Material and Device Processing and Fabrication Techniques Room Bansal Atrium - Session MD-MoP

Material and Device Processing and Fabrication Techniques Poster Session I

MD-MoP-2 Characteristics of n-ITO/Ti/Au Multilayer for Ohmic Contact on β-Ga$_2$O$_3$ Epitaxial Layer*, Yusup Jung*, *H. Kim, S. Kim,* Powercubesemi Inc., Republic of Korea*; Y. Jung, D. Chun,* Hyundai Motor Company, Republic of Korea*; T. Kang, S. Kyoung,* Powercubesemi Inc., Republic of Korea

In this paper, The n-ITO/Ti/Au Multilayer for forming an ohmic contact was deposited on the β-Ga$_2$O$_3$epitaxial layer by using magnetron sputtering system to apply the source and drain of the lateral β-Ga$_2$O$_3$transistor. Multilayer was heated by using Rapid Thermal Annealing (RTA) equipment after deposited multilayer, and the contact resistance, sheet resistance, and linear dependence characteristics were evaluated after measuring the I-V curve using the TLM method. The n-ITO is a transparent conductive material with a band gap of about 3.5eV [1]. It is deposited between β-Ga$_2$O$_3$ and Ti metal to improve band alignment between β-Ga$_2$O$_3$and Ti and to be as an electron injection layer to improve ohmic contact characteristics [2,3]. The n-ITO/Ti/Au Multilayer is deposited on β-Ga$_2$O$_3$ epitaxial layer by using DC/RF magnetron sputtering equipment. After deposition process, post annealing process was proceeded within the range of 500 to 800 degrees in a nitrogen gas atmosphere. The I-V characteristics of the fabricated TLM pattern were measured with a keithley 2410. As a result, when the thicknesses of n-ITO, Ti and Au metal were 20nm, 50 nm, and 100 nm, the specific contact resistivity is 1.3 mΩ.cm^2 and exhited strong linear dependence curve at post annealing temperature of 700 degrees.

[Reference]

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MD-MoP-3 β-Ga$_2$O$_3$ Schottky and Heterojunction Diodes Operating at Temperatures Up to 600°C*, Kingsley Egbo*, *S. Schaefer, W. Callahan, B. Tellekamp, A. Zakutayev,* National Renewable Energy Laboratory

Semiconductor device performance and reliability under extreme conditions are essential for several applications in the industrial, energy, and automotive sectors. Wide bandgap oxides such as β-Ga$_2$O$_3$ are important materials for high-power device applications and are also well-suited for high-temperature electronics due to reduced temperature-activated parasitic leakage and resistance to oxidation.

Here, we explore the high-temperature operation of Ga$_2$O$_3$ based Schottky and *p-n* junction diodes. Vertical heterojunction NiO/β-Ga$_2$O$_3$ diodes and Ni/β-Ga$_2$O$_3$ Schottky diodes were fabricated and studied using current-voltage (*I-V*) and capacitance-voltage (*C-V*) measurements in the range of 25 – 600 °C. For the *p-n* diode, a 200nm thick NiO film was grown on a Sn-doped β-Ga$_2$O$_3$ (100) substrate ($\approx 2\times10^{18}$ cm^{-3}) by pulsed laser deposition, where the (100) substrate face is effective at promoting (100)-textured NiO. After NiO deposition, the device area was mesa isolated by argon dry etching.[1] The Schottky diode was fabricated on a 300 nm unintentionally doped (UID) layer grown on Sn-doped Ga$_2$O$_3$ (001) substrates by molecular beam epitaxy (MBE).[2] Schottky diodes were formed by depositing 30 nm Ni / 100 nm Au via e-beam evaporation. For both types of devices, a stable Ohmic back contact to Ga$_2$O$_3$ was formed by 5 nm Ti / 100 nm Au annealed under N$_2$ at 550 °C for 90 seconds.[3]

In the Schottky diode, the turn-on voltage and rectification ratio were found to be 1.2V and 10^8 (±2V), respectively, at room temperature. The rectification ratio decreased strongly with increasing operating temperature to $\approx 10^2$ at 600 °C. The temperature dependence of the on-state voltage and increasing leakage current are attributed to barrier inhomogeneity and instability at Ni/β-Ga$_2$O$_3$ interface and low built-in potential at the Schottky barrier (≈1.0 eV measured by *C-V*). The NiO/β-Ga$_2$O$_3$ diodes turn-on voltage at RT was found to be 1.9V. Compared to the Schottky diode, a similar rectification ratio of the order of 10^8 was obtained at RT however the rectification ratio only decreased to $\approx 10^4$ at 600 °C. The NiO heterojunction diode also showed lower reverse leakage current up to -10V compared to the Ni-based Schottky diode at high temperatures. These results suggest that while Ga$_2$O$_3$ based Schottky barrier diodes hold some potential for high-temperature operation, they are more fundamentally limited by thermally driven leakage current increases. We show that heterojunction *p-n* diodes can significantly improve high-temperature electronic device and sensor performance due to a higher built-in voltage and favorable band offsets.

MD-MoP-4 Structural Properties of Ga$_2$O$_3$ Surfaces Treated by Nitrogen Radical Irradiation*, Kura Nakaoka*, *S. Taniguchi, T. Kitada, M. Higashiwaki,* Department of Physics and Electronics, Osaka Metropolitan University, Japan

Recently, we found that nitrogen (N) radical irradiation has an effect to significantly restore Ga$_2$O$_3$ surface damage and can improve not only Ga$_2$O$_3$ Schottky characteristics but also their in-plane uniformity. It can be expected that the nitridation would be one of the key processes for fabrication of various types of Ga$_2$O$_3$ devices. In this work, we studied structural properties of nitridated Ga$_2$O$_3$ (100) and (010) surfaces to investigate an origin of the improvements in electrical properties.

Surfaces of Ga$_2$O$_3$ (100) and (010) substrates were simultaneously nitridated by irradiation of N radicals generated using an RF-plasma cell in a molecular beam epitaxy growth chamber. The process was performed at a substrate temperature of 660℃ for 30, 60, and 120 min. The RF plasma power and N$_2$ gas flow rate were 500 W and 0.6 sccm, respectively. We observed nitridated Ga$_2$O$_3$ surfaces by atomic force microscopy (AFM) and analyzed elemental compositions of the Ga$_2$O$_3$ near-surface region using X-ray photoelectron spectroscopy (XPS).

Roughening of the Ga$_2$O$_3$ (100) and (010) surfaces occurred by the nitridation process, and the roughness monotonically increased with nitridation time. For the (100) and (010) surfaces, the root-mean-square roughness values were less than 0.2 nm before the N radical irradiation and reached 0.49 and 0.99 nm after the 120-min irradiation, respectively.

Next, we performed XPS analyses for the samples with and without the 120-min N radical irradiation to investigate the progress of nitridation. A clear N 1*s* peak was observed only for the nitridated surfaces, indicating that a large amount of N atoms were successfully incorporated into the Ga$_2$O$_3$ by the N radical irradiation. Ga 3*d* peaks of the nitridated surfaces were separated into four gaussian components corresponding to the Ga-O bonding, the Ga-N bonding, the O 2*s* core level, and the N 2*s* core level. The ratios of integrated intensities between the Ga-O and Ga-N peaks, i.e., Ga-N/Ga-O values were 0.51 and 0.74 for the Ga$_2$O$_3$ (100) and (010) surfaces, respectively. This result indicates that nitridation more advanced on the (010) surface than the (100) one, which can be attributed to a difference in the density of dangling bonds.

In this study, we investigated structural properties of nitridated Ga$_2$O$_3$ (100) and (010) surfaces. Improvements in electrical properties of the Ga$_2$O$_3$ Schottky interfaces by N radical treatment are considered due to replacement of a large amount of O atoms by N atoms.

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MD-MoP-6 Process Optimization of Sputtered High-K (Sr,Ba,Ca)Tio$_3$ for Ga$_2$O-$_3$ Dielectric Layers*, Bennett Cromer*, *C. Gorsak, W. Zhao, L. Li, H. Nair, J. Hwang, B. Van Dover, D. Jena, G. Xing,* Cornell University

β-Ga$_2$O$_3$ provides a unique electrostatic challenge due to its large intrinsic breakdown field of 8 MV/cm and moderate dielectric constant of 10. Maintaining oxide fields near 0.5 MV/cm to minimize leakage and degradation thus requires an oxide ε_r of at least 160. Further, high-k dielectrics such as titanates have significant process-property variation which inhibit process integration. Despite pioneer work on Metal/BaTiO$_3$/β-Ga$_2$O$_3$ heterojunction diodes[1] and (BaTiO$_3$/SrTiO-$_3$)$_{15}$ high-k field plates[2], key information such as optimal anneal condition and effective dielectric constant at frequency are yet to be explored. In this work, we use metal-insulator-metal (MIM) and co-planar waveguide (CPW) structures to characterize the complex dielectric constant of BaTiO$_3$, CaTiO$_3$, and SrTiO$_3$

thin films from quasistatic to high frequency. By varying parameters such as deposition and anneal temperatures, we identify a desired process window wherein the dielectric constant is large enough to support intrinsic Ga_2O_3 breakdown with minimal leakage current at application-based operating frequencies.

Thin films of $BaTiO_3$, $CaTiO_3$, and $SrTiO_3$ were deposited by RF magnetron sputtering at 25 °C, 350 °C, and 500 °C on HR-Si as test substrates. Deposition conditions were 50 or 100 W bias for 60 minutes at 5 mTorr with 30 sccm gas flow of 9:1 $Ar:O_2$. Films were characterized by X-Ray diffraction, spectral reflectance, scanning electron microscopy, and atomic force microscopy pre- and post- anneal to assess crystallinity, surface morphology, and grain size if observable. After annealing, MIM and CPW structures were patterned by standard lithography and deposition of Ti/Au contacts. From these structures complex dielectric constant was extracted from measured impedance. Leakage current was captured from DC IV measurements of the MIM structures. The set of process conditions for each high-k dielectric ($BaTiO_3$, $CaTiO_3$, and $SrTiO_3$) which yielded the most promising leakage and dielectric properties was then replicated on vertical field-plated diode and lateral MOSFET test structures and compared directly to low-k and non-field plated structures.

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MD-MoP-7 Electrical Characteristics of MOCVD Grown β-Ga_2O_3 Schottky Diodes on (010) β-Ga_2O_3 Substrates

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Monoclinic beta-gallium oxide (Ga_2O_3) is a promising material for power electronics and RF switching due to its ultrawide bandgap. Metal-organic chemical vapor deposition (MOCVD) has emerged as a promising technique for growing high-quality Ga_2O_3 films with smooth surface morphology, controllable doping, and high mobility, making it a preferred method for Ga_2O_3 power devices. However, there are limited reports on the fabrication and characterization of vertical power devices using high growth rate MOCVD-grown Ga_2O_3 films, and the performance of Ga_2O_3 vertical power devices has yet to reach its full potential. Vertical Schottky barrier diodes (SBDs) were fabricated on MOCVD-grown Ga_2O_3 films with varying growth rates, showing promising electrical and structural properties for high-power applications.

In this work, three different Si-doped homoepitaxial Ga_2O_3 films were grown on Sn-doped (010) Ga_2O_3 substrates by MOCVD, labeled S1, S2, and S3. The growth rate for S1 is 3 µm/hr, while S2 and S3 have rates of 650 nm/hr. The epilayer thickness for S1, S2, and S3 are 9.5, 3, and 2 µm, respectively. The S1 sample has the roughest surface of the three samples due to its faster growth rate compared to S2 and S3. The Schottky diodes fabricated with the three samples show excellent rectifying behavior. The diode characteristics such as ideality factor, barrier height, and specific on-resistance show an increase with the growth rate and epilayer thickness, as macro and micro-scale surface roughness also increase.At the same growth rate, the sample with a thicker epilayer exhibits lower forward current density and higher leakage current, which can be attributed to the surface roughness. Notably, though the S3 sample exhibits the highest forward current densities (3386 A/cm^2 at 2.5 V) and lowest specific on-resistance (0.707 $m\Omega.cm^2$), S1 exhibits the lowest leakage currents (8.32×10^{-8} A/cm^2 at -2 V), and highest ON-OFF ratios ($>10^9$). The capacitance-voltage characteristics showed that all three structures have completely depleted Ga_2O_3 layers on the reverse bias side. The extracted doping density of S1, S2, and S3 are 2.02×10^{16}, 1.73×10^{16}, and 6.08×10^{16} cm^{-3}, respectively.

Overall, the fabricated SBDs exhibit promising electrical and structural properties, with a high current rectification ratio and low reverse leakage current, indicating their potential for high-power applications. The results of our study contribute to the understanding of the growth and characterization of MOCVD-grown Ga_2O_3 films and provide valuable insights for developing high-performance power devices based on this promising material.

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