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Growth of Bulk Single Crystals of Novel Semiconductor Materials (AlN, Ga_2O_3, etc.) for Next Generation Efficient Power Electronics

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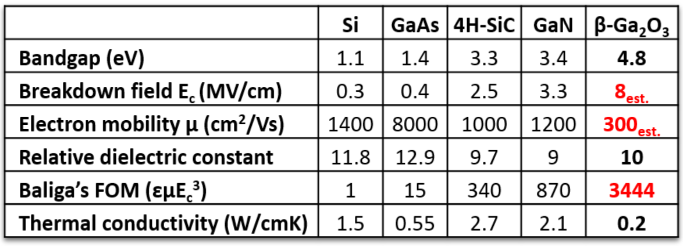
The accelerating world energy consumption is one of the critical economic challenges with huge societal and ecological impact. Electrical power has a big and increasing share due to photovoltaics and wind harvesting, the rise of electrical mobility, computer power and heat pumps. Improving the efficiency of distributing and delivering electrical energy by reducing the losses during transport and operation is thus an important target. Semiconductor transistors are already the most efficient power switching devices available, but electric power transmission and distribution losses still add up to 8% of the global output [1]. Enabling higher voltages and reducing switching losses, wide bandgap semiconductor materials can contribute significantly to avoiding a world energy crisis.



	Si	GaAs	4H-SiC	GaN	β-Ga_2O_3
Bandgap (eV)	1.1	1.4	3.3	3.4	**4.8**
Breakdown field E_c (MV/cm)	0.3	0.4	2.5	3.3	**$8_{est.}$**
Electron mobility μ (cm^2/Vs)	1400	8000	1000	1200	**$300_{est.}$**
Relative dielectric constant	11.8	12.9	9.7	9	**10**
Baliga's FOM ($\varepsilon\mu E_c^3$)	1	15	340	870	**3444**
Thermal conductivity (W/cmK)	1.5	0.55	2.7	2.1	**0.2**

Baliga's figure of merit is an indicator of the semiconductor material's potential towards efficient power switching. It scales cubically with the breakdown voltage, and that property scales quadratic with the bandgap; this is why the bandgap is so important. As shown in the table, Si and GaAs have bandgaps of 1–1.5 eV (1st generation), SiC and GaN have ~3.4 eV (2nd generation); Ga_2O_3 (4.8 eV) and AlN (6.0 eV) can be considered 3rd generation ("ultra-wide bandgap") semiconductors.

Semiconductor devices consist of epitaxial layers with utmost structural quality. Such layers are best prepared on a slice of a single crystal ("substrate") of the same material. Single crystals of silicon are conveniently grown by pulling from the melt (Czochralski technique) at 1 mm/min growth rate with up to 300 mm in diameter and 2–3 m in length; a silicon substrate costs merely one dollar. GaAs must be prepared under elevated pressure but can still be grown from the melt. GaN is prepared from supercritical ammonia, SiC and AlN can only be grown from the vapor phase at temperatures exceeding 2000°C. The respective growth rates are three orders of magnitude lower than that for Si, and the process stability is still an issue, thus the price of a substrate is also three orders of magnitude higher. But nevertheless, the power electronics industry has started to transition from Si towards SiC, its use in electric vehicles and wind turbines is enabling a billion-dollar market. GaN devices are even appearing in first consumer products (power supplies, chargers). This underlines the importance of wide bandgap materials.

Ga_2O_3 and AlN are not yet available on an industrial scale. However, as Ga_2O_3 can be grown from the melt, there is speculation that the substrate price could be at least competitive to SiC once the material becomes mature. AlN, on the other hand, could enable peak performance devices due to the even higher bandgap. In my presentation, I will show how the details and issues in the preparation of bulk crystals impact their properties and availability. While aiming to inform the audience on the general perspective of power semiconductor materials, due to time constraints I will focus on highlighting the status, issues and perspectives of the novel semiconductor materials Ga_2O_3 and AlN.

[1] https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS

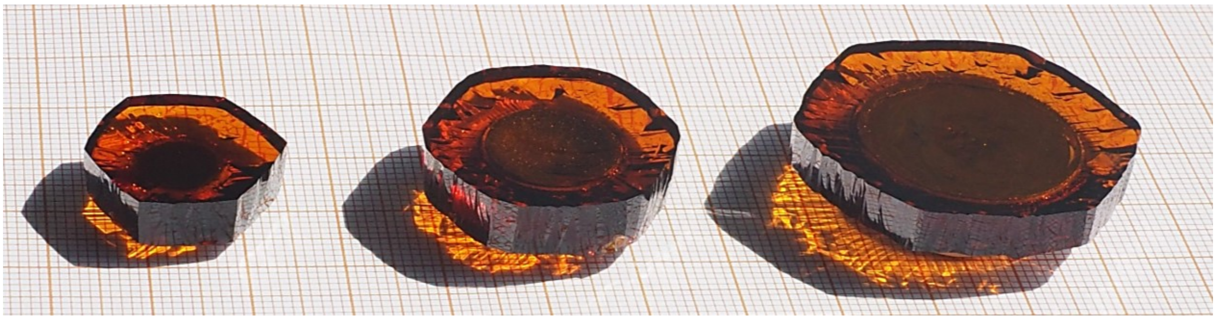


Fig. 1: AlN bulk crystals grown by physical vapor transport, 0,75”, 1” and 1.5” in diameter (IKZ)

Fig. 2: Single crystal slab of Ga_2O_3, 2” in diameter (IKZ)