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Epitaxial Growth
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Epitaxial Growth Poster Session

EG-TuP-1 α-phase Gallium Oxide Thin Films Stabilized on a-, r- and m-plane Sapphire Substrates via Reactive Magnetron Sputtering and Pulsed Laser Deposition, ***Edgars Butanovs***, Institute of Solid State Physics University of Latvia

Gallium oxide Ga_2O_3 has recently attracted a lot of scientific attention as a prospective ultra-wide bandgap semiconductor. It has five different polytypes α, β, δ, γ and ε among which the most studied and thermodynamically stable phase is β-Ga_2O_3. However, corundum-structured α-Ga_2O_3 with 5.2 eV bandgap is a better alternative for power electronics and ultraviolet optoelectronics applications. α-Ga_2O_3 is a metastable phase and it cannot be obtained as bulk crystals used for homoepitaxial growth. On the other hand, sapphire (α-Al_2O_3) is a convenient substrate for heteroepitaxy since some of its crystalline planes have a small lattice mismatch with α-Ga_2O_3, but there are only few and recent reports on the use of other orientation sapphire substrates than c-plane. In this work, we demonstrate growth of α-Ga_2O_3 thin films on a-, r- and m-plane sapphire wafers at various substrate temperatures via two different methods – reactive magnetron sputtering and pulsed laser deposition. Crystalline structure, elemental composition, surface morphology and optical properties were characterized by X-ray diffraction, X-ray photoelectron spectroscopy, scanning and transmission electron microscopy, atomic force microscopy and UV-VIS measurements. α-phase stability dependence on film thickness was also investigated. Such epitaxial stabilization of high-quality thin films with commonly used deposition methods is a perspective way how to integrate α-Ga_2O_3 on available substrates.

The financial support of Latvian Council of Science FLPP project LZP-2020/1-0345 is greatly acknowledged.

EG-TuP-2 Epitaxial Growth of $(Al_xGa_{1-x})_2O_3$ by Suboxide MBE, ***Jacob Steele***, *K. Azizie, J. McCandless,* Cornell University*; T. Asel,* Air Force Research Lab*; H. Xing, D. Jena, D. Schlom,* Cornell University

Ga_2O_3 has garnered significant interest due in part to its ultra wide bandgap (~4.7ev) and large breakdown field which make it optimal for next-generation power devices. This already exceeds benchmark materials such as SiC and GaN but it is possible to alloy with Al to form $(Al_xGa_{1-x})_2O_3$ and further raise the bandgap up to 8.3 eV, higher than diamond. This can be desirable but presents a challenge for the most commonly researched phase, β-Ga_2O_3, as it is structurally unstable at higher Al concentrations, limiting the range of possible alloying. In contrast, α-phase Ga_2O_3 has been shown to alloy over the full range of x with one technique for growing α-$(Al_xGa_{1-x})_2O_3$ being molecular beam epitaxy (MBE). MBE is a powerful technique with one drawback being its relatively slow growth rate, which has a maximum of roughly 0.2 µm/hour. Fortuitously, the recent development of suboxide MBE, has enabled the epitaxial growth of β-Ga_2O_3 with growth rates exceeding 1 µm/hr without compromising film quality.

This work investigates the application of suboxide MBE to the growth α-$(Al_xGa_{1-x})_2O_3$ thin films. The goal of this project is to determine whether suboxide MBE can grow high quality epitaxial α-$(Al_xGa_{1-x})_2O_3$ over the full range of x with growth rates exceeding 1 µm/hr. For this suboxide MBE study, gallium suboxide and elemental aluminum sources were used and the ozone pressure, growth temperature, Al_2O_3 substrate orientation, gallium suboxide flux, and elemental aluminum flux were varied to map out promising growth conditions. Our experiments reveal that a-plane sapphire substrates consistently enable the epitaxial growth of α-$(Al_xGa_{1-x})_2O_3$ over a broad range of growth conditions. We also show that the growth rates of α-$(Al_xGa_{1-x})_2O_3$ using suboxide MBE approach 1 µm/hr with high surface quality by rocking curves and atomic force microscopy measurements. Lastly, we demonstrate that the aluminum content of the α-$(Al_xGa_{1-x})_2O_3$ films covers a large range of x including the high x values where β-Ga_2O_3 is unstable.

EG-TuP-5 Free Carrier Control in Homoepitaxial β-Ga_2O_3 Thin Films by Tin Impurity Doping, ***Neeraj Nepal***, *B. Downey, V. Wheeler, D. Katzer, E. Jin, M. Hardy, V. Gokhale, T. Growden,* US Naval Research Laboratory*; K. Chabak,* Air Force Research Laboratory*; D. Meyer,* US Naval Research Laboratory

Ultra-wide bandgap (UWBG) semiconductors such as c-BN, AlN, high Al content AlGaN, β-Ga_2O_3, anddiamond, with a bandgap greater than 3.4 eV, have higher figures of merit values than GaN and SiC for power and rf devices making them candidates for next generation high-power/temperature electronic materials [1-3]. The availability of inexpensive large-area bulk substrates synthesized by melt growth techniques at atmospheric pressure provides a scaling advantage for β-Ga_2O_3 over other UWBG semiconductors [2]. In addition, homoepitaxial growth on bulk substrates offers the potential of low defect density films for vertical power devices. Further, controlled n-type doping with a shallow donor level (15-50meV [4]) is another advantage of β-Ga_2O_3 compared to AlN and high Al-content AlGaN. For these reasons, homoepitaxial growth of unintentionally- and impurity-doped Ga_2O_3 films and their electrical and structural properties are of great interest.

In this paper, we report MBE growth and Sn impurity doping of β-Ga_2O_3 thin films on (010) β-Ga_2O_3 substrates from Novel Crystal Technology and Northrop Grumman SYNOPTICS vendors. Maintaining smooth surface in in-situ RHEED, the growth rate was increased approximately from 1 to 3nm/min by optimizing the growth conditions such as Ga flux, plasma conditions and growth temperature (T_g). At optimal conditions with a T_g of 725 °C, surface roughness, and X-ray rocking curve full-width at half maximum were about 0.36 nm, and 20 arc-sec for ~390 nm thick films, respectively. Optimal growth conditions that resulted in high structural and surface quality were used to explore doping parameter space using Sn impurity. The Sn cell temperature was varied from 570 to 630 °C to control incorporated Sn concentration and hence free carrier density. Hall effect measurements were carried out on Sn-doped layers using In-dots contacts, and selected samples were processed into van der Pauw Hall measurement structures to verify the In-dot-based Hall effect values. Hall effect measurements demonstrate that free carrier density can be controlled in the range $1x10^{16}$ to $3x10^{19}$ cm^{-3}. A mobility of 49 cm^2/V-s with free carrier density of $3x10^{19}$ cm^{-3} was measured which is comparable to the previously reported values for Sn-doped β-Ga_2O_3 [5].

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EG-TuP-6 MBE Growth of Doped and Insulating Homoepitaxial β-Ga_2O_3, ***Jon McCandless***, *V. Protasenko, B. Morell,* Cornell University*; E. Steinbrunner, A. Neal,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA*; Y. Cho, N. Tanen, H. Xing, D. Jena,* Cornell University

The group IV atoms Si, Ge, and Sn have been investigated as *in-situ* n-type dopants in the molecular beam epitaxy (MBE) growth of β-Ga_2O_3. However, it has remained challenging to achieve controllable and intentional n-type doping of low doping densities in MBE due to the tendency of the dopants to oxidize during the growth. As a result, doping is restricted to a small window of growth conditions. Recently, we have overcome this doping challenge by modifying the effusion source design. This modification allowed us to achieve room temperature mobilities of ~130 cm^2/Vs at 1×10^{17}/cm^3 with Si doping.

Variations in the transport measurements between samples doped under similar conditions was observed. For example, some unintentionally doped samples (UID) exhibit electrically insulating behavior in Hall effect measurements, while others exhibit measurable conductivity. Secondary ion mass spectrometry (SIMS) measurements revealed that Si, which is universally observed at the substrate-film interface, and Fe (the compensating acceptors included in the substrate to make it semi-insulating) varied from sample to sample. Depending on the chosen substrate, this resulted in the variability of the nominal conductivity of UID samples.

To address this it is necessary to grow an additional layer, doped with deep, compensating acceptors, on top of the substrate to compensate the

interface charge. Here we will present our latest research on controllable doping, design of a compensating layer to achieve insulating films, and the impact these have on the growth of field-effect transistors.

EG-TuP-7 High Conductivity Homoepitaxial β-Ga_2O_3 Regrowth Layers by Pulsed Laser Deposition, ***Hyung Min Jeon***, KBR; *K. Leedy,* Air Force Research Laboratory

With a high critical field strength, wide bandgap, and transparence, β-Ga_2O_3 is a unique material for high power switching and amplifier applications, as well as optoelectronic applications as it is a transparent conductive oxide. In semiconductor devices, doping of the semiconductor is necessary to modulate a semiconductor's electrical properties. Degenerately doped semiconductors have particular use as an ohmic contact regrowth layer. Highly conductive, measured 2323 S/cm (4.3 x10^{-4} Ω-cm resistivity), homoepitaxial Si-doped epitaxial β-Ga_2O_3 films by pulsed laser deposition has been fabricated in this work. A commercial pulsed laser deposition system with a KrF excimer laser was used for deposition with a Ga_2O_3 - 1 wt. % SiO_2 target. The base pressure of PLD chamber was 2.66 × 10^{-6} Pa with 55 sccm Ar gas introduced during deposition. The substrate temperature, rotating at 30 º/sec, was 590 ºC. The exceptional electrical properties of the Si-doped epitaxial β-Ga_2O_3 films are 2.24 × 10^{20} cm^{-3} carrier concentration and 64.5 cm^2/Vs Hall mobility. The calculated electrical activation efficiency is 77 % calculated using the Si content from secondary ion mass spectrometry depth profile. For practical use of this highly conductive layer in a semiconductor device, large area deposition uniformly is essential. However, PLD suffers from limitation of scale up area due to the point laser energy source. We found that locally non-uniformed and less-conductive layers cause degradation of the electrical properties in large area film. We examined the growth conditions that address this local conductivity non-uniformity and present solutions using improved deposition parameters.A uniform, low resistivity β-Ga_2O_3 layer is anticipated to enable increased tunneling current between metal contacts and β-Ga_2O_3 transistor channel layers reducing power dissipation and improving overall transistor performance. Moreover, wide bandgap β-Ga_2O_3 with unusually high conductivity can be a suitable candidate for future optoelectronic applications.

EG-TuP-9 Highly conductive β-Ga_2O_3 and $(Al_xGa_{1-x})_2O_3$ epitaxial films by MOCVD, ***Fikadu Alema***, Agnitron Technology; *T. Itoh, J. Speck,* Materials Department, University of California, Santa Barbara; *A. Osinsky,* Agnitron Technology

We report on the growth of highly conductive (n>1020 cm-3) Si or Ge doped β-Ga2O3 and β-$(Al_xGa_{1-x})_2O_3$ epitaxial films grown on (010) β-Ga_2O_3 substrates by MOCVD. Triethylgallium (TEGa), triethylaluminum (TEAl), and pure oxygen were used as Ga, Al, and O_2 sources. Silane (SiH_4) and germane (GeH_4) diluted in nitrogen were used as sources for Si and Ge. The layers were grown at a lower substrate temperature (~500-600 °C); the effects of O_2 flow, film growth, pressure, and dopant flow rates on the incorporation and activation efficiency of the dopants were studied. By carefully adjusting these process conditions, doping limitations for epitaxial β-Ga_2O_3 and AlGaO alloys with various Al composition were defined. With Si dopant, films with the conductivity of ~2515 S/cm (μ=50.7 cm^2/Vs, n =3.1x10^{20} cm^{-3}) were achieved as determined by Hall effect measurements. This result sets a record compared to the best conductivity value reported in the literature, 2323 S/cm in a layer grown by PLD [1]. Similarly, despite the challenges with Ge doping due to its severe process dependence, highly conductive Ge-doped layers with the conductivity of ~1580 S/cm (μ=38 cm^2/Vs, n = 2.6x10^{20} cm^{-3}) were realized. Temperature-dependent Hall measurement showed no charge density dependence on temperature both for heavily Ge and Si-doped films, indicating degenerate doping. The heavy Si doping process developed for β-Ga_2O_3 has also been extended to β-$(Al_xGa_{1-x})_2O_3$ with varying Al content. The AlGaO layer thickness and Al content in the films were estimated by HRXRD measurement, while Hall effect measurements were used to study the electrical characteristics of the layers. For coherently strained, ~70-75 nm thick, AlGaO layers with Al content of 12.3%, films with a conductivity of 612 S/cm (μ=31.1 cm^2/Vs, n =1.23x10^{20} cm^{-3}) were achieved. However, this value was reduced to ~220 S/cm (μ=25 cm^2/Vs, n =5.5x10^{19} cm^{3}) when the Al content increased to 22%. The effects of AlGaO layer thickness and Al content on Si incorporation, surface roughness, free carrier concentration, and electron mobility in AlGaO were studied and will be discussed. The high free carrier concentration in Ga2O3 and AlGaO thin films achieved by MOCVD at low epitaxial growth temperature enables low resistance ohmic contact layers to realize high-performance β-Ga_2O_3 and β-$(Al_xGa_{1-x})_2O_3$/β-Ga_2O_3 heterostructure devices [2].

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