, in high power electronics, optoelectronics, displays, flexible and transparent electronics, photovoltaics, high temperature gas detectors, and nuclear radiation detectors. Some applications use the bulk material, others are based on films that require single crystal substrates to unleash their full potential.

As all the TSOs are thermally unstable at high temperatures, growing bulk crystals from the melt is very challenging and requires unique technologies such as high oxygen concentration technique combined with iridium crucibles. In recent years, a diversity of bulk single crystals of oxide semiconductors have been developed and grown at IKZ. Consequently, several new TSOs became available as bulk crystals for the first time [1].

β-Ga_2O_3 single crystals are the largest ones among all other TSOs. They are grown at IKZ by the Czochralski method with a volume up to 200 cm^3 [1–3]. We also provided a groundbreaking investigation of dopant incorporation and alloying of β-Ga_2O_3 with many elements during growth [4]. Further studies were performed on the growth and characterization on several other TSOs such as gallates ($MgZnO_4$, $ZnGa_2O_4$, $InGaZnO_4$) [5], stannates ($BaSnO_3$, $ZnSnO_3$), indates ($LaInO_3$), and binary oxides such as ZnO, SnO_2 or In_2O_3, see Fig. 1 [1,6]. They are grown with different methods such as Czochralski, Kyropoulos, Vertical Gradient Freeze or even Physical Vapor Transport in individually adjusted conditions to increase growth stability and enable large crystal volumes, Fig. 2.

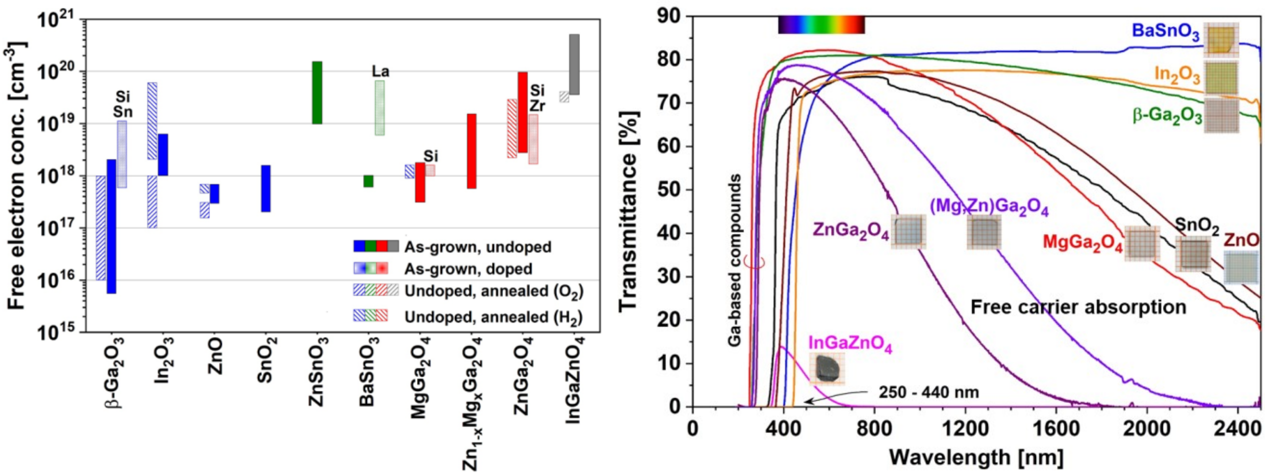

Fig. 1: Ranges of experimentally achieved free electron concentration (left) and resulting near-IR transmittance as well as optical bandgap (right) of different TSO single crystals [6].

The bandgaps of the TSOs range between 2.8 and 5 eV. Depending on doing and annealing, TSOs can be electrical insulators, *n*-type semiconductors, or degenerate *n*-type semiconductors. When electrically insulating, the TSOs are transparent in the visible and near-infrared spectral regions. However, the latter region is strongly affected by the free carrier absorption when semiconducting, and this can also result in a blueish coloration of the crystals. The highly electrically conducting TSOs are $InGaZnO_4$, $ZnGa_2O_4$, $BaSnO_3$, and In_2O_3. In SnO_2, In_2O_3, and $BaSnO_3$, electron mobilities exceeding > 200 $cm^2V^{-1}s^{-1}$ are achieved even for high electron concentrations in the range of 10^{18}–10^{20} cm^{-3} [6]. These values outpace the limits of classical III-V semiconductors, and the materials enable novel and improved electronic applications.

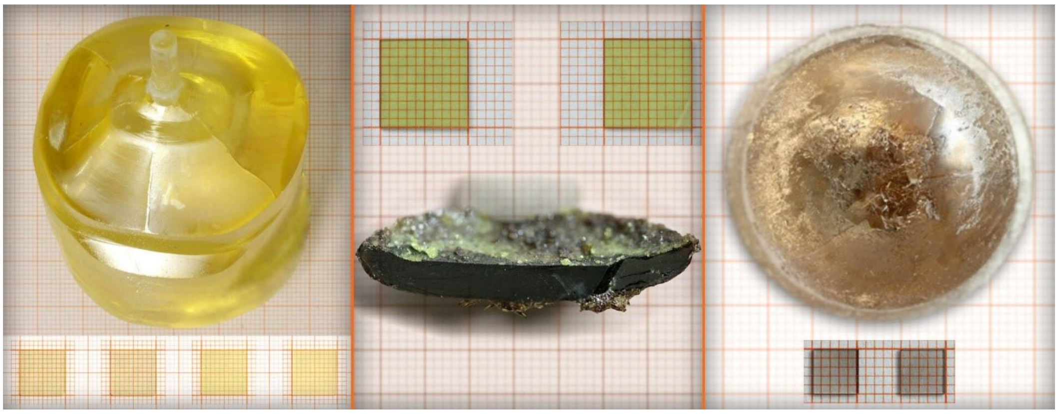

Fig. 2: Single crystals and polished wafers (substrates) of β-Ga_2O_3 (left), In_2O_3 (middle) and SnO_2 (right) [1].

[1] Z. Galazka; "Transparent Semiconducting Oxides – Bulk Crystal Growth and Fundamental Properties", Jenny Stanford Publishing (2020)

[2] Z. Galazka, M. Bickermann et al., „Scaling-up of Bulk β-Ga_2O_3 Single Crystals by the Czochralski Method", ECS J. Solid State Sci. Technol. **6**, Q3007 (2017)

[3] Z. Galazka, M. Bickermann et al., "2 Inch Diameter, Highly Conducting Bulk β-Ga_2O_3 Single Crystals Grown by the Czochralski Method for High Power Switching Devices", Appl. Phys. Lett. **120**, 152101 (2022)

[4] Z. Galazka, M. Bickermann et al., "Czochralski-Grown Bulk β-Ga_2O_3 Single Crystals Doped with Mono-, Di-, Tri-, and Tetravalent Ions", J. Crystal Growth **529**, 125297 (2020)

[5] Z. Galazka, M. Bickermann et al., "Bulk Single Crystals of β-Ga_2O_3 and Ga-Based Spinels as Ultra-Wide Bandgap Transparent Semiconducting Oxides", Prog. Cryst. Growth Charact. Mater. **67**, 100511 (2021)

[6] Z. Galazka, M. Bickermann et al., "Experimental Hall Electron Mobility of Bulk Single Crystals of Transparent Semiconducting Oxides", J. Mater. Res. **36**, 4746 (2021)