Growth and Characterization of Low Sheet Resistance Metalorganic Vapor-Phase Epitaxy-Grown β-\((\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) Heterostructure Channels

Praneeth Ranga\(^1\), Arkka Bhattacharyya\(^1\), Adrian Chmielewski\(^2\), Saurav Roy\(^1\), Rujun Sun\(^1\), Michael A. Scarpulla\(^1,3\), Nasim Alem\(^2\) and Sriram Krishnamoorthy\(^1\)

\(^1\) Department of Electrical and Computer Engineering, The University of Utah, Salt Lake City, UT 84112, USA
\(^2\) Department of Materials Science and Engineering, Pennsylvania State University, University Park, State College, PA 16802, USA
\(^3\) Department of Materials Science and Engineering, University of Utah, Salt Lake City, Utah 84112, USA

\(^a\) Arkka Bhattacharyya and Praneeth Ranga contributed equally to this work.

We report on growth and characterization of metalorganic vapor-phase epitaxy-grown \(\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) modulation-doped heterostructure. Electron channel is realized in the heterostructure by utilizing a delta-doped \(\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3\) barrier. Electron channel characteristics are studied using transfer length method, capacitance-voltage and Hall characterization. Hall sheet charge density of \(1.1 \times 10^{13} \text{ cm}^{-2}\) and mobility of \(111 \text{ cm}^2/\text{Vs}\) is measured at room temperature. Fabricated transistor showed peak current of \(22 \text{ mA/mm}\) and on-off ratio of \(8 \times 10^6\). Sheet resistance of \(5.3 \text{ k}\Omega/\text{Square}\) is measured at room temperature, which is the lowest reported value for a single \(\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) heterostructure.

Ultrawide bandgap materials such as \(\beta-\text{Ga}_2\text{O}_3\) has attracted a lot of interest because of their suitable properties for high-power electronics and deep-UV optoelectronic applications. The high bandgap (~4.6 eV) results in a very large predicted breakdown field strength of 6-8 MV/cm, which is much larger than other wide bandgap materials like GaN and SiC\(^1\). In addition, the availability of high-quality single crystal bulk substrates and wide range of controllable conductivity make \(\beta-\text{Ga}_2\text{O}_3\) an attractive platform for next generation power electronics\(^2\). Growth of high-quality \(\beta-\text{Ga}_2\text{O}_3\) has been realized using a variety of epitaxial techniques\(^3\)–\(^6\). Significant advances have been made in growth, characterization, and fabrication of \(\beta-\text{Ga}_2\text{O}_3\) devices within the last decade. Vertical and lateral devices with high breakdown voltages and high critical fields have been demonstrated by multiple research groups\(^7\)–\(^11\).

Room temperature mobility of uniformly-doped \(\beta-\text{Ga}_2\text{O}_3\) is limited by polar optical phonon scattering, which limits the maximum mobility to \(\sim 200 \text{ cm}^2/\text{Vs}\)\(^12\). Moreover, the mobility reduces drastically with increasing impurity doping concentration. In modulation-doped structure the carriers are separated from the donor atoms, leading to a 2DEG (two-dimensional electron gas) with high carrier mobility. 2DEG channel mobility is not limited by impurity scattering unlike doped semiconductors. This is due to the absence of ionized impurity donors in the electron channel. For realizing a 2DEG, growth of high-quality modulation-doped \(\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) with sharp dopant profile is necessary. Theoretical studies indicate that \(\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3\) is stable up to a composition of \(x = 0.8\) which has a bandgap of \(\sim 6.5 \text{ eV}\). This high band gap results in a
large conduction band offset suitable for confining electrons at the $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ interface. Moreover, DFT calculations indicate that n-type shallow doping is achievable for the entire composition range of stable $\beta-(Al,Ga_{1-x})_2O_3$. All the above material properties suggest that formation of 2DEG at $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ is very favorable. Recently reported transport calculations performed by Kumar et al. indicate that mobility of a 2DEG can significantly exceed that of bulk $\beta-Ga_2O_3$. This is expected to happen when the 2DEG sheet charge exceeds $5 \times 10^{12}$ cm$^{-2}$. At such high charge densities, the plasmon screening of LO (Longitudinal optical) phonons leads to increase in polar optical phonon (POP) limited mobility. Having a high 2DEG sheet charge and mobility can lead to a significant improvement in device performance over conventional $\beta-Ga_2O_3$ devices. Development of 2DEGs in other material systems (AlGaN/GaN, AlGaAs/GaAs etc.) has led to development of devices with improved operation frequency range and efficiency. Hence, it is important to study $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructures which will allow researchers to understand the performance limits of devices based on $\beta-Ga_2O_3$ 2DEG channels.

Demonstration of $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructure MODFET has already been made using MBE-grown material. There are multiple of reports of MBE-grown $\beta-Ga_2O_3$ 2DEG channels with a wide range of sheet charge and mobility. However, all the current literature is based on MBE-grown $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructures. 2DEG sheet charge densities between $1 \times 10^{12} - 5 \times 10^{12}$ cm$^{-2}$ and mobilities of $75 - 180$ cm$^2$/Vs have been achieved using MBE technique. Currently the maximum sheet charge density reported in MBE-grown $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ is less than $5 \times 10^{12}$ cm$^{-2}$ for a single heterostructure without parallel channel in $\beta-(Al,Ga_{1-x})_2O_3$. Furthermore, composition of MBE-grown $\beta-(Al,Ga_{1-x})_2O_3$ films is limited to $x < 0.25$ because of the limited growth temperature window. Recently, MOVPE (Metalorganic vapor phase epitaxy) has emerged as a promising technique for growth of high-quality $\beta-Ga_2O_3$. Uniformly-doped $\beta-Ga_2O_3$ films with high room temperature mobility values have been demonstrated. Moreover, recent growth studies show that high mobility $\beta-Ga_2O_3$ can be grown across a large growth window using MOVPE technique. High composition MOVPE-grown (100)-oriented $\beta-(Al,Ga_{1-x})_2O_3$ films with $x \sim 0.52$ has been realized recently. N-type doping of MOVPE-grown $\beta-(Al,Ga_{1-x})_2O_3$ films with composition up to $x \sim 0.3$ has already been demonstrated. Recently, delta-doped $\beta-Ga_2O_3$ films with sheet charge up to $1 \times 10^3$ cm$^{-2}$ is reported using MOVPE. For achieving sharp dopant profiles with low FWHM (Full width at half maximum), it is necessary to suppress surface segregation of donor atoms. Recent work on MOVPE-grown delta-doped films grown at low temperatures suggests that by suppressing surface segregation Si delta sheets with FWHM comparable to MBE-grown films can be realized. All the above factors indicate the promise of MOVPE technique for studying high charge density $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructures.

In this work, we report growth and characterization of delta-doped $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructure with sheet charge density ($n_s$) $\sim 1.1 \times 10^{13}$ cm$^{-2}$ and room temperature mobility of $\mu \sim 111$ cm$^2$/Vs using MOVPE technique. Sheet resistance of $5.3$ k$\Omega$/square has been realized for a room temperature sheet charge of $1.1 \times 10^{13}$ cm$^{-2}$. This value is the lowest sheet resistance value for a single $\beta-(Al,Ga_{1-x})_2O_3/\beta-Ga_2O_3$ heterostructure (with and without parallel channel) among all reported literature. The sheet charge and mobility are confirmed using capacitance voltage (CV), transfer length measurements (TLM) and Hall measurements. Additionally, FET devices with peak current of $22$ mA/mm, transconductance of $7$ mS/mm and a subthreshold slope of $112$ mV/dec is demonstrated.
**Fig.1** Schematic of MOVPE-grown β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/ β-Ga\textsubscript{2}O\textsubscript{3} heterostructure FET (HFET) with regrown ohmic contacts. Sample A and B have identical structure, except the spacer layer thickness (Sample A spacer layer thickness- 2 nm; Sample B spacer layer thickness- 4 nm).

β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/β-Ga\textsubscript{2}O\textsubscript{3} heterostructures are grown using Agnitron Agilis using TEGa (Triethyl Gallium), TMAI (Trimethyl Aluminium) and O\textsubscript{2} (oxygen) as precursors and Argon as carrier gas. The following growth parameters are utilized – TEGa – 3.9 μmol/min, TMAI – 1.32 μmol/min, O\textsubscript{2} – 500 sccm, Pressure - 15 Torr Temperature - 650 °C. Growth is performed on Fe-doped (010) substrates from Novel Crystal Technology. As-received substrates are cleaned with Acetone, Methanol and DI water followed a HF dip for 20 mins. A schematic of the grown β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/β-Ga\textsubscript{2}O\textsubscript{3} heterostructure is shown in fig.1. The film consists of a 250 nm UID β-Ga\textsubscript{2}O\textsubscript{3} buffer layer followed by a thin β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} spacer layer (2 / 4 nm) and a thick β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} barrier (21 nm). Next, delta doping of β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} layer is performed by using a growth interruption process. The process consists of a growth interruption step with a pre- and post-purge steps (30 secs) before and after the delta doping. The delta sheet density is controlled by controlling the silane flow period (60 secs) and the silane gas flow (30.8 nmol/min). Additional details and study of the delta doping process in β-Ga\textsubscript{2}O\textsubscript{3} are reported elsewhere\textsuperscript{31,32}. After the delta doping process, growth of additional 21 nm β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} barrier is continued until the desired total thickness is reached (~ 23 - 25 nm including the spacer layer). The two samples, sample A and B are grown using identical growth conditions, with the only difference being in the spacer layer thickness. In sample B, the β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} spacer layer thickness is doubled (~ 4 nm) with respect to sample A (~ 2 nm spacer layer thickness) while keeping the other parameters the same. The composition of the β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} barrier is controlled by setting the [Al]/([Ga] + [Al]) molar ratio to ~ 0.25. Composition of the β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3} barrier is verified using XRD (X-ray diffraction)\textsuperscript{33}. The measured composition is x-0.27 for sample A and x-0.29 for sample B, which is close to the precursor molar ratio.
FET, TLM and Van der Pauw structures were realized after mesa isolation using dry etching with SF6/Ar chemistry (35 sccm/5 sccm, 150 W RF power). Next the samples are prepared for n+ layer regrowth for ohmic contact formation. The samples are patterned using Ni/SiO2 mask followed by a 50 nm etch using SF6/Ar plasma (35 sccm/5 sccm, 150 W RF power). After the etch, Nickel mask layer is removed using wet etch (aqua regia) and samples are loaded into the MOVPE reactor. Low temperature n+ regrowth is performed using MOVPE at a growth temperature of 600 °C. The low growth temperature is chosen to minimize any potential damage to the epitaxial layer. The doping of the n+ layer is set to 8 x 1019 cm-3 and the thickness of the n+ layer is 150 nm. After the completion of the n+ regrowth process, the SiO2 hard mask is removed by a HF dip. Standard photolithography process is utilized for patterning Ohmic and Schottky contact pads. After the deposition of Ohmic contacts, the contacts are annealed using a RTA (Rapid thermal anneal - 90s, 450 °C) system under nitrogen environment. Both the Ohmic (30 nm Ti /100 nm Au /30 nm Ni) and Schottky contacts (30 nm Ni/50 nm Au/30 nm Ni) are deposited by ebeam evaporation.

CV, TLM and Hall measurements are utilized to independently measure apparent charge density profile, sheet charge, mobility, and sheet resistance. CV measurements performed on samples A and B are shown in fig.2(a). According to the lever rule for modulation-doped heterostructure, for a given donor sheet charge and band offset, the 2DEG charge reduces with increasing spacer thickness. The apparent charge density extracted from the charge profile decreased from 1.1 x 1013 cm-2 to 6.4 x 1012 cm-2 with increasing spacer thickness. Extracted apparent charge density profile of the 2DEG sheet charge is plotted in fig.2(b). The shift in the peak of the apparent charge density profile in sample B is attributed to larger spacer thickness and overall β-(AlxGa1-x)2O3 thickness of sample B compared to sample A. Room temperature Hall measurements are also performed to measure sheet charge and mobility. Details of all the electrical measurements are summarized in Table. 1. Hall sheet charge of 1.1 x 1013 cm-2 and 6.4 x 1012 cm-2 is recorded for sample A and B. The measured Hall charge density is in good agreement with the CV data. Room temperature electron mobility values of 111 cm2/Vs and 125 cm2/Vs are measured for samples A and
B, respectively. IV characteristics of the TLM and Hall pads showed very good Ohmic behavior at room temperature. Additionally, TLM measurements are performed to extract electron channel sheet resistance. TLM Sheet resistance values of 5.5 kΩ/Square and 8.2 kΩ/Square are measured for samples A and B. The sheet charge, sheet resistance of Hall, CV and TLM measurements closely agree with each other (Table 1). These electrical measurements indicate that all the measured parameters can be directly attributed to the β-(Al,Ga1-x)2O3/β-Ga2O3 heterostucture channel.

| Sample | Spacer thickness (nm) | Hall sheet charge (x 10^{12} cm^{-2}) | Hall mobility cm^{2}/Vs | RT Hall Sheet resistance (kΩ/square) | RT TLM Sheet resistance (kΩ/square) |
|--------|-----------------------|--------------------------------------|--------------------------|--------------------------------------|--------------------------------------|
| A      | 2                     | 10.6                                 | 3                        | 111                                  | 1680                                 | 5.3                                 | 5.5                                 |
| B      | 4                     | 6.4                                  | 3.1                      | 125                                  | 689                                  | 7.7                                 | 8.2                                 |

To understand the nature of the heterostructure electron channel, low temperature Hall measurements are performed at liquid nitrogen temperatures (77K). For an ideal 2DEG with no parallel channel in the β-(Al,Ga1-x)2O3 layer, the Hall measured sheet charge density is not expected to freeze out upon reaching cryogenic temperatures. The results of the Hall measurements are listed in Table 1. The sheet charge of samples A and B reduced to ~ 3 x 10^{12} cm^{-2} at 77 K. Correspondingly, the Hall mobility increased to 1680 cm^{2}/Vs and 689 cm^{2}/Vs for samples A and B. The Hall measured sheet charge density reduced to 1.2 kΩ/square (sample A) and 2.9 kΩ/square (sample B) at 77K. This indicates that there is a significant amount of donor freezeout at 77 K. This reduction in sheet charge is attributed to freezeout of parallel channel in β-(Al,Ga1-x)2O3. In a delta-doped heterostructure with a narrow dopant profile, all the donor atoms are located in the β-(Al,Ga1-x)2O3 barrier layer. However, attaining silicon delta sheets with low FWHM is challenging. Based on SIMS data of MOVPE-grown β-(Al,Ga1-x)2O3/β-Ga2O3 heterostructure, the FWHM of a silicon delta sheet grown at 600 °C is around 11 nm (see supplementary). Because of the spread-out dopant profile, considerable amount of charge ends up in the UID β-Ga2O3 layer. A finite amount of charge reduction could result from carrier freeze out in the UID β-Ga2O3 layer. Reports of charge freeze out at low temperature have been observed in β-(Al,Ga1-x)2O3/β-Ga2O3 single and double heterostructures and uniformly doped β-(Al,Ga1-x)2O3 thin films. High background charge (1.5x10^{17}. 3x10^{18} cm^{-3}) was required to model mobility in MBE-grown β-(Al,Ga1-x)2O3/β-Ga2O3 heterostructures. The above analysis indicates that getting a very high 2DEG charge in β-(Al,Ga1-x)2O3/β-Ga2O3 heterostructures is still challenging. For attaining high charge densities, it is important to realize a sharp dopant profiles in β-(Al,Ga1-x)2O3 barrier with a high conduction band offset. Higher Al composition barrier in conjunction with thicker spacer layer and sharp doping profile would be necessary to leverage the predicted high electron mobilities in β-Ga2O3 2DEGs.
High resolution high angle annular dark field-scanning transmission electron microscopy (HAADF-STEM) investigations are performed on \(\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) grown on Sn-doped (010) \(\beta-\text{Ga}_2\text{O}_3\) structures with growth conditions identical to sample A (2 nm spacer). HAADF-STEM imaging is carried out using a FEI Titan G2 60-300 transmission electron microscope (TEM) at 300kV. A condenser aperture of 70um is used with a convergence angle of 30 mrad and the annular detector collection angles in the 42-250 mrad range. The camera length is set to 1.15m and the probe current is approximately 80 pA.

As the contrast is proportional to the Z number of the atom in the STEM mode, the heavier the atom, the brighter it will appear on the projected image. Figure 3(a) is a HAADF-STEM image of the \(\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) interface in the [00\(\bar{1}\)] projection at low magnification. This zone axis allows to have the distance between Ga atoms easily resolved by the TEM. The top of the image corresponds to the Nickel contact layer whereas the \(\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) interface is easily observable due to the contrast change. A zoom-in image of the interface is shown in fig. 3(b). The yellow dashed lines represents the heterostructure interface. The \(\beta-\text{Ga}_2\text{O}_3\) substrate has a homogeneous bright contrast whereas the \(\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3\) film is darker overall which is due to the presence of lighter Al atoms. Interestingly, different types of point defects are observed in the \(\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3\) film such as Al/Ga interstitials and Ga vacancies. Some of these defects have already been studied in the literature. For instance, Johnson et al. have shown the formation of Ga interstitial sitting in between two Ga vacancies creating a 2VGa-Ga complex in Sn doped \(\beta-\text{Ga}_2\text{O}_3\) \(^{34}\). More recently, A. Chmielewski et al. reported the formation of di-interstitial di-vacancy complexes at the MBE grown \(\beta-(\text{Al}_{0.2}\text{Ga}_{0.8})_2\text{O}_3/\beta-\text{Ga}_2\text{O}_3\) interface that are created by either an Al or Ga interstitial in the tetrahedral site \(^{35}\).

Figure. 3(c) is a HAADF-STEM image of another area of the sample. A zoom-in image of the defective area is shown in the red square in which a similar structure to the \(\gamma\)-phase is observed. A mixture of \(\beta\) and \(\gamma\) phases in MOCVD grown \(\beta-(\text{Al}_{1-x}\text{Ga}_x)_2\text{O}_3\), when Al composition ranged between 27% and 40%, has already been reported in the literature \(^{36}\). Although these contrast are very similar to those of a \(\gamma\)-phase, similar structures were observed when two \(\beta\)-lattices with a relative shift of 2.72 Å in the (102) direction are superimposed along the (010) viewing direction \(^{37}\). As of now, there is no general consensus
towards the understanding of this contrast and a deeper analysis will be necessary to have a better comprehension of it. However, here, it is clearly observable that these defects are present further from the $\beta-(\text{Al}_{0.28}\text{Ga}_{0.72})_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ interface as shown by the inserts in Figure 3(b).

![Fig. 4](image)

Fig.4 (a) Output and (b) transfer characteristics of $\beta-(\text{Al}_x\text{Ga}_{1-x})_2\text{O}_3/\beta\text{-Ga}_2\text{O}_3$ heterostructure FET showing peak current density of 22 mA/mm ($V_{ds} = 10$ V, $V_g = 0$ V ) and transconductance of 7 mS/mm ($V_{ds} = 10$ V, $V_g = 0$ V )

Lateral heterojunction field effect transitors (HFETs) are fabricated with n+ regrown contacts (sample A) with Lg, Lsd, Lgd of 2 μm, 3 μm and 8 μm respectively. Output and transfer characteristics of the FET are shown in Fig. 4(a) and 4(b). The devices showed a peak current of 22 mA/mm at zero gate bias and drain bias of 10 V. From the TLM measurements, the contact resistance to the heterostructure channel was extracted to be as high as 16.5 ohm.mm. The peak current is currently limited by the device dimension and the performance of the source/drain ohmic contacts. The device showed good pinch off characteristics with a pinch off voltage close of -4 V, correlating well with the CV measurements. The device also showed a high on-off ratio of $8 \times 10^6$ and sub-threshold swing of 112 mV/dec. A peak transconductance of 7 mS/mm is measured at zero gate bias.
The measured room temperature sheet resistance and Hall mobility values are plotted as a function of the charge density in fig.5. In this work, we report the lowest sheet resistance (5.3 kΩ/Square) for a single β-(AlxGa1-x)2O3/β-Ga2O3 heterostructure channel. Additionally, we report β-(AlxGa1-x)2O3/β-Ga2O3 heterostructure device grown and fabricated completely based on MOVPE process, including contact regrowth. However, the complete charge cannot be ascribed to modulation-doped carriers because of parallel channel in β-(AlxGa1-x)2O3 layer as evidenced from observed carrier freezeout at low temperature. Nevertheless, the low sheet resistance value obtained in this work, with room temperature mobilities exceeding 100 cm²/Vs is a promising step towards high performance MOVPE-grown β-(AlxGa1-x)2O3/β-Ga2O3 modulation-doped devices.

In conclusion, we report on growth and characterization of MOVPE-grown β-(AlxGa1-x)2O3/β-Ga2O3 heterostructure channel with low sheet resistance. Electrical characteristics of the heterostucture channel are measured using TLM, CV and Hall measurements. Room temperature Hall measurements showed a high sheet charge of 6.4 x 10^{12} – 1.1 x 10^{13} cm⁻² and mobility of 111-125 cm²/Vs. TEM investigation of β-(AlxGa1-x)2O3/β-Ga2O3 heterostructure showed formation of defects away from the interface. FET showed a peak current density of 22 mA/mm and on-off ratio of 8x10⁶.
Acknowledgements:

This material is based upon work supported by the Air Force Office of Scientific Research under award number FA9550-18-1-0507 and monitored by Dr. Ali Sayir. Any opinions, findings, conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the United States Air Force. Praneeth Ranga acknowledges support from University of Utah Graduate Research Fellowship 2020-2021. This work was performed in part at the Utah Nanofab sponsored by the College of Engineering and the Office of the Vice President for Research. The authors thank the Air Force Research Laboratory’s Sensors Directorate for their discussions with them. The electron microscopy work was performed in the Materials Characterization lab (MCL) at the Materials Research Institute (MRI) at the Pennsylvania State University. The work at PSU was supported by the AFOSR program FA9550-18-1-0277 (GAME MURI, Dr. Ali Sayir, Program Manager).

Data availability statement:

The data that support the findings of this study are available from the corresponding author upon reasonable request.
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Growth and Characterization of Low Sheet Resistance Metalorganic Vapor-Phase Epitaxy-Grown β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/β-Ga\textsubscript{2}O\textsubscript{3} Heterostructure Channels

Praneeth Ranga\textsuperscript{1, a)}, Arkka Bhattacharyya\textsuperscript{1, a)}, Adrian Chmielewski\textsuperscript{2}, Saurav Roy\textsuperscript{1}, Rujun Sun\textsuperscript{1}, Michael A. Scarpulla\textsuperscript{1,3}, Nasim Alem\textsuperscript{2} and Sriram Krishnamoorthy\textsuperscript{1}

\textsuperscript{1} Department of Electrical and Computer Engineering, The University of Utah, Salt Lake City, UT 84112, United States of America

\textsuperscript{2}Department of Materials Science and Engineering, Pennsylvania State University, University Park, State College, PA 16802, USA

\textsuperscript{3} Department of Materials Science and Engineering, University of Utah, Salt Lake City, Utah 84112, USA

b) Arkka Bhattacharyya and Praneeth Ranga contributed equally to this work.

Supplementary information

SIMS scan of delta-doped β-(Al\textsubscript{0.26}Ga\textsubscript{0.74})\textsubscript{2}O\textsubscript{3}/ Ga\textsubscript{2}O\textsubscript{3}

Fig. S1 SIMS profile of silicon delta sheet in β-(Al\textsubscript{0.26}Ga\textsubscript{0.74})\textsubscript{2}O\textsubscript{3}/ β-Ga\textsubscript{2}O\textsubscript{3} heterostructure. The delta sheet was grown at 600 °C with a full width at half maximum of 11 nm.
SIMS profile of modulation-doped $\beta$-(Al$_{0.26}$Ga$_{0.74}$)$_2$O$_3$/\(\beta\)-Ga$_2$O$_3$ heterostructure grown at 600 °C. The heterointerface is indicated by the dashed line in fig. S1. A significant amount of silicon density is observed in the UID \(\beta\)-Ga$_2$O$_3$ layer.

**X ray diffraction scan of $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$/Ga$_2$O$_3$ heterostructures**

Fig.S2 XRD scan of $\beta$-(Al$_x$Ga$_{1-x}$)$_2$O$_3$/\(\beta\)-Ga$_2$O$_3$ heterostructure (a) Sample A (27% - Al) (b) Sample B (29 % - Al). Incident X-ray has both Kα1 and Kα2 wavelengths.
Low temperature capacitance-voltage extracted apparent charge density

![Capacitance-voltage data](image)

Fig.S3 Capacitance-voltage data of a) sample A and b) Sample B measured at 300 K and 77 K. Apparent charge density profile extracted from capacitance-voltage measurements at 77 K and 300 K (c) Sample A (d) Sample B

CV measurements of the β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/β-Ga\textsubscript{2}O\textsubscript{3} heterostructure revealed no significant difference upon going from 300 K to 77 K. However, low temperature hall measurements clearly showed carrier freeze out. This discrepancy can be explained by understanding that CV extracted charge density doesn’t follow the actual carrier profile at 77 K. Instead, CV measures the apparent charge profile (donor density), leading to observation of high apparent charge density at 77 K, whereas, Hall measurement can only measure free carriers present in the β-(Al\textsubscript{x}Ga\textsubscript{1-x})\textsubscript{2}O\textsubscript{3}/β-Ga\textsubscript{2}O\textsubscript{3} channel layer. It should be noted that the amount of ionization of the donors also change with reverse bias, further complicating the interpretation of CV measurements.