Improving Interface Quality and Repeatability in Contacts to ß-Ga2O3 by Metal-First Processing

CNF Project Number: 2802-19
Principal Investigator(s): Huili Grace Xing[1], Debdeep Jena[1]
User(s): Kathleen Smith[2]

Affiliation(s): 1. School of Electrical and Computer Engineering,
2. Department of Applied and Engineering Physics; Cornell University

Primary Source(s) of Research Funding: Air Force Office of Scientific Research (AFOSR), Semiconductor Research Corporation (SRC), Defense Advanced Research Projects Agency (DARPA)

Contact: grace.xing@cornell.edu, djena@cornell.edu, kts57@cornell.edu

Primary CNF Tools Used: SC4500 Odd-Hour E-Beam Evaporator, Angstrom E-Beam Evaporator, ABM Contact Aligner, AS200 i-Line Stepper, AJA Ion Mill, Glenn 1000 Resist Strip, PT720/740, PT770, RTA AG610

Abstract:

A metal-first process for forming contacts to β-Ga_2O_3 is developed that demonstrates improved contact repeatability compared to conventional liftoff processing by minimizing surface modification and results in non-alloyed contact resistances as low as 70 mΩ-mm. The metal-first process is further applied to a range of ohmic and Schottky metals with varied work functions to demonstrate that metal-first processing results in a high-quality interface that at least partially alleviates Fermi-level pinning in contacts to β-Ga_2O_3.

Summary of Research:

β-Ga_2O_3 is an ultra-wide bandgap semiconductor (~4.8 eV) with a high critical electric field, wide range of demonstrated, controllable n-type doping, sufficient electron mobility, and low-cost, native substrates that makes it potentially suitable for kilovolt device applications. Metal-semiconductor interfaces in Ga_2O_3 devices, however, are complex and inconsistent: in Schottky contacts, the Fermi-level is dramatically pinned (ie. the Schottky barrier height Φ_B does not trend linearly with the metal work function Φ_M) and measures of Φ_B can vary by over 1 eV for the same contact metal [1]. Similar variation of contact quality is observed in ohmic contacts.

The contacts reported here are formed by a metal-first process, in which the contact metal is blanket-deposited on the as-grown semiconductor surface, then patterned with photoresist (Figure 1a). The metal between the contact pads is then removed by wet and/or dry etching. This contrasts with conventional liftoff processing, where the contact area is first exposed to photoresist during patterning, then metal is deposited and the excess metal between the pads is lifted off in solvent (Figure 1b).

We fabricated both metal-first and lifted-off Ti/Au (10/110 nm) transfer length method (TLM) patterns on n+ (> 5 × 10^{19} cm^{-3}) Si-doped (010) β-Ga_2O_3 by electron-beam evaporation. For the metal-first contacts, TLM measurements have linear-ohmic IV behavior with a contact resistance (Rc) of 0.73 Ω-mm.

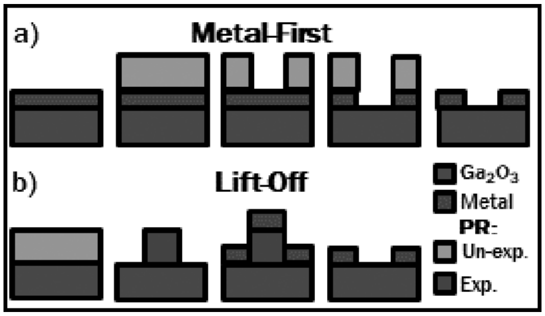

Figure 1: Process flow schematic for a) metal-first and b) liftoff contact processing.

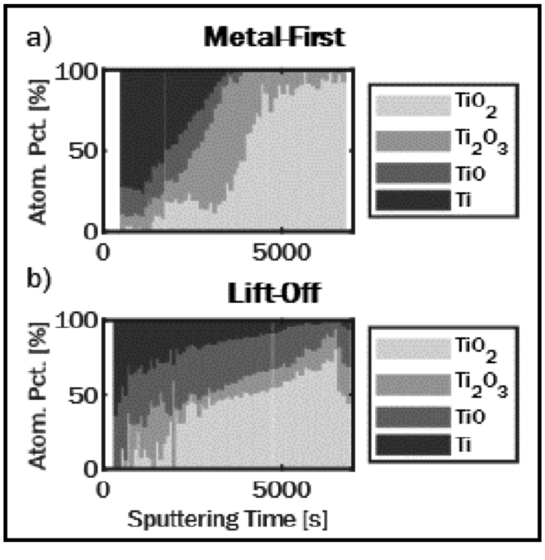

Figure 2: Comparison of Ti oxidation state from depth-resolved XPS for a) metal-first and b) lifted off Ti/Au ohmic contacts. For the metal-first contacts, Ti is fully oxidized to Ti4+ near the Ga_2O_3 interface, while for the lifted-off contacts, Ti is only partially oxidized.

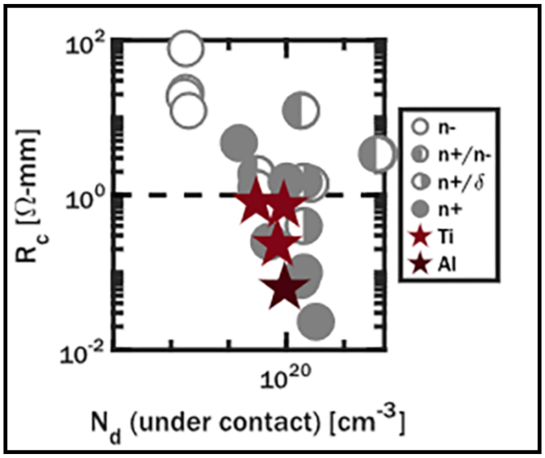

Figure 3: Bench-marking of ohmic contacts to Ga_2O_3 from literature (grey) and this work (red). The non-alloyed metal-first contacts are highly competitive with existing reports.

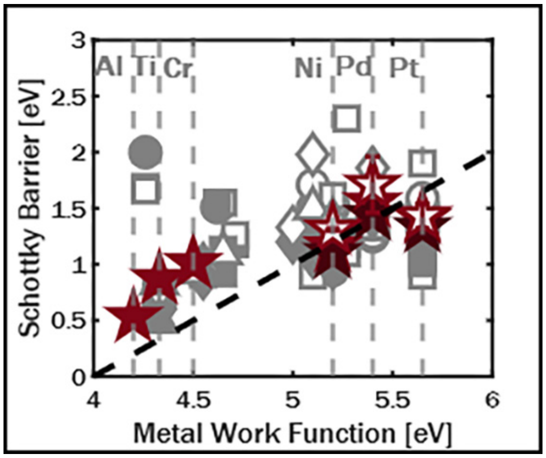

Figure 4: Measured Φ_B vs. Φ_M for contacts to Ga2O3 from literature (grey) and this work (red). The extracted Φ_B in this work increases with increasing Φ_M with a slope of 0.46 and R2 of 0.986, while reports from literature show significant Fermi-level pinning with very little dependence of Φ_B on Φ_M.

The lifted-off contacts, however, are non-conductive. Depth-resolved x-ray photoelectron spectroscopy (XPS) measurements of the oxidation state of titanium near the metal-semiconductor interface for the metal-first contacts demonstrate a smooth transition from metallic Ti to fully-oxidized TiO_2 near the Ga_2O_3 surface (Figure 2a). In the lifted-off contacts, however, the oxidation state of Ti is far more disordered, and the Ti layer is not fully oxidized even at the Ga_2O_3 surface (Figure 2b).

This implies that liftoff processing can detrimentally modify the β-Ga_2O_3 surface and inhibit ohmic contact formation.

The metal-first process was then applied to fabricate TLM patterns with three ohmic (low Φ_M) metals (Al, Ti, and Cr). TLM measurements have linear-ohmic IV behavior for Al and Ti contacts, with highly-leaky Schottky behavior for Cr contacts due to the higher Φ_M. The Al contacts have an ultra-low contact resistance of 70 mΩ-mm, which is among the lowest reported values of Rc (Figure 3). Metal-first anode Schottky barrier diodes were also fabricated with three Schottky (high Φ_M) metals (Ni, Pd, and Pt). For the ohmic metals, Φ_B was extracted from the specific contact resistance using the thermionic field emission (TFE) model. For the Schottky metals, Φ_B was extracted from C-V, forward I-V fitting with the TFE model, and reverse I-V fitting with a numerical reverse leakage model developed by W. Li, et al [2]. The resulting barrier heights have a linear dependence on Φ_M with a slope of 0.46 and reasonable R2 value of 0.986, indicating that the Fermi-level is at least partially un-pinned by using metal-first contact processing to minimize damage or modification of the β-Ga_2O_3 surface (Figure 4).

Conclusions and Future Steps:

In this work, we demonstrate that metal-first contact processing decreases surface modification in β-Ga_2O_3 compared to liftoff processing and results in ultra-low non-alloyed contact resistances (70 mΩ-mm). Further, metal-first processing can at least partially un-pin the Fermi level in ohmic and Schottky contacts to β-Ga_2O_3, leading to an S value of 0.46. The surface orientation dependence of Fermi-level pinning bears further investigation, as this work included only a limited set of orientations, as does the temperature stability of these metal-first contacts, which is critical for high voltage device performance.

References:

[1] L. A. M. Lyle, J. Vac. Sci. Technol. A, 40, 060802 (2022).

[2] W. Li, D. Saraswat, Y. Long, K. Nomoto, D. Jena, and H. G. Xing, Appl. Phys. Lett., 116, 192101 (2020).