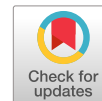


LETTER

MOCVD grown β -Ga₂O₃ metal-oxide-semiconductor field effect transistors on sapphire

To cite this article: Ji-Hyeon Park *et al* 2019 *Appl. Phys. Express* **12** 095503

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MOCVD grown β -Ga₂O₃ metal-oxide-semiconductor field effect transistors on sapphire

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Received July 18, 2019; revised August 9, 2019; accepted August 13, 2019; published online August 27, 2019

We fabricated β -Ga₂O₃:Si metal-oxide field-effect transistors (MOSFETs) on c-plane sapphire substrates which typically showed maximum drain current of 100 mA mm⁻¹. β -Ga₂O₃:Si thin films were realized on c-plane sapphire substrates through a combination of metalorganic chemical vapor deposition and post-annealing. The MOSFET device presented excellent on/off drain current ratio of $\sim 10^{11}$ with very low gate leakage current, sharp pinch off behavior, and a breakdown voltage of 400 V at $V_G = -40$ V. The growth and fabrication of β -Ga₂O₃:Si MOSFETs on c-plane sapphire is valuable to its demonstration of the great potential for future high-power electronic devices.

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β -Ga₂O₃ has various applications like solar blind photo-detectors; however, where it holds the most potential is the area of high power electronic devices.^{1–7)} The global need for stable and clean energy supplies in the near future motivates the fast development of high-power electronics with efficient energy conversion and utilization. Wide-bandgap semiconductors such as SiC and GaN are currently the best candidates to realize those high-power devices. They have high breakdown voltage and lower losses than existing silicon-based devices. However, those materials are expensive, requiring high-quality substrates, hence unideal for mass production. With an ultra-wide bandgap of ~ 4.9 eV and very large electrical breakdown field strength of ~ 8 MV cm⁻¹, outperforming SiC and GaN, β -gallium oxide (β -Ga₂O₃) is considered a promising next generation semiconductor materials for power electronics. Its Baliga's power device figure of merit is estimated to be 3444, several times larger than those of 4H-SiC (340) and GaN (870), projecting higher breakdown voltages and efficiencies for β -Ga₂O₃ power devices.⁸⁾ Another important property of β -Ga₂O₃ is that native substrates can be processed from bulk single crystals fabricated by the same melt-growth mechanisms employed for the production of sapphire substrates.

Nowadays, large and high-quality sapphire substrates are manufactured for low prices and in numbers comparable to those for silicon. As a result, one can expect that melt grown β -Ga₂O₃ substrates will reap the same benefits. Recently, high quality β -Ga₂O₃ have become achievable by homo-epitaxy, which has opened the way of β -Ga₂O₃ materials for real-world applications.^{9,10)} However, at this stage, the technology is still limited by the lack of supply of low-cost homo substrates, which hinders the development of growth and fabrication based on β -Ga₂O₃. In order to solve this problem, it is useful to develop the growth of high quality β -Ga₂O₃ on low-cost foreign substrates such as sapphire or silicon.^{11,12)}

Ga₂O₃-based high power transistors that have been actively reported in the literature are thin (~ 200 – 300 nm) and low-doped channels fabricated using silicon-ion implantation and doping by epitaxial growth techniques like molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD).^{13–17)} Mechanical exfoliation has also been used to realize metal oxide semiconductor field effect transistors (MOSFETs) based on β -Ga₂O₃ nanostructures.^{18–20)}

However, as far as we know, there are no reports of β -Ga₂O₃ based MOSFETs on sapphire substrates as a potential high-power device. In this letter, we report the demonstration and characterization of *n*-type β -Ga₂O₃:Si thin film MOSFETs on c-plane sapphire substrates in order to present a possibility for its potential application in high-power devices. To realize the β -Ga₂O₃ thin film, a metastable κ -Ga₂O₃:Si thin films grown by MOCVD on c-plane sapphire substrates were phase-transformed to β -Ga₂O₃:Si through high-temperature rapid thermal annealing (RTA).

A commercial horizontal-flow MOCVD reactor (AIXTRON 200/4 RF) was used to grow Ga₂O₃:Si thin films on c-plane sapphire substrates at growth temperatures of 670 °C using trimethylgallium (TMGa) and high purity deionized water as the gallium and oxygen precursors, respectively. H₂ was used as the carrier gas. TMGa and water were injected into the reactor via separate manifolds and isolated within the chamber using a quartz divider plate in order to prevent parasitic pre-reactions. Before initiating nucleation, the c-plane sapphire substrate was desorbed in situ at high temperature (~ 1100 °C) for 10 min to prepare the surface. Ga₂O₃:Si was then grown for 15 min with a VI/III flow ratio of 324. Silane (SiH₄) was used as a silicon dopant for *n*-type doping. The thickness of the as-grown Ga₂O₃:Si thin film was about 150 nm and the growth rate was 10 nm min⁻¹.

After growth, the surface morphology and crystalline structure of the Ga₂O₃ thin films were studied using scanning electron microscopy (SEM), atomic force microscopy (AFM) and X-ray diffraction (XRD). Figures 1(a) and 1(b) show typical SEM and (5 μ m $\times$ 5 μ m) AFM images of post-annealed Ga₂O₃:Si thin films after annealing in a N₂ atmosphere at 1000 °C for 1 min using a RTA system; for comparison, both insets show the as-grown film surface. The surface morphology of the as-grown Ga₂O₃:Si thin films on c-plane sapphire substrates is very uniform and smooth [Figs. 1(a) and 1(b) insets]. Even after high temperature annealing, the surface morphology was maintained, and no cracks were observed that could have been caused by the differing thermal expansion of the β -Ga₂O₃ film and sapphire substrate. The root-mean-squared (RMS) roughness was measured at 3.4 nm before and 3.0 nm after annealing.

XRD omega/2theta scans of the typical Ga₂O₃:Si thin film on c-plane sapphire substrate are shown in Fig. 2(a). Three

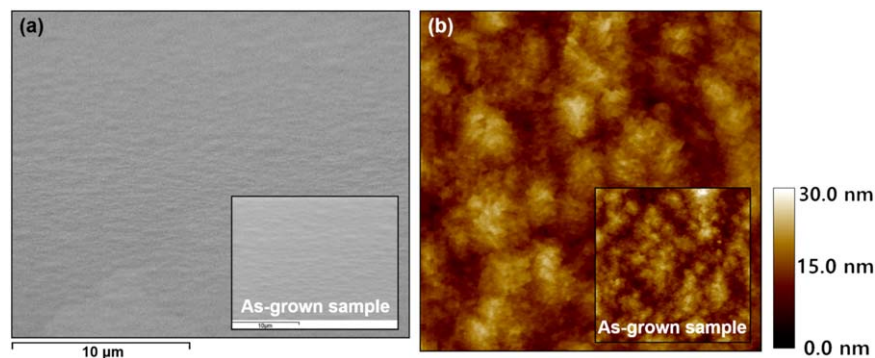


Fig. 1. (Color online) (a) Tilted view SEM image and (b) AFM image (5 μm × 5 μm) of post-annealed Ga₂O₃:Si thin film. Both insets show the as-grown thin film.

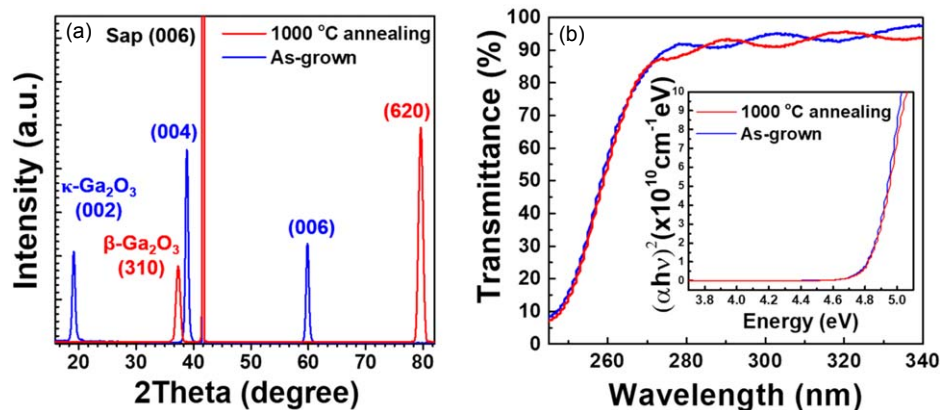


Fig. 2. (Color online) (a) XRD pattern and (b) optical transmission spectra of as grown and after annealing Ga₂O₃:Si thin film; inset is plot of $(\alpha h\nu)^2$ versus $h\nu$.

sharp peaks (located at $\sim 18.96^\circ$, $\sim 38.84^\circ$ and $\sim 59.76^\circ$) were observed for the as-grown Ga₂O₃:Si thin film. The Ga₂O₃ associated with these XRD peaks position can typically be either hexagonal ϵ - or orthorhombic κ -phase; exact differentiation between these two phases requires additional nanoscale analysis. We have previously investigated our Ga₂O₃ as-grown thin films using transmission electron microscopy (TEM) and found them to be κ -Ga₂O₃.²¹⁾ These three sharp peaks corresponding to κ -Ga₂O₃ (002), (004), and (006), respectively, is consistent with a strong preferential (002) orientation along the growth direction. However, after annealing at 1000 °C, XRD clearly shows the phase transforms into monoclinic β -Ga₂O₃:Si (310). Fornari et al. reported that similar phase transition occurs in ϵ -phase (002) when ϵ -Ga₂O₃ thin films is heat treated at a high temperature of 1000 °C with followed by a rapid cooling.²²⁾ Figure 2(b) shows the optical transmission spectra of as grown and post-annealed Ga₂O₃:Si thin films and the inset plots $(\alpha h\nu)^2$ versus $h\nu$ where α is the optical absorption coefficient, h is Planck's constant, and ν is the photon frequency. As-grown and post-annealed Ga₂O₃:Si thin films show a transmission of over 90% for wavelengths above 280 nm. From fitting, the inset of Fig. 2(b) bandgap values were estimated to be 4.82 and 4.83 eV, respectively, for as-grown and post-annealed Ga₂O₃:Si thin films. This result indicates that there is no significant change in the bandgap during the phase transition from the κ -phase to the β -phase.

While no significant change occurred in the surface morphology and bandgap of the κ -Ga₂O₃:Si thin film after

annealing and phase change to the β -phase, a huge change was observed in the electrical properties as measured by the Hall measurement. The carrier concentration of as-grown sample was $1.05 \times 10^{16} \text{ cm}^{-3}$ and the mobility was measured to be as $1.5 \text{ cm}^2 \text{ V}^{-1} \cdot \text{s}^{-1}$ for a dilute (25 ppm) SiH₄ flow of 20 sccm. Unfortunately, for κ -Ga₂O₃:Si thin films with SiH₄ flow rates of less than 20 sccm, the electrical characteristics could not be evaluated due to excessively high resistivity. However, after conversion to β -Ga₂O₃:Si these low flow-rate films became conductive and Hall characteristics could be evaluated. After phase-transition to β -Ga₂O₃:Si decreasing the dilute SiH₄ flow causes the mobility to increase from $3.1 \text{ cm}^2 \text{ V}^{-1} \cdot \text{s}^{-1}$ to $22.6 \text{ cm}^2 \text{ V}^{-1} \cdot \text{s}$ and the carrier concentration systematically decrease three orders of magnitude from $4.2 \times 10^{18} \text{ cm}^{-3}$ to $1.3 \times 10^{15} \text{ cm}^{-3}$ (Fig. 3). The measured mobility values are still relatively low compared to reported cases of Ga₂O₃ grown on the homo-substrate.²³⁾ This low value of the mobility is most likely related to the high density of planar defects and in-plane rotational domains when Ga₂O₃ was grown on the sapphire substrate.²¹⁾ The exact cause of the dramatic change of the electrical characteristics could be the subject of further discussion, but in this letter, we will focus on the characteristics of MOSFET devices fabricated using these thin films.

In order to evaluate the potential of using MOCVD grown β -Ga₂O₃:Si on sapphire for power-electronics application, MOSFET devices were fabricated and characterized using the as-grown and post-annealed thin films according to the design shown in Fig. 4. Figures 4(a) and 4(b) show a schematic

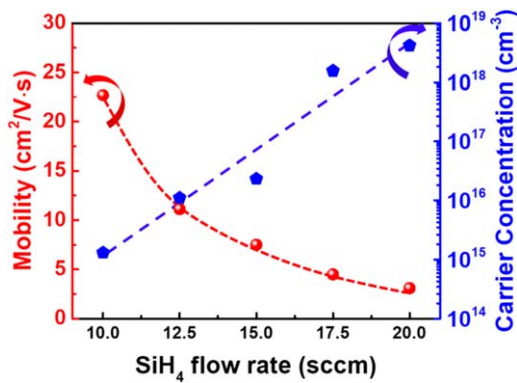


Fig. 3. (Color online) Carrier concentration and mobility of post-annealed β -Ga₂O₃:Si thin film as a function of SiH₄ flow rate.

illustration of the cross sectional and isometric view of the Ga₂O₃:Si MOSFET design. To fabricate the MOSFETs first, a 200 μ m wide channel was etched by electron cyclotron resonance reactive ion etching (ECR-RIE) for mesa isolation.

Then conventional photolithography and lift-off was used to electron-beam deposit Ti (20 nm)/Au (100 nm) source and drain metal contacts on the MOSFETs. Plasma-enhanced chemical vapor deposition (PECVD) at 350 °C using SiH₄ and NO₂ was used to deposit a 100 nm thick SiO₂ of gate dielectric. The MOSFETs had gate length (L_G), gate-source spacing (L_{GS}), and gate-drain spacing (L_{GD}) of 10, 10, and 20 μ m, respectively, as shown in Fig. 4(c). The gate metal contact [Fig. 4(d)] was then formed by the evaporation of Pt(20 nm)/Ti (20 nm)/Au(100 nm) on the SiO₂ gate. Then, fabricated MOSFETs were tested using a semiconductor parameter analyzer and probe station.

Figure 5(a) shows the DC output I–V (I_D – V_{DS}) curves for MOSFET of the κ -Ga₂O₃:Si with SiH₄ flow rate 20 sccm from gate voltages (V_G) 10 to –50 V with a gate step of –10 V. A gate voltage (V_G) over 10 V was found to degrade the devices. The maximum I_D is around 9.1 mA mm^{–1} at V_G = 10 V. Three-terminal breakdown appeared at a V_{DS} of 390 V with V_G = –30 V. The I_D is effectively modulated by the V_G as shown in Fig. 5(b). The on/off ratio was measured

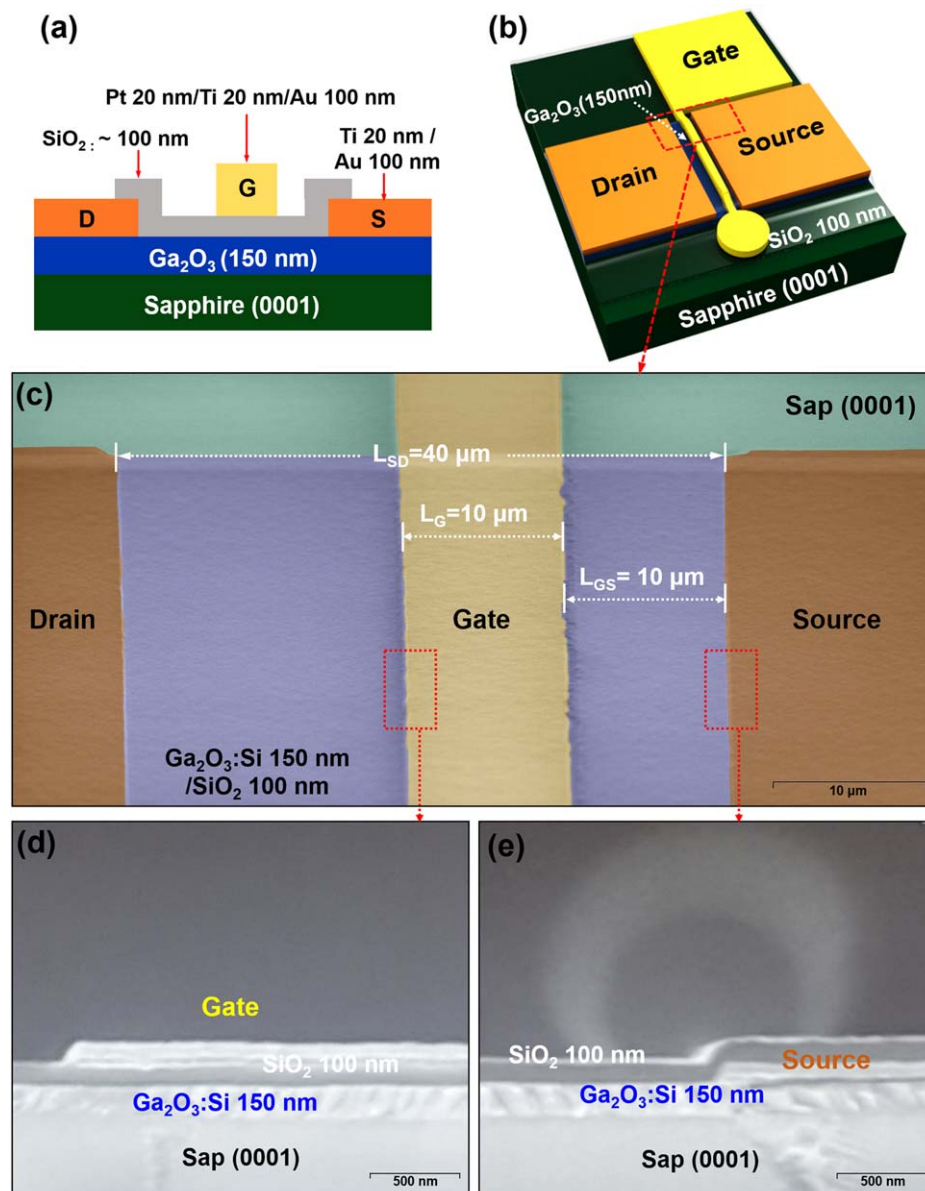


Fig. 4. (Color online) Schematic illustration of the (a) cross sectional and (b) isometric view of Ga₂O₃:Si MOSFET design; (c) bird's eye view SEM image of Ga₂O₃:Si MOSFET, (d) cross sectional SEM image of gate metal pad and (e) cross sectional SEM image of source metal pad.

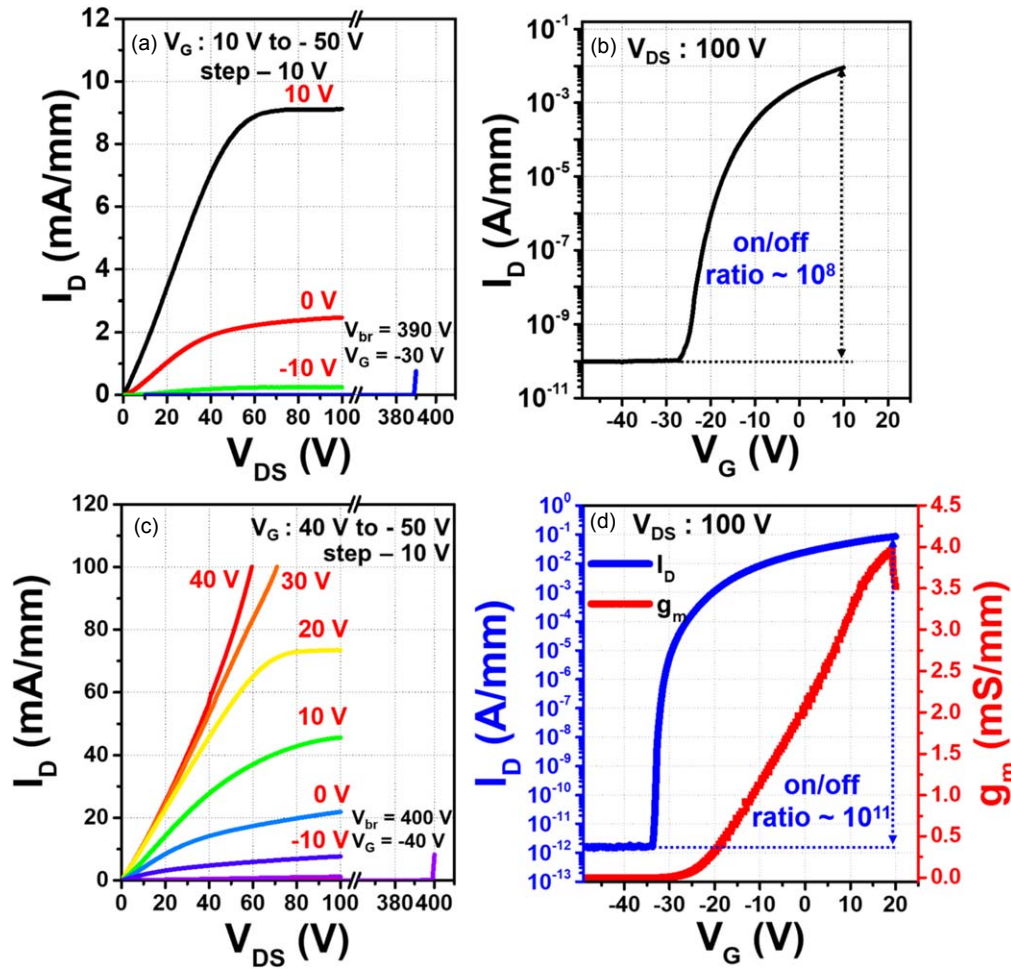


Fig. 5. (Color online) (a) DC I-V characteristics and (b) transfer characteristics of MOSFETs using κ -Ga₂O₃:Si with a SiH₄ flow rate 20 sccm; (c) DC I-V characteristics and (d) transfer characteristics of MOSFET using β -Ga₂O₃:Si with a SiH₄ flow rate 15 sccm.

as high as $\sim 10^8$. MOSFETs fabricated from β -Ga₂O₃:Si with various SiH₄ flow rates were then investigated. It was observed that at higher flow rates greater than 17 sccm with high doping concentration, the IV curve is linear. This phenomenon is related to the Mott semiconductor-metal transition and was observed to occur at high doping levels ($> 4 \times 10^{18} \text{ cm}^{-3}$) in Ga₂O₃.^{24,25} On the other hand, when the SiH₄ flow rate is less than 5 sccm, drain current only shows a few pA mm⁻¹ due to the very high channel resistance. The best performance was obtained for β -Ga₂O₃:Si MOSFETs fabricated using an intermediate SiH₄ flow of 15 sccm, corresponding to β -Ga₂O₃:Si with an electrical mobility of $7.5 \text{ cm}^2 \text{ V}^{-1} \cdot \text{s}^{-1}$ and a carrier concentration of $2.3 \times 10^{16} \text{ cm}^{-3}$. Figure 5(c) shows the DC output characteristics of this β -Ga₂O₃:Si MOSFET at V_G from 40 to -50 V in steps of -10 V while the V_{DS} was swept from 0 to 100 V. Degradation did not occur until the gate bias (V_G) exceeded 40 V. This β -Ga₂O₃:Si MOSFET generally shows a 10 times higher maximum I_D than MOSFETs fabricated from the as-grown κ -Ga₂O₃:Si thin film. Because of limitations of our characterization system, the maximum I_D that we can measure is 100 mA mm^{-1} at $> V_G = 30 \text{ V}$. The three-terminal breakdown voltage in the off state is as high as 400 V at $V_G = -40 \text{ V}$. Figure 5(d), demonstrates the depletion mode performance of the device which reveals a high on/off ratio of $\sim 10^{11}$. The gate leakage current shows a very low gate leakage current of $\sim 1.5 \text{ pA mm}^{-1}$. The on/off ratio value

exhibits a significant improvement of about 3 orders magnitude compared to the as-grown un-annealed thin film. The maximum transconductance (g_m) is calculated from transfer characteristic [Fig. 5(d)] to be 3.96 mS mm^{-1} and a sub-threshold swing (SS) of 210 mV dec^{-1} is obtained. The peak field-effect mobility (μ_{FE}) of the device was calculated as well using Eq. (1):

$$\mu_{FE} = \frac{L}{W} \frac{g_m}{V_{DS} C_{OX}} \quad (1)$$

where L and W are the channel length and width, respectively, and C_{OX} is the oxide capacitance. Using this equation the μ_{FE} is calculated to be $11.4 \text{ cm}^2 \text{ V}^{-1} \cdot \text{s}^{-1}$.

In order to give more prospect and comparison of the device performance, Table I summarizes the basic characteristic of β -Ga₂O₃ FETs on native and sapphire substrate using different methods of growth. According to reported studies up to now, β -Ga₂O₃ FET devices using native substrate have shown progressive performance improvements by various doping and growth techniques. However, despite the development of β -Ga₂O₃ thin film growth technology through diverse growth and doping technologies on sapphire substrates,^{31,32} there is not much research performed on β -Ga₂O₃ MOSFETs on sapphire substrates. Therefore, we believe that this study will lead to a new chapter in research of β -Ga₂O₃ MOSFETs based on sapphire substrates and other hetero-substrates. The device presented in this work

Table I. Summary of some key parameter in β -Ga₂O₃ FETs on native and sapphire substrate.

Material growth	Substrate	On/off ratio	Max I_D (mA mm ⁻¹)	V_{br} (V)	References
MBE	β -Ga ₂ O ₃	$>10^{10}$	39	370	26
MBE	β -Ga ₂ O ₃	10^4	15 mA	257	8
MBE	β -Ga ₂ O ₃	$\sim 10^6$	1.4	~ 40	27
MBE	β -Ga ₂ O ₃	$\sim 10^3$	236	51	15
HVPE	β -Ga ₂ O ₃	$\sim 10^9$	>1 kA cm ⁻²	960	28
MOVPE	Sapphire	$<10^2$	42 nA	—	29
MOCVD	Sapphire	$\sim 10^{11}$	100	400	This work
Exfoliation	SiO ₂ /p ⁺⁺ Si	$\sim 10^{10}$	600	185	18
Exfoliation	SiO ₂ /p ⁺ Si	$\sim 10^5$	60	~ 100	30

using MOCVD growth, showed the best MOSFET performance among the β -Ga₂O₃ grown on sapphire substrates. These excellent properties are comparable to β -Ga₂O₃ MOSFET devices grown on native substrates and nanomembrane devices.³³⁾ The growth of β -Ga₂O₃:Si thin films on c-plane sapphire substrates through post-annealing and the improved MOSFET characteristics not only show improved device characteristics, but also demonstrate that β -Ga₂O₃ grown on sapphire has tremendous potential for future power electronic devices.

In summary, we have successfully demonstrated β -Ga₂O₃:Si MOSFETs on c-plane sapphire via MOCVD growth. The β -Ga₂O₃:Si MOSFETs show a maximum I_D of 100 mA mm⁻¹ with an excellent breakdown voltage of 400 V at $V_G = -40$ V. The devices exhibit high on/off ratios of $\sim 10^{11}$ with extremely low gate leakage current of ~ 1.5 pA mm⁻¹. Moreover, this excellent performance of β -Ga₂O₃:Si MOSFET demonstrated strong potential of the cost effective and scalable MOCVD growth of β -Ga₂O₃:Si using low-cost readily available c-plane sapphire substrates for future power electronic device applications.

Acknowledgments This material is based upon work supported by the National Science Foundation under Grant No. ECCS-1748339.

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