**Delta-doped β-gallium oxide field-effect transistor**

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We report silicon delta doping in gallium oxide (β-Ga2O3) grown by plasma-assisted molecular beam epitaxy using a shutter pulsing technique. We describe the growth procedures that can be used to realize high Si incorporation in an oxidizing oxygen plasma environment. Delta doping was adopted to realize thin (12 nm) low-resistance layers with a sheet resistance of 320 Ω/square (mobility of 83 cm2 V−1 s−1, integrated sheet charge of 2.4 × 1014 cm−2). A single delta-doped sheet of carriers was employed as a channel to realize a field-effect transistor with current \( I_{\text{D},\text{max}} = 236 \text{ mA/mm and transconductance } g_m = 26 \text{ mS/mm.} \) © 2017 The Japan Society of Applied Physics

- Ga2O3 is an emerging ultrawide-band-gap semiconductor, which holds promise for next-generation wide-band-gap devices due to the availability of high-quality substrates grown by melt-based techniques and its ability to achieve a wide range of conductivity. Epitaxial growth of β-Ga2O3 using growth techniques such as MBE, metal organic CVD (MOCVD), hydride vapor phase epitaxy (HVPE), and low pressure CVD (LPCVD) has been reported. The estimated breakdown field of 8 MV/cm and the calculated low impact ionization coefficient make Ga2O3 attractive for power switching applications with high blocking voltage capability. β-Ga2O3-based devices have been reported in the literature consist of thick (~200–300 nm) low-doped channels realized using Si ion implantation and doping by MBE or MOCVD, epitaxial growth techniques. Mechanical exfoliation and transfer have also been used to realize FETs based on β-Ga2O3.

In addition to the potential for high blocking voltage for power switching applications, β-Ga2O3 could also be used to realize power amplifiers for RF and millimeter-wave applications. The high breakdown field of β-Ga2O3 could potentially enable higher breakdown voltage and higher channel charge density than those of the state-of-art GaN-based high-electron mobility transistors (HEMTs), and the availability of low-dislocation-density substrates can enable high reliability at high fields. However, challenges related to the poor thermal conductivity of β-Ga2O3 (which is significantly lower than that of SiC substrates used in AlGaN/GaN HEMTs) and surface passivation will need to be overcome for such devices.

Since lateral high-frequency FETs require good aspect ratio, high-charge-density channel layers are critical to evaluating the performance of β-Ga2O3 for RF applications. In this work, we describe techniques for epitaxial delta doping of high-sheet-charge-density channel layers, and evaluate the transport and device performance of these layers. Well-designed growth protocols can enable silicon delta doping in β-Ga2O3 grown by plasma-assisted MBE with high mobility and low sheet resistance.

We first evaluated the growth rate for our system using a combination of capacitance voltage and secondary ion mass spectroscopy (SIMS) measurements. Homoepitaxial β-Ga2O3 was grown on a (010)-oriented bulk substrate using O2 plasma-assisted molecular beam epitaxy equipped with standard effusion cells for gallium, silicon, and an RF plasma source for oxygen. The (010) orientation of β-Ga2O3 was chosen for the study as it has been shown to support a higher growth rate than other planes such as (001) and (100) β-Ga2O3. The growth of undoped β-Ga2O3 was initiated on commercially obtained β-Ga2O3 bulk substrates at a substrate temperature of 700 °C (measured by thermocouple), a plasma power of 300 W, and a chamber pressure of 1.5 × 10−5 Torr. The growth rate was estimated by growing undoped films on Sn-doped (010) n-type substrates and performing capacitance–voltage (C–V) measurements. Pt/Au/Ni Schottky contacts were evaporated on the grown films, and Ti/Au/Ni ohmic contacts were evaporated on the back surface of the sample after a BC13/Ar-chemistry-based inductively coupled plasma reactive ion etching (ICP-RIE) process.

The thickness was estimated from the depletion width measured from the C–V profiles, and indicated a fully depleted epitaxial layer. Ga fluxes of 4 × 10−8 and 8 × 10−8 Torr resulted in Ga-limited growth rates of 155 and 240 nm/h, respectively. The film thickness/growth rate extracted from the C–V measurements matched the thickness estimated by SIMS. A smooth surface morphology with an rms roughness of 0.75 nm was measured by atomic force microscopy (AFM) (Fig. 1).

To evaluate the effect of silicon oxidation in the plasma environment, we investigated the Si incorporation in the films as a function of time/thickness and Si cell temperature. A Ga flux of 8 × 10−8 Torr, corresponding to a growth rate of...
240 nm/h, was used. The Si cell temperature used for growth is shown together with the amount of Si incorporated measured by SIMS (Fig. 2). Between the layers, growth was interrupted, all shutters were closed, and the Si cell temperature was raised to 1290 °C to desorb any oxide that may have formed on the surface of the solid Si source. The measured SIMS profile is shown in Fig. 2. Although a high Si doping concentration (∼6 × 10^{19} \text{cm}^{-3} – 10^{21} \text{cm}^{-3}) is seen at the start of each Si-doped layer, the doping concentration dropped rapidly as the growth proceeded. We attribute this to the oxidation of the Si source leading to the reduction of Si flux during the growth of each layer. The growth of thick Si-doped layers by MBE using a solid Si source is limited by source oxidation. A second limitation is related to the growth of the film itself. Continuous growth with Si cell temperatures above 850 °C was found to result in dimming and the disappearance of reflection high-energy electron diffraction (RHEED) patterns, indicating a loss of crystallinity at high doping levels.

Therefore, to avoid source oxidation and obtain flat doping profiles, a shutter pulsing scheme was adopted. The Si source was pulsed (1 s with a duty cycle of 1 min) while maintaining the Si source at a relatively high temperature (850–950 °C), with the Ga and O shutters open throughout [Fig. 3(a)]. Such an approach is expected to result in delta doping of Si with undoped Ga₂O₃ spacers. The SIMS profile of Si-doped Ga₂O₃ layers grown by the delta doping/pulsed doping approach is shown in Fig. 3(b). Nearly flat and abrupt Si doping profiles with average doping concentrations in the range of 4 × 10^{17} to 4 × 10^{19} \text{cm}^{-3} were observed in the SIMS measurement. It should be noted that the absolute value of the doping concentration (peak) cannot be compared between the continuous doping and pulsed doping SIMS experiments, as the amount of Si in the source was reduced in the case of the pulsed doping experiment. Nevertheless, the doping profile measured from the SIMS profile indicates the possibility of achieving nearly flat doping profiles by the pulsed doping approach.

Electrical characteristics of the delta-doped layers were investigated using an epitaxial structure consisting of an undoped β-Ga₂O₃ buffer layer and delta-doped layers grown on Fe-doped semi-insulating (010)-oriented β-Ga₂O₃ substrates [Fig. 4(a)]. The growth conditions were similar to those in the doping experiments described earlier, with a growth rate of 4 nm/min. Silicon delta-doped layers were separated by 4 nm undoped Ga₂O₃ layers. Energy band and charge profile diagrams of the delta-doped layer are shown in Fig. 4(b). The thickness of the spacer layers is of the same order as that of the Debye length. The Fermi level remains above the conduction band edge throughout the delta-doped region, with no barriers to out-of-plane (vertical) transport. Delta-doped layers can therefore be used as an efficient means of realizing high-conductivity access regions.

Ohmic contacts were patterned by stepper lithography, and a Ti/Au/Ni metal stack was deposited after BCl₃/Ar treatment for ohmic contact formation. Device isolation was performed by ICP-RIE using a BCl₃-based chemistry. Ohmic contacts were annealed at 470 °C for 1 min. A contact resistance of 0.35 Ω mm with a low specific resistance of 4.3 × 10⁻⁸ Ω cm² was measured using the transfer length measurement (TLM) structure [Fig. 4(c)]. Our results suggest that delta-doped layers can be used as excellent contact layers. Hall measurements indicated a total charge of 2.4 × 10^{14} \text{cm}^{-2} with a high mobility of 83 cm² V⁻¹ s⁻¹ and a sheet resistance of 320 Ω/sq. Mobility in the range of 77–81 cm² V⁻¹ s⁻¹ was measured in multiple samples grown by the pulsed doping approach, with a measured sheet charge density ranging from 2.7 × 10^{14} to 3.5 × 10^{15} cm⁻² (equivalent volume charge density of 6.8 × 10^{19}–1.7 × 10^{20} cm⁻³). These samples consisted of multiple delta-doped layers (20–40 nm total thickness) separated by 4 nm undoped Ga₂O₃ layers. The measured mobility values are higher than the mobility values reported in the literature, even for a relatively low doping concentration (<60 cm² V⁻¹ s⁻¹) for a

![Fig. 2](image-url)  
**Fig. 2.** SIMS profile of Si dopants showing strong oxidation of the source and reduction of Si flux during the growth. The source was heated to 1290 °C between growths of layers to remove oxide from the source (marked red).

![Fig. 3](image-url)  
**Fig. 3.** (a) Shutter pulsing scheme used to avoid Si source oxidation during growth. (b) SIMS profile of Si dopants showing nearly flat profile while using the delta doping approach.
doping concentration of $\sim 3 \times 10^{19} \text{ cm}^{-3}$). The carrier mobility is expected to be higher than that of a uniformly doped material with the same equivalent doping density because of the spread of the electron population into undoped regions, which leads to less impurity scattering.26)

To evaluate the application of delta doping for the fabrication of field effect transistors, the device structure shown in Fig. 5(a) was used. The top two delta-doped layers were etched (BCl$_3$-based ICP-RIE) in the channel region to realize a channel with one delta-doped sheet, while all three sheets were left intact for the contact region. A gate dielectric (Al$_2$O$_3$) was deposited by atomic layer deposition (ALD), followed by patterning and evaporation of the Pt/Au/Ni gate stack. The ALD process was similar to that described earlier.27) A channel charge density of $3.3 \times 10^{13} \text{ cm}^{-2}$ with a mobility of $34 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ was measured by Hall measurements after the gate recess. The reduction in electron mobility after the gate recess could be due to etching-induced surface damage and remote scattering,28) but further investigation is required to confirm the origin of this effect.

Output and transfer characteristics ($V_{DS} = 7 \text{ V}$) of the delta-doped FET are shown in Figs. 5(b) and 5(c), respectively. Current (charge) modulation and channel pinch-off were clearly observed in the output characteristics. A very high current ($I_{D,max} = 236 \text{ mA}$) was measured at $V_{DS} = 7 \text{ V}$ and $V_G = +2 \text{ V}$. Channel pinch-off was observed at a gate bias of $-14 \text{ V}$ ($I_D = 215 \mu\text{A}$ at $V_{DS} = 7 \text{ V}$). A peak transconductance of $26 \text{ mS}$ was measured at a gate bias of $-3.8 \text{ V}$. A three-terminal off-state breakdown voltage of $51 \text{ V}$ ($V_{GS} = -16 \text{ V}$, $V_{DS,BR} = 35 \text{ V}$) was measured for the device [Fig. 5(d)]. Flat capacitance voltage curves (not shown here) confirmed the spatial confinement of the charge ($\sim 22-24 \text{ nm}$ from the gate metal) in the delta-doped layer. However, channel pinch-off could not be observed in $C-V$ characteristics of large-area $C-V$ test structures owing to gate leakage at large negative gate biases. The current and transconductance values observed in this device are much higher than those previously reported for epitaxial $\beta$-Ga$_2$O$_3$ FETs.

In summary, we reported delta doping/pulsed doping as a promising approach to achieving high electron mobility.
(\sim 80\text{cm}^2\text{V}^{-1}\text{s}^{-1}) at high charge density \((2.4 \times 10^{14}\text{cm}^{-2})\).
Delta doping enables the scaling of the gate-channel distance, which is critical for high-frequency devices. Delta doping also enables high-conductivity contact layers for transistors and other device applications. We also reported a delta-doped \(\beta\)-Ga\(_2\)O\(_3\) FET with \(I_{D,max}=236\text{mA/mm}\) and \(g_{m,max}=26\text{mS/mm}\). The results reported in this work indicate the promise of delta-doping-based devices for achieving high current density/mobility, enabling new device architectures for high-performance \(\beta\)-Ga\(_2\)O\(_3\)-based high-frequency devices.

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