Material and Device Processing and Fabrication Techniques Room Davis Hall 101 - Session MD+AC+EP-TuA

Process/Devices II

Moderator: Yuhao Zhang, Virginia Tech

3:45pm **MD+AC+EP-TuA-9 Large Area Trench β-Ga_2O_3 Schottky Barrier Diode with Extreme-K Dielectric Resurf*, Saurav Roy,*** *A. Bhattacharyya,* University of California Santa Barbara*; J. Cooke,* University of Utah*; C. Peterson,* University of California Santa Barbara*; B. Rodriguez,* University of Utah*; S. Krishnamoorthy,* University of California Santa Barbara

We report the first combination of high-k dielectric RESURF with trench geometry to realize low reverse leakage large area (1mm^2 and 4mm^2) β-Ga_2O_3 Schottky Barrier Diodes with high current values (15A pulsed, 9A DC). 1.2 µm deep trenches are etched on HVPE-grown 11 µm epilayer with 8×10^{15} cm^{-3} apparent charge density concentration using dry etching and 300 nm $BaTiO_{3-}$ (BTO)is then sputter deposited which is followed by annealing at 700°C to enhance the dielectric constant. The fins are then opened using dry etching. Pt/Au Schottky contacts are deposited using e-beam evaporation with planetary rotation for conformal deposition. To further improve the breakdown voltage field plates are used with Si_3N_4 as the field plate oxide. A planar SBD, a BTO field-plated SBD, and a trench SBD with high-k RESURF are fabricated for comparison. The on resistance ($R_{on,sp}$ normalized to the device footprint) of the planar and field plated SBDs are extracted to be 7.9 and 8.2 mΩ-cm^2, respectively, and an increased on resistance of 10.8 mΩ-cm^{-2} is measured for small area (200×200 µm^2) trench SBD with high-k RESURF, indicating dry etching induced damage. The breakdown voltage of the BTO field-plated SBD increases to 2.1 kV from 816 V (planar SBD) whereas the breakdown voltage increases to 2.8-3kV for the trench SBD with high-k RESURF. A very low leakage current density of 2×10^{-4} A/cm^2 is measured for the trench SBD at 2.8 kV. The 1 mm^2 trench SBD exhibits a current of 3.7A(Pulsed)/2.9A(DC) and the 4mm^2 trench SBD exhibitsa current of 15A(Pulsed)/9A(DC) at 5V. The breakdown (catastrophic) voltage of the 1mm^2 and 4mm^2 trench SBDs are measured to be 1.4 and 1.8kV. The leakage currents at breakdown are significantly lower compared to other high current SBDs reported in the literature despite the large area of the device, due to the much-reduced parallel field at the metal/semiconductor interface. Temperature dependence of on resistance shows lower temperature co-efficient (α = 0.87) which is lower than SiC SBDs. The large area high-k RESURF trench SBDs also has lowest $V_{on}I_{leakage}$ product for any β-Ga_2O_3 SBDs with more than 1kV breakdown voltage and 1A current, which is important to reduce both the on and off-state power dissipation. The 4mm^2 high-k RESURF trench SBD has the highest current (5A(DC)/9A(Pulsed)) at V_F = V_{on}+2V with breakdown voltage more than 1.3kV and exhibits lowest leakage current for similar rated device from literature.

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4:00pm **MD+AC+EP-TuA-10 Fabrication and Characteristics of Ga_2O_3 MOSFET using p-NiO for Normally-off Operation*, Daehwan Chun,*** *Y. Jung, J. Park, J. Hong, N. Joo, T. Kim,* Hyundai Motor Company, Republic of Korea

In order to increase sales of electric vehicles, it is essential to have market competitiveness by reducing price and improving performance, as well as improving mileage. To increase the mileage of an electric vehicle, it is important to efficiently use the limited power of the battery. The inverter/converter/OBC plays a role in converting electrical energy into a form suitable for electrical components, and the power semiconductor performs switching and rectification operations in the components responsible for such power conversion. Therefore, the performance of power semiconductors is directly related to the mileage of electric vehicles.

Existing power semiconductors mainly used Silicon(Si) materials, but recently, Silicon Carbide(SiC) power semiconductors with improved performance have been mass-produced and started to be installed in vehicles. Gallium Oxide(Ga_2O_3), which has a wider energy bandgap(4.7~4.9eV) than SiC, has a high critical electric field, excellent electron transport ability, and high-quality large-area substrate growth, so it has the advantage of not only performance compared to existing GaN or SiC semiconductor but also easy manufacturing process. In particular, the unit price of Ga_2O_3 epitaxial wafer is expected to be reduced to 1/3 of that of SiC. Therefore, the manufacturing cost is also expected to be lower than that of SiC power semiconductors.

In this paper, we present the fabrication results of Ga_2O_3-based lateral MOSFETs for inverter/converter/OBC applications of electric vehicles. Normally-off operation was secured through the application of NiO, which does not require an ion implantation process, and a breakdown voltage of 600V was achieved. In addition, Al_2O_3 was used as a gate insulating film to suppress gate leakage current, and high-concentration ITO was applied to form an ohmic junction.

Applying NiO to form the depletion layer in the channel region when the MOSFET is off-state ensures normally-off operation of the Ga_2O_3 MOSFET. However, there is a limit to gate voltage application due to leakage current because of the existence of a pn heterojunction diode in the gate region. To solve this problem, an insulating film(Al_2O_3) was formed between NiO and the gate metal. The threshold voltage of the MOSFET with this structure formed a high value of 30V or more, so the threshold voltage was lowered by modifying the concentration of the Ga_2O_3 epitaxial layer. As a result, some drain-source leakage current occurred, but an IV characteristic graph that clearly distinguishes the On/Off state of the MOSFET was obtained.

4:15pm **MD+AC+EP-TuA-11 On the Mg-Diffused Current Blocking Layer for Ga_2O_3 Vertical Diffused Barrier Field-Effect-Transistor (VDBFET)*, Ke Zeng,*** *Z. Bian, S. Chowdhury,* Stanford University

To truly realize the potential of the Ga_2O_3 in a transistor, it is imperative to design a buried gate barrier junction to circumvent the pre-mature breakdown near the gate often seen in lateral structures. Owing to the high diffusivity of dopants and defects in Ga_2O_3, in contrast to that of, for example, SiC at a moderate temperature, we propose the use of diffusion doping as a rapid and non-invasive platform to explore the possibility of an effective current blocking layer (CBL) in vertical Ga_2O_3 transistors. In this work, we will discuss the development and characteristics of the Mg diffused CBL that was recently utilized to demonstrate an efficient Ga_2O_3 VDBFET with remarkable pinch-off characteristics.

The process (Fig. 1) starts with a commercially available Ga_2O_3 HVPE epitaxial wafer. The wafer was first coated with a highly Mg-doped spin-on-glass (SOG) layer which was subsequently cured and then patterned by HF to form the selective Mg dopant source. A thick PECVD layer was deposited onto the sample to isolate and stabilize the diffusion doping process. The Mg was then diffused into the wafer under a 950 ℃ furnace annealing for ~1 hr to form the CBL. The dopant oxide stack was stripped clean by an HF dip afterward. A Ni/Au anode was then deposited on top of the CBL region for the 2-terminal CV and IV studies shown in Fig. 2. Furthermore, for the 3-terminal VDBFET, a high dose titled Si triple ion implantation was done to form the source contact region inside the CBL area, followed by an activation annealing. The Ti/Au and Ni/Au composite source electrode was deposited on top of the source and CBL region respectively. A Ti/Au drain contact was then deposited on the back of the wafer. A 25nm ALD Al_2O_3 was used as the gate oxide, and a Ti/Ni/Au stack was deposited as the gate contact on top of the wafer.

From a simple CV analysis on the metal-isolation-semiconductor (MIS) structure, it’s confirmed that the conductivity of the Ga_2O_3 epitaxial layer was successfully modulated by the Mg diffusion process for a depth of ~ 1.6 µm. The same MIS structure measured a reverse breakdown voltage of 466 V. However, when the surface is further doped with implanted Si^{++} layer, the formed NIN diode only blocks ~72V, the same as the final device blocking voltage. The VDBFET showed amazing transistor characteristics with decent saturation, on-current without any optimization, as well as a current on/off ratio > 10^9. Due to the compensation of electrons by Mg in the gate region, the transistor exhibited enhancement mode operation with a turn-on voltage of ~7V. The breakdown voltage, however, was only measured to be 72 V under a gate bias of 0 V.

4:30pm **MD+AC+EP-TuA-12 Electrical Properties of p-NiO/β-Ga_2O_3 Vertical PN Heterojunction Diode for Power Device Applications*, Youngkyun Jung,*** *D. Chun,* Hyundai Motor Company, Republic of Korea

In this paper, the p-type NiO/β-Ga_2O_3 vertical pn heterojunction diode for power device application was fabricated, and the electrical characteristics of the device was evaluated. The β- Ga_2O_3 has a wide energy bandgap of about 4.8eV, and that is expected to be a material for next-generation power semiconductors with high breakdown voltage and low power loss. Compared to SiC (Silicon carbide) and GaN (Gallium Nitride), which are used as common materials for power semiconductors, it has a breakdown field (8MV/cm) that is about 3 times higher, and Baliga's FOM (3,400), which represents the semiconductor figure of merit, it has a value 4 to 10 times higher than that of GaN and SIC materials. Recently, β-Ga_2O_3 has been fabricated in the form of an epitaxial layer on a wafer and applied to power devices such as MOSFETs, MESFETs, Schottky barrier diodes, and pn junction diodes. The p-NiO has a wide band gap of 3.6 eV or more, p-type characteristics of NiO generally is induced by nickel vacancies or oxygen interstitials, that are defects provide the hole carriers. The carrier concentrations of p-NiO can be controlled in the range of 10^{16} to 10^{19} cm^{-3} with the amount of oxygen gas during the sputtering deposition process. The depletion region width of p-NiO/β-Ga_2O_3 can be changed according to the change in the carrier concentration of p-NiO. To fabricate the pn vertical heterojunction diode, p-NiO was deposited on the β-Ga_2O_3 epitaxial layer with a thickness of 250nm by using RF magnetron sputtering, and 100 nm of Ni metal for ohmic contact was deposited on the deposited p-NiO by using DC magnetron sputtering. The I-V characteristics of the fabricated pn heterojunction diode were measured by keithley 2410, and the C-V characteristics were measured by Keysight 4284A. As a result of measuring electrical characteristics, the pn heterojunction diode has a lower leakage current value than the previously reported Schottky Barrier Diode, and on/off ratio is about 10^9. When the carrier concentration of deposited p-NiO was $10^{19}cm^{-3}$, the turn-on voltage, current density, Ron value and breakdown voltage values of pn heterojunction diode were shown 2.2V, $242A/cm^2$@4V, $17m\Omega.cm^2$@4V, and –465V respectively.

4:45pm **MD+AC+EP-TuA-13 Effects of Oxygen Reactive Ion Etching and Nitrogen Radical Irradiation on Electrical Properties of Ga_2O_3 Schottky Barrier Diodes***, **Shota Sato**, K. Eguchi,* Department of Physics and Electronics, Osaka Metropolitan University, Japan*; Z. Wang,* National Institute of Information and Communications Technology, Japan*; T. Kitada, M. Higashiwaki,* Department of Physics and Electronics, Osaka Metropolitan University, Japan

β-Ga_2O_3 has attracted great attention as a new wide bandgap semiconductor mainly for power devices. Oxygen reactive ion etching (O_2 RIE) is often used to remove a resist and/or an organic contamination in Ga_2O_3 device processing. However, this process usually causes damage to a Ga_2O_3 surface degrading device characteristics. On the other hand, we found that nitrogen (N) radical irradiation can significantly restore the Ga_2O_3 surface damage. In this study, we investigated effects of the O_2 RIE and N radical irradiation on electrical properties of Schottky barrier diodes (SBDs) fabricated on *β*-Ga_2O_3 (100) and (010) substrates.

Ga_2O_3 SBD structures were fabricated using unintentionally doped *β*-Ga_2O_3 (100) and (010) bulk substrates with an effective donor concentration of less than 2×10^{17} cm^{-3}. We evaluated electrical properties of the Ga_2O_3 SBDs fabricated on the substrates treated by four different processes: (a) no surface treatment, (b) O_2 RIE, (c) N radical irradiation, (d) O_2 RIE followed by N radical irradiation. The O_2 RIE was performed at an RF power of 50 W for 90 seconds. The N radical irradiation was conducted using an RF plasma cell in a molecular beam epitaxy growth chamber at a substrate temperature of 700°C and an RF power of 500 W for 2 hours.

We first studied current density–voltage (*J*–*V*) characteristics of the Ga_2O_3 (100) SBDs processed by the four different methods. In case of the devices with no treatment, a large variation of the turn-on *V* in a wide range of 0.5–1.1 V was observed. The O_2 RIE process further spread the variation to 0.2–1.0 V, indicating that the Ga_2O_3 (100) surface was more damaged. Furthermore, some devices showed kinks in their *J*–*V* curves. The curves with the kinks look like an overlap of *J*–*V* characteristics for a few area with different Schottky barrier heights under the anode electrode. In contrast, with and without the O_2 RIE, *J*–*V* characteristics of both SBDs treated by the N radical irradiation showed an almost constant turn-on *V* of 0.3 V and no kink. These results indicate that the N radical irradiation has effects to significantly restore the Ga_2O_3 surface damage and equalize the surface condition. Qualitatively the same effects of nitridation were confirmed for the Ga_2O_3 (010) SBDs.

In conclusion, we found that N radical irradiation is effective for restoring Ga_2O_3 surface damage, which leads to improvements in electrical properties of the Schottky interface.

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