Nanomembrane β-Ga_2O_3 High-Voltage Field Effect Transistors

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There is considerable excitement recently in the field of transparent conducting-oxide-semiconductors due to the successful realization of large-area single crystals of the wide-bandgap semiconductor β-Ga_2O_3 by bulk growth methods [1]. The availability of bulk β-Ga_2O_3 crystals led to the rapid demonstration of high-voltage metal-semiconductor field-effect transistors (MESFETs) by controlled Sn-doped epilayers grown by molecular beam epitaxy (MBE) [2]. β-Ga_2O_3 has an energy bandgap of ~4.9 eV, significantly larger than both GaN and SiC. Coupled with the availability of low-cost bulk crystals, this material is highly attractive for high-voltage switching applications. Here we show preliminary results that show that similar to layered crystals [3] and rather surprisingly, one can peel-off nanoscale layers of β-Ga_2O_3 from a nominally undoped bulk single-crystal. Conducting channels can then be created electrostatically in these nanomembranes with a back-gate, and the resulting transistors are able to sustain very high voltages and still switch by several orders of magnitude.

The process-flow for the fabrication of β-Ga_2O_3 nanomembrane field-effect transistors is shown in Fig. 1. The crystal β-Ga_2O_3 was grown by Czochralski method at IKZ Berlin [1]. Nanomembranes ~50 to 100 nm thick were mechanically exfoliated and transferred to a back-gated substrate. The source and drain contacts were defined by electron beam lithography (EBL) using Ti/Au (5/150 nm) contacts. The final device went through an annealing process in Ar/H_2 at 300 ^{o}C for 3 hours to reduce the contact resistance. Optical transmission spectra of the flake are shown in Fig. 2 and it clearly shows an optical bandgap of 4.8 eV. Figure 3(a) shows the drain current versus gate-source bias, I_D *vs.* V_{GS}, at room temperature at three drain biases. The gate modulation is ~10^7x and the device shows n-type semiconducting behavior. Electron-beam evaporated Ti/Au contacts do not result in ohmic contacts, but rather show leaky Schottky barrier characteristics. Nevertheless, from the transfer characteristics, we extract an "extrinsic" field-effect mobility of ~ 10 cm^2/Vs as shown in Fig. 3(b). This value represents a lower limit; it should be possible to obtain ~300 cm^2/V.s with de-embedding for this device or better still by lowering the contact resistance [2]. The subthreshold swing (SS) of the device in Fig. 3(c) can approach ~150 mV/dec, not significantly different from two-dimensional transition-metal dichalcogenide semiconductor FETs. The family of I_D-V_{DS} curves at various V_{BG} in Fig. 3(d) shows a typical transistor performance including resistive behavior at low V_{DS} and current saturation at high V_{DS}. Figure 4(a) shows a comparison of electrical breakdown voltage of various thin-film channel materials (β-Ga_2O_3, MoS_2, and $MoTe_2$) of similar geometries and back-gates. A $MoTe_2$ FET shows the lowest breakdown voltage around 0.05 MV/cm due to the lowest bandgap (~0.6 eV). For the MoS_2 FET, avalanche breakdown field occurs around 0.1 MV/cm. β-Ga_2O_3 FETs shows a decent gate modulation even under a high drain voltage of 40 V. These properties of β-Ga_2O_3 FET are attractive for high-power and high-voltage device applications. The cross-section TEM image in Fig. 5 shows the crystalline nature of β-Ga_2O_3 and the contact metals and the back gate SiO_2 dielectric. The low subthreshold value observed may be related to the qualitatively sharp interface observed between β-Ga_2O_3 and SiO_2 but more studies are needed to quantify this observation.

In summary, nanomembrane high-voltage FETs with β-Ga_2O_3 channels were fabricated and characterized for the first time. The large bandgap leads to a high on/off ratio. A flat interface between β-Ga_2O_3 and SiO_2 leads to a steep slope of ~ 150 mV/dec. The high breakdown field of β-Ga_2O_3 allow significantly higher voltages to be applied to the drain, while still switching by orders of magnitude. Since β-Ga_2O_3 has been found to have a rather poor thermal conductivity, nanoscale membranes might offer opportunities for efficient heat removal. Nanoscale membranes can also be self-depleted even when doped lightly, and thus form semi-insulating layers, which may make it possible to make FETs without controlled epitaxy. A primary challenge is the formation of ohmic contacts.

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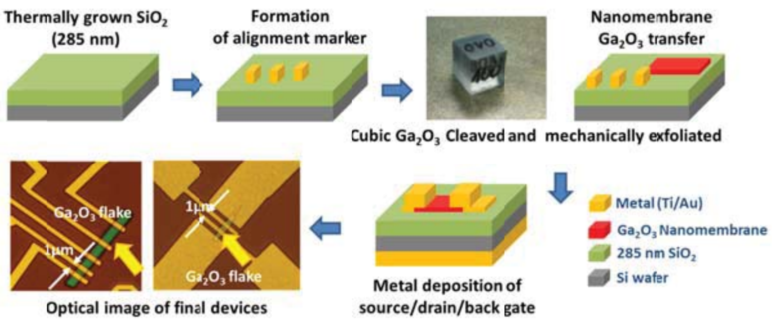

FIG. 1. Schematic process flow for nanomembrane β-Ga$_2$O$_3$ field-effect transistors. The nanomemgrane thicknesses are in the range of 50 to 100 nm.

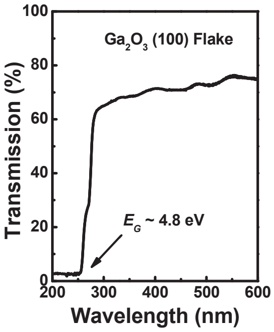

FIG. 2. Optical transmission spectra of Ga$_2$O$_3$ flake indicating bandgap of 4.8 eV.

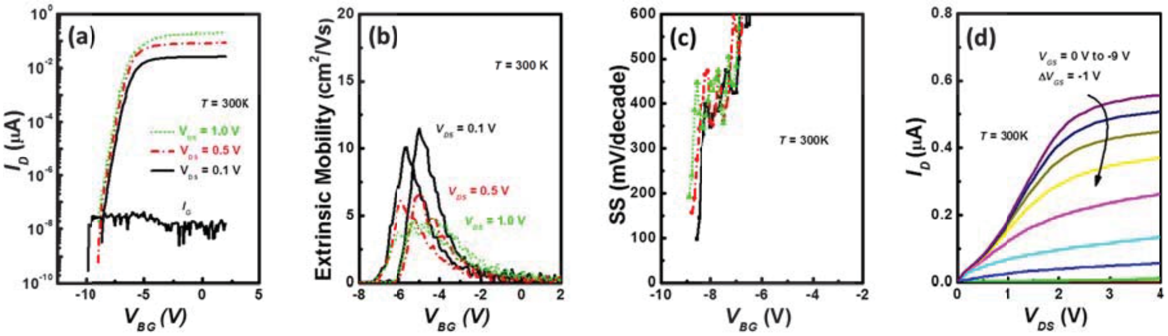

FIG. 3. Transport properties of β-Ga$_2$O$_3$ field-effect transistor with W/L = 2/2 μm. (a) Drain current, I_D *vs*. back gate-to-source voltage, V_{BG}, showing ~10^7 on/off current ratio and *n*-type semiconductor behavior. (b) Field-effect mobility and (c) subthreshold swing *vs.* V_{BG}. (d) Common-source transistor characteristics, I_D *vs.* V_{DS}, showing current saturation.

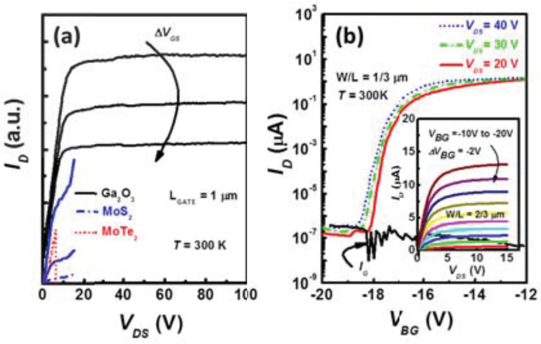

FIG. 4. (a) Comparison of breakdown voltage of various multilayered channel materials (Ga$_2$O$_3$, MoS$_2$, and MoTe$_2$). (b) Transfer characteristic of the β-Ga$_2$O$_3$ FET at high drain voltage. Insert show a family of I_D *vs.* V_{DS} showing robust device characteristic even at high V_{DS}.

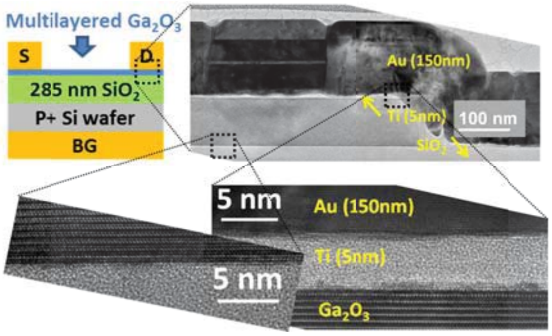

FIG. 5. Cross-sectional TEM image of β-Ga$_2$O$_3$ FET, showing a flat interface between Ga$_2$O$_3$ and the SiO$_2$ dielectric, as well as between the Ga$_2$O$_3$ and the Ti/Au electrode.