Recent Progress of B-Ga2O3 MOSFETs for Power Electronic Applications

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Abstract: *We review AFRL's major device results in the fabrication of β-Ga_2O_3 MOSFETs over the past 2 years. This includes: (1) AFRL's standard fabrication process, (2) improvement of current density, (3) improvement of contact resistance, (4) review of the critical field measurement and (5) review of enhancement mode operation of a β-Ga_2O_3 finFET.*

Keywords: β -Ga_2O_3; MOSFET; Power Electronics;

Introduction

β-Ga_2O_3 has experienced a recent surge of attention in the past five years due to its promising material properties.[1-4] An obvious application space for this ultra-wide band gap (UWBG) semiconductor is power electronics. Its band gap is near 5 eV which empirically translates to an electric field strength of ~8 MV/cm.[5] Bulk crystal growth has enjoyed rapid development. Boules can be pulled with relative ease by a variety of methods [6, 7] enabling access to homoepitaxy, and as a result has also experienced rapid progress.[1, 2, 8, 9] The availability of native substrates will be necessary to enable quality epitaxial growth. Although bulk growth is still relatively immature, 2" substrates can already be purchased, while 4" and 6" are currently under development. Due to the rapid development on bulk and epitaxy growth, device results have followed quickly

We will review device and epitaxy results from the past two years. Epitaxy optimization has caused current densities to improve rapidly. Highly doped cap layers have been found to reduce contact resistance considerably. World record breakdown strength for a lateral MOSFET has been measured.[10] Finally, we will take a brief look into the world's first enhancement mode (E-mode) β-Ga_2O_3 MOSFET.[11]

Fabrication

β-Ga_2O_3 can be doped effectively with a variety of group 4 elements such as Silicon, Tin, and Germanium.[2, 9] Multiple samples will be referenced throughout the text, but it should be noted that all three dopants work effectively. It is not currently clear which donor is the best performer. Doped β-Ga_2O_3 was homoepitaxially grown by multiple different methods including metal-organic vapor phase epitaxy (MOVPE) [9], Molecular Beam Epitaxy (MBE) [2], and Low Pressure Chemical Vapor Deposition (LPCVD). Epitaxy was grown on compensation doped (Mg or Fe) single crystal substrate with (010) or (100) crystal orientations. Both compensation donor type and crystal orientation are being looked at but we cannot currently comment on the comparative performance of these samples. Device isolation was performed with an ICP/RIE etch using BCl_3 chemistry. Source-drain electrodes were formed using evaporated Ti/Al/Ni/Au (20/100/50/50 nm) metals and observed to be ohmic after annealing for 60 s in a nitrogen ambient at 470 °C. A blanket 20-nm thick Al_2O_3 or HfO_2 layer was deposited by atomic layer deposition which served as the gate oxide. Both gate oxides performed well, but the interface quality has been found to be different when analyzed by CV. The gate oxide was removed in the ohmic regions using a buffered oxide etch. Finally, interconnect and gate metal were patterned and deposited simultaneously using a 20/480 nm Ti/Au metal stack. Figure 1 shows the process pictorially.

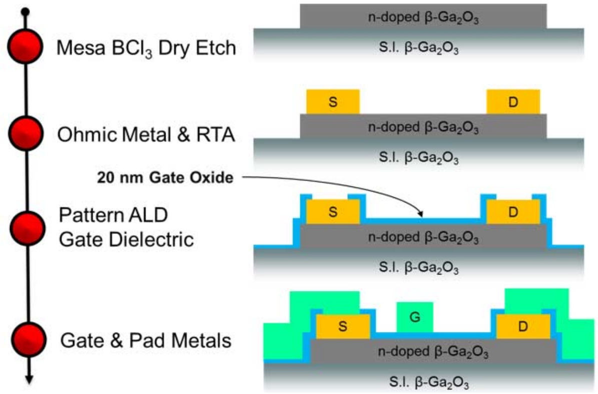

Figure 1. Fabrication of basic Lateral MOSFET structure including (1) mesa isolation, (2) ohmic metallization, (3) gate dielectric deposition, and (4) gate and pad metallization.

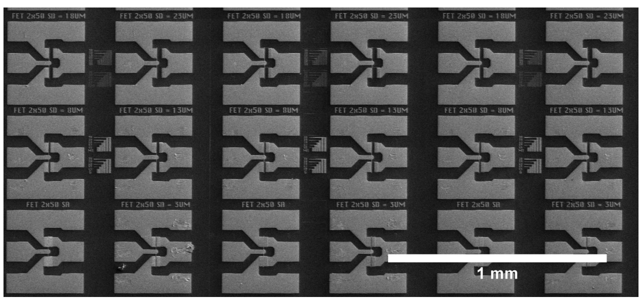

Figure 2. Split-finger (2x50 um) MOSFETs on 200 nm Sn-doped β-Ga_2O_3 homoepitaxy grown by MOVPE on a (100) β-Ga_2O_3 Mg-doped substrate.

A variety of gate to drain spaces were fabricated all with a 2 µm gate length (L_G). The mesa isolated FETs are in a split flinger geometry with 100 µm total periphery. Also included in the reticle are Hall, TLM, and cross bridge structures for doping, contact resistance, and sheet resistance measurements.

Results and Discussion

Current Density: Current density is largely a function of epitaxial quality. We have noticed a factor of four change in mobility over the past year due to new optimization techniques that reduce stacking faults. Figure 3 below shows DCIV data for generation 1 and 2 epitaxy.

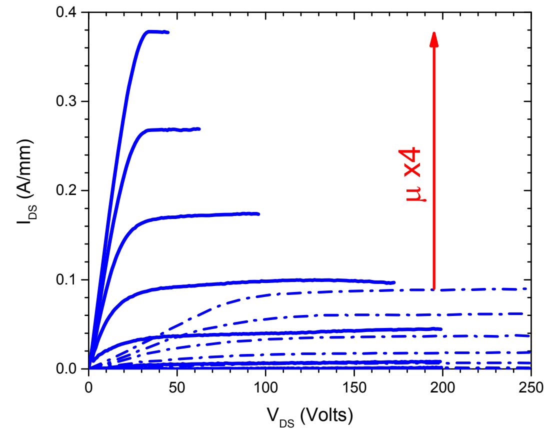

Figure 3. DCIV data for β-Ga_2O_3 MOSFETs. The mobility was improved by a factor of four due to epitaxial optimization

Figure 4 below shows mobility as a function of doping for several different growth techniques and donor types.

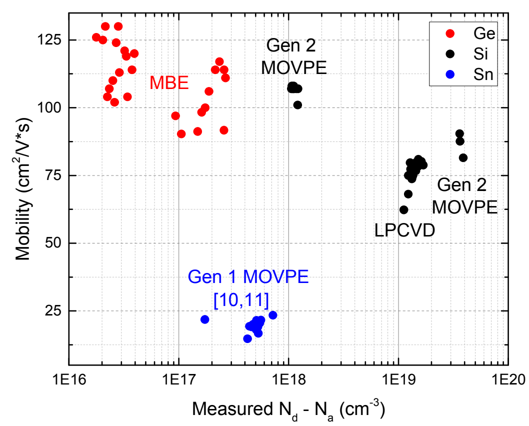

Figure 4. Mobility as a function of doping for multiple growth techniques and donor types.

Hall mobility around 100 cm^2/V*s is common across multiple different donor types and epitaxial techniques (< 1E18 cm^{-3} donor concentration). We do not observe a significant difference in the mobility with respect to the donor type. The degradation of mobility is relatively moderate across a large doping range as seen above. This is expected since the mobility is mainly limited by polar optical phonon scattering.[12] We recently published on the Sn doped samples seen at the bottom of Figure 3. These can be seen in reference [10] and [11].

Contact Resistance: Contact resistance has also been a major limiting factor in the reduction of total on resistance. In the First Generation MOSFET[10], contact resistance accounted for approximately 32% of the total resistance at V_G = 0 V. Significantly reduced contact resistance is observed experimentally when making a contact to a highly doped film. This can be seen in figure 5 below.

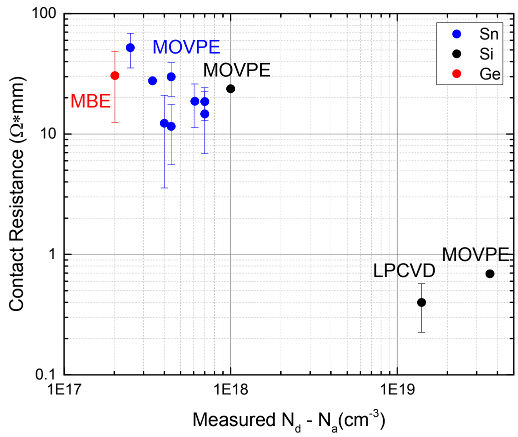

Figure 5. Contact Resistance (Ω*mm) is plotted as a function of donor concentration (cm^{-3}). The contact resistance was measured by the Transmission Line Method and the donor concentration was measured with the Hall Effect.

Fabricating a MOSFET with reasonable current density and threshold voltage has given us a standard epitaxy target of 200 nm thickness with a doping of 1E18 cm^{-3}. As seen in figure 5, this film will have a high contact resistance of 20 Ω*mm. Additional epitaxy/processing will be needed if β-Ga_2O_3 is to be competitive with current power electronics materials such as GaN or SiC. Using an epitaxial capping layer with a donor concentration above 1E19 cm-3 will give contact resistances below 1 Ω*mm as seen in figure 4. A result of using a capping layer is that it will need to be removed in the channel region to retain the ability to pinch off with reasonable gate voltages. The effects of dry etching the MOSFET channel is not currently known and are under investigation.

Critical Field: β-Ga_2O_3's wide band gap is projected to have a breakdown strength of 8 MV/cm. This is the material's premier attribute due to the BFOM scaling with the cube of the critical field. Last July we published a MOSFET with a gate to drain spacing of 0.6 µm holding 230 V across the drift region. This translates to an average field strength of 3.8 MV/cm. A Sentaurus simulation was performed to look at the potential as a function of positions. The simulation concluded that the maximum field experienced at the β-Ga2O3/Al2O3 interface was 5.3 MV/cm. The potential map can be seen in figure 6 below. Looking forward it will be important to retain the high field strength over the larger drift region thus maximizing breakdown voltage.

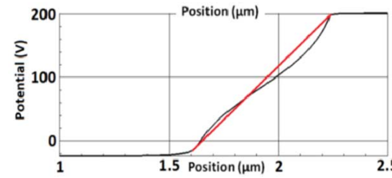

Figure 6. A Sentaurus simulation was used to plot the potential against position along the semiconductor/oxide interface. The slope of the black line is the electric field. The slope red line represents the minimum electric field experienced. Here the Gate and Drain voltages are -30 V and 200V respectively.

Enhancement Mode Operation: One approach towards enhancement mode operation is to thin the active region so that the gate and substrate depletion width is larger than the total channel thickness. Figure 7 below shows the fabrication process utilizing this strategy Chromium is used as a hard mask to etch the β-Ga2O3. This is necessary for submicron features due to the extremely low selectivity of e-beam resists when dry etching β-Ga2O3. Subsequent processing steps are the same as described in the fabrication section.

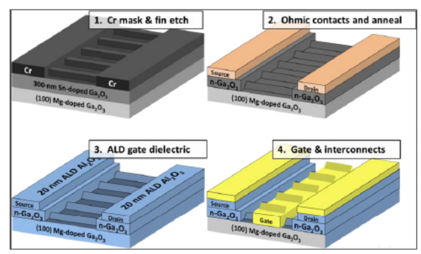

Figure 7. Fabrication steps for an E-mode β-Ga2O3 finFET. Chromium is used as a hard mask to etch the β-Ga_2O_3 channel. Fabrication steps 2-4 are used in the standard fabrication as seen in Figure 1.

Figure 8a below shows a top-down SEM image of the gated active region and source drain electrodes. Figure 8b shows transfer characteristics with a threshold voltage at +0.8 V with an ION/OFF ratio >10^5. These devices were also able to hold significant blocking voltages. A finFET device with a gate-drain spacing of 16 µm was able hold a blocking voltage of 567V. Please see reference [11] for more information.

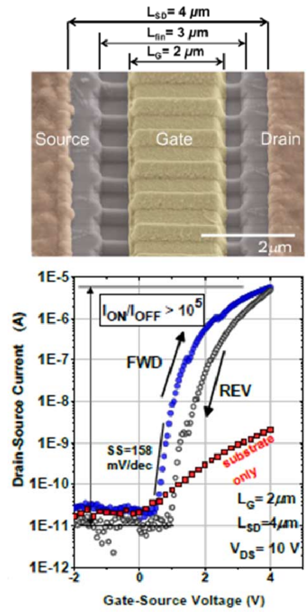

Figure 8. (a) Colored SEM image of a β-Ga2O3 finFET. (b) Transfer Characteristics showing a VTH of +0.8V.

Conclusions

We have reviewed five significant improvements by AFRL in the past two years. Significant progress in mobility, contact resistance, breakdown voltage and processing capability has been discussed.

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