L.3: Growth of β-Ga_2O_3 single crystal: A transparent conducting oxide

Monoclinic (C2/m) gallium oxide (β-Ga_2O_3) is receiving considerable attention due to its wide band-gap (~4.7 eV) as well as high electrical conductivity which makes it useful for a variety of applications such as transparent conducting electrode, gas sensors, as a substrate material for the growth of gallium-nitride based laser emitting diode devices etc. As a substrate material it simultaneously provides the transparency of sapphire as well as the electrical conductivity of SiC, which are commercially used substrate materials for these devices. Of late it has also been identified as the most promising contender for power electronics due to high breakdown voltage.

At Melt Crystal Growth Laboratory of Laser Materials Section, RRCAT, single crystals of undoped and doped (Si, Sn, Ge, Al) β-Ga_2O_3 have been grown in optical floating zone furnace. As the conductivity of the crystal is greatly influenced by the growth ambience, crystals have been grown in ambience containing different oxygen partial pressure. The dimension of the grown crystals are: 5-10 mm in diameter and 20-30 mm in length (Figure L.3.1).

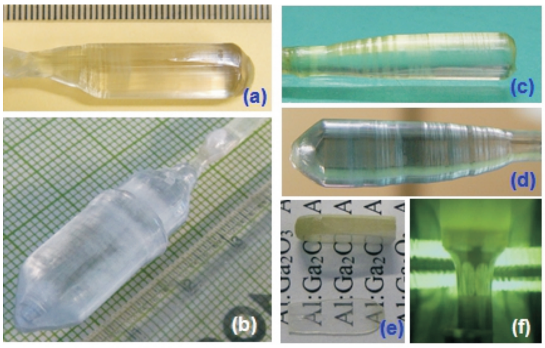

Fig. L.3.1: β-Ga_2O_3 crystals: (a) undoped grown in air; (b) undoped, (c) Si doped, (d) Sn doped, (e) Al doped grown in 5% O_2. (f) On-line image of growth.

For several applications knowledge of the optical parameters such as refractive index is necessary but was not reported in literature for β-Ga_2O_3 single crystal prior to our investigation. Temperature dependent (in the range of 30-175 °C) refractive index of the grown crystal at five discrete wavelengths has been measured using Prism coupling and fitted with Sellmeier equation. Figure L.3.2 shows the refractive index measured at 30 °C along [010] and a direction to (100). The measured thermo-optics co-efficient (dn/dT) is ~10^{-5}/°C (Figure L.3.3). As the doping influences the conductivity of β-Ga_2O_3, conductivity has been measured using four probes. It has been observed that the tetravalent Si, Ge and Sn increases the conductivity of the crystal as they introduce oxygen vacancy in the lattice which, in turn, increases the free electron concentration in lattice. The maximum conductivity achieved is ~38 $\Omega^{-1}cm^{-1}$ for 0.2 mol.% Si (for undoped sample: ~0.02 $\Omega^{-1}cm^{-1}$) grown in 2 lpm flow of N_2 and O_2 (95:5).

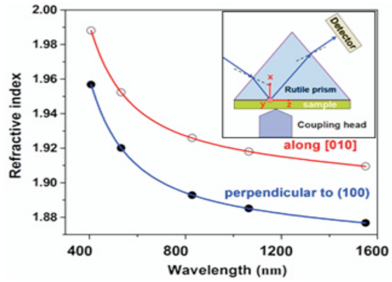

Fig. L.3.2: Refractive index at 30 ºC fitted with Sellmeier's equation. Inset: Prism coupling technique.

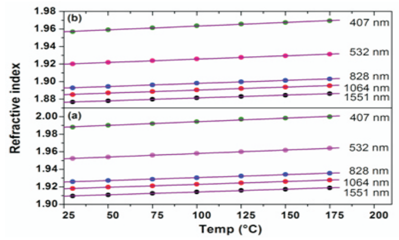

Fig. L.3.3: Temperature dependent refractive index (a) along [010] (b) along to (100).

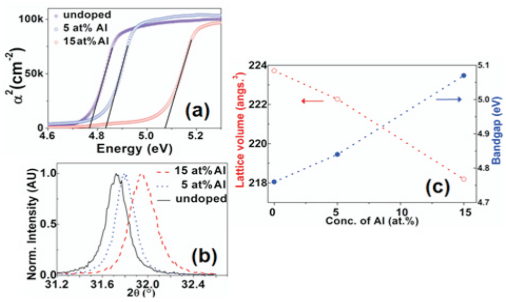

Fig. L.3.4: (a) Tauc plot, (b) Shift of (002) diffraction peak with Al doping, (c) Effect of Al on the band-gap and lattice volume of β-Ga_2O_3.

Further, tunability of band gap is an important aspect as it allows great flexibility in designing and optimizing the devices. For β-Ga_2O_3 as TCO material it is desirable to increase the band-gap of the material so that its transparency window broadens. With this objective Al has been doped in β-Ga_2O_3. Our study reveals that doping of Al increases the band gap of the material. On doping with 15 at.% of Al band gap increases to 5.07 eV. Also it has resulted a shrinkage in the lattice parameters and volume due to the lower ionic radii of substituting Al ion in comparison to the Ga ions (Figure L.3.4).

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