Program Overview

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Heterogeneous Material Integration
Room Jefferson 1 & Atrium - Session HM-MoP
Heterogeneous Material Integration Poster Session

HM-MoP-1 Structural and Thermal Transport Analysis of Wafer Bonded β-Ga_2O_3 |4H-SiC, ***Michael Liao**, K. Huynh, Y. Wang,* UCLA*; Z. Cheng,* UIUC*; J. Shi,* GaTech*; F. Mu,* IMECAS, China*; T. You, W. Xu, X. Ou,* ShanghaiTech, China*; T. Suga,* Meisei University, Japan*; S. Graham,* GaTech*; M. Goorsky,* UCLA

The impact of post-bond annealing on the structural and thermal characteristics of 140-nm thick exfoliated ($\underline{2}01$) β-Ga_2O_3 (via H^+ ion implantation [1]) direct wafer bonded to (0001) 4H-SiC was studied. For these studies, 30 nm amorphous alumina was grown on the β-Ga_2O_3 substrates prior to bonding as an interlayer between the β-Ga_2O_3 and 4H-SiC. The surface activated bonding technique was utilized for bonding, which induces a thin ~nm amorphous interfacial region at the bonded interface (alumina | 4H-SiC) [2]. We demonstrate annealing the bonded structure at 800 °C in ambient air up to 1 hour is beneficial: (1) removal of residual strain in the exfoliated β-Ga_2O_3 layer that was due to the exfoliation implant, (2) reduction of lattice mosaicity in the β-Ga_2O_3 layer, and (3) recrystallization of the amorphous bonded interfacial region. The thermal characteristics correspondingly improve with the improvement in structural characteristics. The thermal conductivity of the as-bonded β-Ga_2O_3 layer was 2.9 W/m·K and the thermal boundary conductance (TBC) of the bonded interface was 66 $MW/m^2 \cdot K$ [2]. After annealing at 800 °C for 1 hour, triple-axis X-ray diffraction ω:2θ measurements showed a reduction in strain for the β-Ga_2O_3 layer and the symmetric ($\underline{2}01$) rocking curve widths. Transmission electron microscopy images of the bonded interface show that the amorphous bonded interfacial region recrystallized. We simultaneously observe a doubling of the β-Ga_2O_3 thermal conductivity to 6.0 W/m·K and a twenty percent increase in the TBC. While the previous results showed the promise of exfoliation of b-Ga_2O_3 on 4H-SiC, here we demonstrate that annealing further improves both structural and thermal properties.

References:

1. M. Burel, et al., Jpn. J. Appl. Phys., 36, 1636 (1997).
2. Z. Cheng, et al., ACS Appl. Mater. Interfaces, 12, 40 (2020).

The authors M.E.L., K.H., Y.W., Z.C., J.S., S.G., and M.S.G. would like to acknowledge the support from the Office of Naval Research through a MURI program, grant No. N00014-18-1-2429.

HM-MoP-2 Advances in Plasma-Enhanced Atomic Layer Deposited (PEALD) Ga_2O_3 Films, ***Virginia Wheeler**, A. Lang, N. Nepal, E. Jin, D. Katzer, V. Gokhale, B. Downey, D. Meyer,* US Naval Research Laboratory

Ga_2O_3 is a promising material for next generation electronics. Recently, we demonstrated that plasma-enhanced atomic layer deposition (PEALD) can be used to attain heteroepitaxial metastable phases [1], specifically α and ε/κ, and the full stoichiometric range of $(Al_xGa_{1-x})_2O_3$ films. PEALD is a conformal, energy-enhanced synthesis method for thin films with many advantages, including: deposition at reduced growth temperatures, access to metastable phases, elimination of miscibility gaps, and improved crystallinity and growth rates over conventional ALD. In this work, we present new insights into the microstructure and uniformity of metastable ε-Ga_2O_3 films integrated on GaN. Additionally, we explore the use of PEALD for fabricating metastable nucleation layers that can be expanded by more traditional, faster deposition techniques.

Transmission electron microscopy (TEM) was used to correlate PEALD parameters with the resulting Ga_2O_3 microstructure on GaN substrates. A low temperature, low pressure PEALD regime produced ~95% epsilon phase films with a strained interfacial layer and 10-50nm grains. The remaining portion was a combination of alpha and beta phases that were primarily segregated towards the surface of the film. In comparison, a higher temperature, high-pressure growth regime produced uniform, pure epsilon phase films with 2-5 nm grains. The abrupt interface was fully relaxed with misfit dislocations at a spacing of ~2nm, explaining the resulting ε-Ga_2O_3grain size. There was no evidence of kappa or gamma phase as often seen with low temperature heterogeneous integration of Ga_2O_3 films.

While PEALD is beneficial for depositing thin films of metastable phases, practical devices often require much thicker barrier and active layers. For this reason, we investigated integrating PEALD metastable Ga_2O_3 films with traditional semiconductor growth techniques, such as molecular beam epitaxy (MBE), capable of extending these layers beyond 100 nm in thickness. The same MBE conditions were used to deposit Ga_2O_3 films on GaN substrates with and without PEALD ε-Ga_2O_3 nucleation layers.Those deposited without the PEALD nucleation layer produced β-phase films, while those with nucleation layers resulted in pure ε-phase films. We also show a similar capability using metal-organic chemical vapor deposition (MOCVD).This shows importance of PEALD for realizing practical device structures using metastable phases.This concept could also be expanded to α-Ga_2O_3 film, though this is more easily achieved directly on sapphire substrates.

[1] Wheeler et al., *Chem. Mater.* 2020, 32, 1140-1152

HM-MoP-3 Grafted Si/Ga2O3 pn Diodes, *H. Jang, D. Kim,* University of Wisconsin - Madison*; J. Gong,* University of Wisconsin at Madison*; F. Alema, A. Osinsky,* Agnitron Technology Inc.*; K. Chabak,* Air Force Research Laboratory*; G. Jessen,* BAE Systems*; G. Vincent,* Northrup Grumann*; S. Pasayat, C. Gupta,* University of Wisconsin - Madison*;* ***Zhenqiang Ma**,* 1415 Engineering Drive

Gallium oxide (Ga_2O_3) is a promising semiconductor for the next-generation power devices, due to its ultra-wide bandgap (4.9 eV), high electron saturation velocity (1.1×10^7 cm/s), and high breakdown electric field (8 MV/cm) and the mature growth technique for large diameter native substrates. While many high-performance unipolar devices, e.g., field-effect transistors (FET) and Schottky diodes, have been reported recently, the lack of p-type Ga_2O_3 limits the development of Ga_2O_3 based bipolar devices. Wafer bonding of p-type diamond with Ga_2O_3 and growth of p-type polycrystalline on Ga_2O_3 have been attempted to realize bipolar (pn) devices with limited performance. The recent semiconductor grafting approach shows the potential of forming semiconductor heterostructures without concerning about lattice mismatch. The grafting approach could be exploited to form p-n heterojunctions by combining n-type Ga_2O_3 with monocrystalline p-type semiconductors. In this talk, preliminary results of p-Si/n-Ga_2O_3 pn diode fabricated by semiconductor grafting will be presented. The Ga_2O_3 epi layer consists of Sn-doped 150 nm n- (2e17 cm^{-3}) on a Sn doped 500-600µm n^+-Ga_2O_3 (5e18 cm^{-3}) substrate. A ~185 nm thick boron doped (5e19 cm^{-3}) single crystalline Si (native oxide free) was released from SOI and transferred to the top of the n-Ga_2O_3 epi substrate. A thermal anneal of 350 °C for 5 mins was performed to form chemical bonding while the top layer of Ga_2O_3 is expected to serve as the interface passivation layer. Ni/Au/Cu/Au metal stack was deposited on the p-Si as anode contact and a Ti/Au/Cu/Au was deposited on the backside (n+) Ga_2O_3 as cathode contact. Without any further thermal annealing, we have achieved an I-V characteristic with I_{on}/I_{off} = 1.5e8 at ±2 V and ideality factor n = 1.4. The device performances were compared with a Schottky diodes fabricated using the same epi substrate. The study has shown the feasibility of grafting in developing Ga_2O_3-based bipolar devices, despite that further improvement of device performance is expected.

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