Ga_2O_3 from materials to devices

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Abstract

β-Ga_2O_3 exhibits excellent materials properties as a wide band gap semiconductor for power electronic applications. The wide band gap of 4.7 eV, the availability of large-size, high-quality single crystals grown from the melt and the efficient n-type doping distinguishes it from other wide band gap semiconductors like GaN, SiC and AlN. In this presentation we review recent progress in the research and development on fundamental properties of Ga_2O_3, covering single-crystal bulk growth and wafer production, homoepitaxial thin film growth by metal organic vapor phase epitaxy and b-type doping.

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. Introduction

Monoclinic Ga2O3 (β-Ga2O3) is a semiconductor with a bandgap of 4.7eV and an estimated break down field of 8 M/Vcm. It has recently attracted considerable interest as a promising material for applications such as solar blind UV photo detectors [1] and high-power devices [2-4]. Formation of solid solutions with In_2O_3 and Al_2O_3 is possible though challenging due to their different phase at thermodynamic equilibrium and permits device concepts band gap engineering. While p-type conduction is hampered due to intrinsic obstacles such as self-trapping of holes and a large effective hole mass, n-type conduction is achievable by doping with group-IV elements (Si, Sn, Ge). Devices based on β-Ga_2O_3 thus are principally unipolar. MESFTs, MOSFETs and Schottky barrier diodes have been realized [5]. A proof of concept for a modulation doped field effect transistor has been presented recently [6].

Epitaxial growth of structurally perfect crystalline layers with defined doping is a prerequisite realize all these concepts. In contrast to other wide bandgap semiconductors, large diameter substrates grown from the melt by methods like float zone [7], edge defined film fed growth [8], and Czochralski growth [9] are available. Homoepitaxial growth by molecular beam epitaxy [10], halide vapor phase epitaxy [11], and metal organic vapor phase epitaxy (MOVPE) [12] has been reported.

In this presentation we will review our results on n-type doping of MOVPE grown β-Ga_2O_3 layers grown on (100), (010) and (001) oriented β-Ga_2O_3 with respect to obtain device grade material. We will address elementary growth processes, doping issues, and study compensation mechanisms in epitaxial and bulk crystals.

2. Experimental

Epitaxial layers are grown by metal organic vapor phase epitaxy onto semi-insulating (100) and (010) oriented β-Ga_2O_3 single crystals with a defined miscut-angle. Substrates are obtained from β-Ga_2O_3 single crystals, grown by the Czochralski method. [7]. Growth experiments are performed in a commercial vertical reactor from Structured Materials Industries (SMI) at a pressure of 5 mbar and a substrate temperature of 850°C. Triethylgallium(TEGa), tetraethylorthosilicate (TEOS) and tetraethyltin (TESn) were used as metallorganic precursors for Ga, Si and Sn, O_2 serves as an oxygen source. The surface morphology of β-Ga_2O_3 layers was studied by atomic force microscopy, while the structural properties were investigated by transmission electron microscopy (TEM, aberration corrected FEI Titan 80–300 operated at 300 kV). Secondary ion mass spectrometry was used to determine the doping profiles and to get independent information on the thickness of homoepitaxial layers obtained by ellipsometry. We performed conductivity and Hall effect measurements at room temperature in van-der-Pauw configuration.

3. Results and Discussion

Our analyses show three main results: Growth on (100) oriented substrates under appropriate conditions grow in step flow growth, while other crystal orientations tend to facet during growth, which causes rough surfaces and interfaces. Due to the low surface diffusivity of adatoms, however, stacking faults in form of twin lamella may form, that are detrimental with respect to electrical transport. The formation of these twin lamellae can be prevented if a proper miscut is chosen. Under the growth condition applied here, we find step-flow growth and defect free material at miscut-angles of 6°. Structurally optimized material exhibits negligible compensation in the case of Si doped samples, while for Sn doping the free carrier concentration drops beyond a Sn concentration of 10^{19}cm^{-3}.

Possible compensation mechanisms were studied in bulk crystals and epitaxial layers. While find full electrical activation of the donors in the as grown state was found for Czochralski-grown material, EFG grown bulk crystals require a high-temperature annealing step in N_2 atmosphere. Local vibrational mode spectroscopy and electro paramagnetic resonance measurements indicate that gallium vacancies and hydrogen are involved in compensation. Silicon and tin, the n-type dopants of practical importance, are effective-mass like shallow donors without any peculiarity.

Based on doped epitaxial layers MOSFETs with a break down voltage of 3.8 MV/cm could be prepared, which is the highest reported for any transistor and surpassing already bulk GaN and SiC theoretical limits [4]. β-Ga_2O_3 MOSFET with record-high transconductance (gm) of 21 mS/mm and extrinsic cutoff frequency (f_T) and maximum oscillating frequency (f_{max}) of 3.3 and 12.9 GHz, respectively, enabled by implementing a new highly doped ohmic cap layer with a sub-micron gate, indicate potential for monolithic or heterogeneous integration of power switch and RF devices using β-Ga_2O_3 [13].

4. Conclusion

β-Ga_2O_3 in the last decade gained renewed interest as a wide band gap semiconductor with applications mainly in the field of power electronics. Advantages as compared to other wide band gap semiconductors like GaN, SiC or AlN are the availability of bulk substrates with sizes up to 6 inch grown from the melt, the ability of n-type doping up to levels of 10^{20}cm^{-3} without exhibiting common problem of other wide band gap semiconductors like significant compensation or formation of DX centers. The poor heat conductivity of the material, amajor drawback requires new device concepts that allow to remove heat efficiently but are more an engineering problem then a fundamental limit to realize devices. Low doped layers, necessary for devices that provide the ultimate break down voltage have up to now been achieved exclusively by halide vapor phase epitaxy. The source of residual donors in MOVPE grown layers are still under investigation. Concepts for normally off devices are not present up to now, but are urgently needed to fully take advantage of this promising materials system.

References

[1] R. Suzuki et al., Appl. Phys. Lett. 94 (2009), 222102.
[2] W. S. Hwang et al., Appl. Phys. Lett. 104 (2014) 203111.
[3] M. Higashiwaki et al., Phys. Status Solidi A 211 (2014), 21.
[4] A. J. Green et al., IEEE ELECTRON DEVICE LETTERS 37, (2016) 902-905.
[5] M. Higashiwaki et al., Semicond. Sci. Technol. 31 (2016) 034001.
[6] E. Ahmadi et al., Applied Physics Express 10 (2017), 071101.
[7] Y. Tomm et al., Sol. Energy Mater. Sol. Cells 66 (2001), 369.
[8] H. Aida et al., Jpn. J. Appl. Phys. 47 (2008), 8506.
[9] Z. Galazka, et al., Cryst. Res. Technol. 45 (2010), 1229.
[10] K. Sasaki, Appl. Phys. Express 5 (2012), 35502.
[11] H. Murakami et al. Appl. Phys. Express 8 (2015), 15503.
[12] G. Wagner et al., Phys. Status Solidi, A 211 (2014) 27.
[13] A. J. Green et al., IEEE ELECTRON DEVICE LETTERS 38 (2017), 790-793.