

Recent Progress in Source/Drain Ohmic Contact with β -Ga₂O₃

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Abstract: β -Ga₂O₃, with excellent bandgap, breakdown field, and thermal stability properties, is considered to be one of the most promising candidates for power devices including field-effect transistors (FETs) and for other applications such as Schottky barrier diodes (SBDs) and solar-blind ultraviolet photodetectors. Ohmic contact is one of the key steps in the β -Ga₂O₃ device fabrication process for power applications. Ohmic contact techniques have been developed in recent years, and they are summarized in this review. First, the basic theory of metal–semiconductor contact is introduced. After that, the representative literature related to Ohmic contact with β -Ga₂O₃ is summarized and analyzed, including the electrical properties, interface microstructure, Ohmic contact formation mechanism, and contact reliability. In addition, the promising alternative schemes, including novel annealing techniques and Au-free contact materials, which are compatible with the CMOS process, are discussed. This review will help our theoretical understanding of Ohmic contact in β -Ga₂O₃ devices as well as the development trends of Ohmic contact schemes.

Keywords: β -Ga₂O₃; Ohmic contact; ion implantation; interface; annealing temperature



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1. Introduction

Si-based devices are the dominant devices used for power applications. However, with the increasing demand for much faster and more convenient network communication, Si-based device techniques cannot meet these requirements due to their physical properties. Thus, new-material devices should be investigated for operating at high temperatures, at high power, and in harsh environments. In recent years, wide-bandgap semiconductors including GaN (3.4 eV) and SiC (3.25 eV) have been developed, and they have replaced Si-based techniques in many fields due to their advantages in terms of their material properties [1–5]. Recently, β -Ga₂O₃, which is mostly thermally and chemically stable in five polymorphs [6–8], has attracted more and more attention for power applications because β -Ga₂O₃ has a wide bandgap of 4.6–4.9 eV and a breakdown field strength as high as 8 MV/cm [9–11]. In addition, for the Baliga figure and Johnson’s figure of merit, when evaluating its application potential in power devices, β -Ga₂O₃ exhibits the best performance [9–11]. The basic physical properties and figures of merit (FOM) of commonly used semiconductor materials are shown in Table 1. For this reason, researchers have obtained plenty of results related to β -Ga₂O₃-based FETs [12–14], SBDs [15–18], and solar-blind ultraviolet photodetectors [19–21]. In 2023, Wang et al. [13] demonstrated a metal–heterojunction composite field-effect transistor that exhibited a breakdown voltage (BV) of around 2160 V. In addition, the corresponding $R_{ON,SP}$ was 6.35 m Ω ·cm². So far, the power figure of merit (P-FOM) achieved the highest value of 0.73 GW/cm² for e-mode β -Ga₂O₃ devices. For SBDs, Hao et al. [17] used an optimized p-type NiO (with a hole

concentration of 10^{17} cm^{-3}) junction-termination extension (JTE) technique that exhibited a BV and $R_{\text{ON,SP}}$ of 2.11 kV and $2.9 \text{ m}\Omega\cdot\text{cm}^2$, respectively. For this reason, the P-FOM was as high as $1.54 \text{ GW}/\text{cm}^2$. For the junction barrier Schottky (JBS) diode, Wu et al. [18] fabricated a device with a well-designed field plate to suppress the crowding effect of the electric field. The forward current and BV could reach 5.1 A and 1060 V, respectively. At the circuit level, the hybrid circuit exhibited more efficiency compared with the Si-based one. An R_{ON} -BV benchmark comparison of $\beta\text{-Ga}_2\text{O}_3$ -based devices with other published results was also presented in their work. The R_{ON} -BV characteristics for $\beta\text{-Ga}_2\text{O}_3$ -based devices were comparable with GaN-based ones [22]. To fully exploit $\beta\text{-Ga}_2\text{O}_3$'s potential in power electronics applications, the material quality, device structure, and process details should be further optimized. By embedding indium tin oxide (ITO) electrodes, Zhang et al. [19] fabricated a fully transparent MSM-structured solar-blind UV photodetector with an excellent dark current, normalized photocurrent-to-dark-current ratio (NPDR), responsivity, rejection ratio, and specific detectivity characteristics. Another advantage of $\beta\text{-Ga}_2\text{O}_3$ material is that single large $\beta\text{-Ga}_2\text{O}_3$ crystals can be cost-effectively mass produced using melt-growth methods, such as EFG [23], FZ [24,25], VB [26,27], and CZ [28,29] methods. Additionally, a high-quality $\beta\text{-Ga}_2\text{O}_3$ epilayer can be realized using MOCVD [30,31], MBE [32,33], HVPE [34,35], and MOVPE [36,37] methods to form a well-controlled n-type doping using Si, Ge, and Sn. However, the p-type doping technique is still challenging because the activation energy of the acceptors and the self-trapping energy of the holes are large [38,39]. For the purpose of achieving p-type Ga_2O_3 , great efforts have been taken by researchers from all over the world [40–51].

Table 1. Physical properties and FOMs of the commonly used semiconductors.

Parameters	Si	GaAs	4H-SiC	GaN	$\beta\text{-Ga}_2\text{O}_3$
Bandgap, E_G (eV)	1.12	1.43	3.25	3.4	4.6–4.9
Breakdown field, E_{br} (MV/cm)	0.3	0.4	2.5	3.3	8
Electron mobility, μ ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)	1480	8400	1000	2000 (2DEG)	300
Saturation velocity, V_s (10^7 cm/s)	1	1.2	2	2.5	1.8–2
BFOM, $\epsilon\mu E_{br}^3$	1	14.7	317	846	2000–3000
JFOM, $E_{br}^2 V_s^2 / (4\pi^2)$	1	1.8	278	1089	2844

For power applications, Ohmic contact is one of the key steps in $\beta\text{-Ga}_2\text{O}_3$ device fabrication processes. Ohmic contact resistance (R_C), specific contact resistance (ρ_c), and thermal stability are important indexes of contact quality. A lower R_C can reduce voltage drop across the contact region and power loss. For GaN-based devices, Au-free low-temperature Ohmic contact techniques are proposed to realize CMOS-compatible and gate-first techniques [52,53]. Until now, because of the wide-bandgap property of $\beta\text{-Ga}_2\text{O}_3$ and Fermi-level pinning [54–56], Ohmic contact methods for Ga_2O_3 -based devices have remained challenging. The metal schemes, annealing conditions (the annealing temperature, durations, and atmosphere), and doping concentration of Ga_2O_3 have been investigated and optimized to obtain low- R_C contact. In this review, we will first give a brief introduction of metal–semiconductor contact theory. After that, the state-of-the-art advances in Ohmic contact techniques for $\beta\text{-Ga}_2\text{O}_3$ will be presented and discussed, including metal electrodes, surface treatments, ion implantation, epitaxial regrowth, and adding an interlayer. Finally, we will give some perspectives for further studies on Ohmic contact with $\beta\text{-Ga}_2\text{O}_3$ in the future.

2. Basic Metal– Ga_2O_3 Contact Physical Theory

Metal–semiconductor contact is a critical part of $\beta\text{-Ga}_2\text{O}_3$ power devices. A device's performance is mainly limited by the Ohmic contact property. Two types of contacts (Schottky and Ohmic) can be formed due to the differences in the work functions of contact metals [57–59]. For wide-bandgap $\beta\text{-Ga}_2\text{O}_3$, the contacts always exhibit Schottky behavior. When metal and Ga_2O_3 come into contact, the energy band of the Ga_2O_3 side bends up to

make their Fermi levels equal. As shown in Figure 1a, the Schottky barrier height from the metal side (Φ_B) can be described as

$$\Phi_B = \Phi_m - \chi,$$

where χ represents the semiconductor's electron affinity (4 eV for Ga₂O₃ in our case [60]) and Φ_m represents the metal work function. Therefore, it is desirable to select a metal with a Φ_m lower than 4 eV to realize a negative Φ_B , which allows electrons to flow freely across it to form an Ohmic contact. Unfortunately, the lack of suitable metal materials with lower work functions makes Ohmic contact formation challenging. Generally, researchers have proposed Ohmic contact schemes to form a lower Φ_B or an n⁺-doped Ga₂O₃ region for electron tunneling. When a semiconductor is heavily doped ($N_D > 10^{18} \text{ cm}^{-3}$), field emission (FE) dominates the electron tunneling [61,62]. In order to obtain a low R_C or ρ_c , a higher N_D is expected.

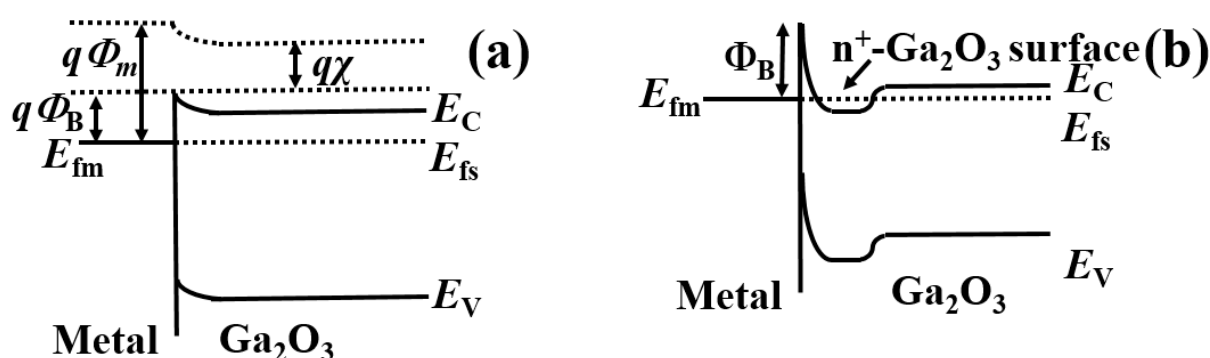


Figure 1. Energy-band diagrams of metal–Ga₂O₃ Schottky contacts with (a) a lower Φ_{bm} and (b) an n⁺-doped Ga₂O₃ region.

The Ohmic contact resistance (R_C , measured in $\Omega \cdot \text{mm}$) and specific contact resistance (ρ_c , measured in $\Omega \cdot \text{cm}^{-2}$) are always determined using the transmission line model (TLM) method [63,64]. Details concerning the TLM measurement technique can be seen in the references mentioned above.

The metal work function, metal schemes, interfacial reactions between metal and a semiconductor during the annealing process, and the doping concentration of Ga₂O₃ in the source/drain region are significant influencing factors for the Ohmic contact property. Until now, researchers from universities and research institutes have proposed Ohmic contact schemes involving optimizing the metal materials, annealing condition, source/drain doping method and concentration, and source/drain etching as well as adding an interlayer in the source/drain region.

3. Approaches to Metal–Ga₂O₃ Ohmic Contact

3.1. Metal Electrode

From the metal–semiconductor contact theory, the work function of the selected metal material crucially affects the Ohmic contact quality. Thus, in the early period, Yao et al. [65] investigated the Ohmic contact properties and surface morphologies of nine metal materials, including Ti, In, Ag, Sn, W, Mo, Sc, Zn, and Zr with Sn-doped (201) β -Ga₂O₃. From their results, the work function is not the main factor influencing the contact quality. Sc, with the lowest work function, cannot form Ohmic contacts under different annealing conditions. Ti/Au metal schemes with a 400 °C annealing process exhibited the lowest R_C values. Cross-sectional transmission electron microscopy (TEM) and energy-dispersive X-ray spectroscopy (EDX) mapping showed that Ga and O diffused into the Ti layer during the annealing process. They concluded that interfacial reactions during the annealing process played a crucial part in Ohmic contact formation. Otherwise, the

ultra-wide bandgap property leads to a pinning effect due to defects and surface states that lie in the mid-gap, which are not beneficial for forming an Ohmic contact.

Other groups have reported Mg/Au and Cr/Au metal schemes for Ohmic contact formation [66,67]. In the Mg (3.66 eV)/Au method, the ρ_c of $2.2 \times 10^{-4} \sim 2.1 \times 10^{-5} \Omega \cdot \text{cm}^{-2}$ was achieved with an annealing process at temperatures varying from 300 °C to 500 °C. Until now, the most common metallization schemes of Ohmic contact for $\beta\text{-Ga}_2\text{O}_3$ have used Ti/Au. Ti is used as an adhesion layer with a low work function. Au serves as a cap layer to prevent the oxidation of metal stacks during the high-temperature process. For the purpose of understanding the mechanism, Lee et al. [68] deposited Ti/Au (20/80 nm) on a Sn-doped $\beta\text{-Ga}_2\text{O}_3$ (010) substrate and carried out a 470 °C rapid thermal annealing (RTA) process for 1 min to form an Ohmic contact. Scanning transmission electron microscopy (STEM), high-resolution transmission electron microscopy (HRTEM), and EDX measurements were taken to understand the interfacial reactions and components. They found that a defective $\beta\text{-Ga}_2\text{O}_3$ layer (3–5 nm), a Ti-TiO_x layer (3–5 nm), and an intermixed Au-Ti layer containing Ti-rich nanocrystalline inclusions were formed sequentially, as shown in Figure 2. They deduced that the Ti-TiO_x layer (3–5 nm) with a small bandgap could provide an efficient path for the electron flow. In addition, the lattice matching between the defective $\beta\text{-Ga}_2\text{O}_3$ layer and the $\beta\text{-Ga}_2\text{O}_3$ substrate could enhance the carrier mobility by reducing the collision probability, resulting in a lower R_c . Before this work, Higashiwaki et al. [69] showed TEM results for an interface and deduced that interface reactions help improve contact quality.

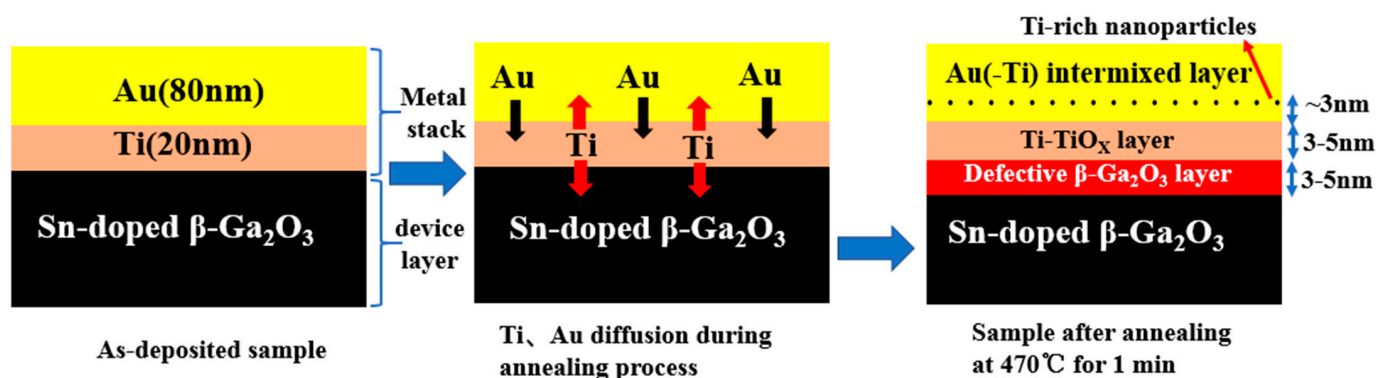


Figure 2. Schematic illustrations of Ti/Au metallization layers on Sn-doped $\beta\text{-Ga}_2\text{O}_3$ with a 1 min 470 °C N₂ annealing process. Reproduced from Ref. [68].

Also, multilayer metal contact schemes were proposed for obtaining lower R_c values, such as Ti/Al/Au [70,71], Ti/Al/Ni/Au [72,73], and Ti/Au/Ni [32,33]. As can be seen in Figure 3, Krishnamoorthy et al. formed a δ -doped $\beta\text{-Ga}_2\text{O}_3$ structure in the source/drain region to form a heavily doped contact area. After Ti/Au/Ni deposition, a 470 °C RTA process was employed for 1 min for Ohmic contact formation. The extracted R_c and ρ_c were 0.35 $\Omega \cdot \text{mm}$ and $4.3 \times 10^{-6} \Omega \cdot \text{cm}^{-2}$, respectively. In addition, the fabricated $\beta\text{-Ga}_2\text{O}_3$ FET exhibited excellent I_D and g_m results. By using Ti/Al/Au contact metals, Zhou et al. [71] achieved a low R_c of 0.75 $\Omega \cdot \text{mm}$ by adopting a highly Sn-doped channel. For AlGaN/GaN HEMT, Ti/Al/Ni/Au is one of the most mature metal schemes for Ohmic contact formation [74,75]. For $\beta\text{-Ga}_2\text{O}_3$ devices, Chen et al. [73] deposited Ti/Al/Ni/Au multilayer metal stacks and carried out an RTA process with the temperature at 470 °C for 70 s. By analyzing the X-ray photoelectron spectroscopy (XPS) results, as shown in Figure 4, they concluded that the use of Al can lead to the formation of a Ti-Al phase with a low work function, which is beneficial for oxygen vacancy generation at the interface. In n-type $\beta\text{-Ga}_2\text{O}_3$, the vacancies act as donors, enhancing the electron flow and realized Ohmic contact.

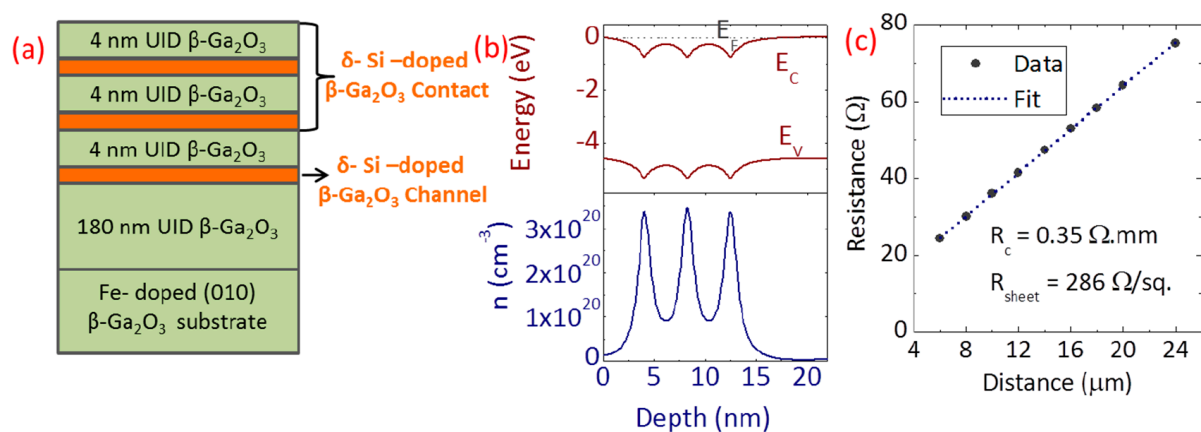


Figure 3. (a) Device structure, (b) equilibrium band diagram and charge profile, and (c) TLM results. Reproduced from Ref. [33].

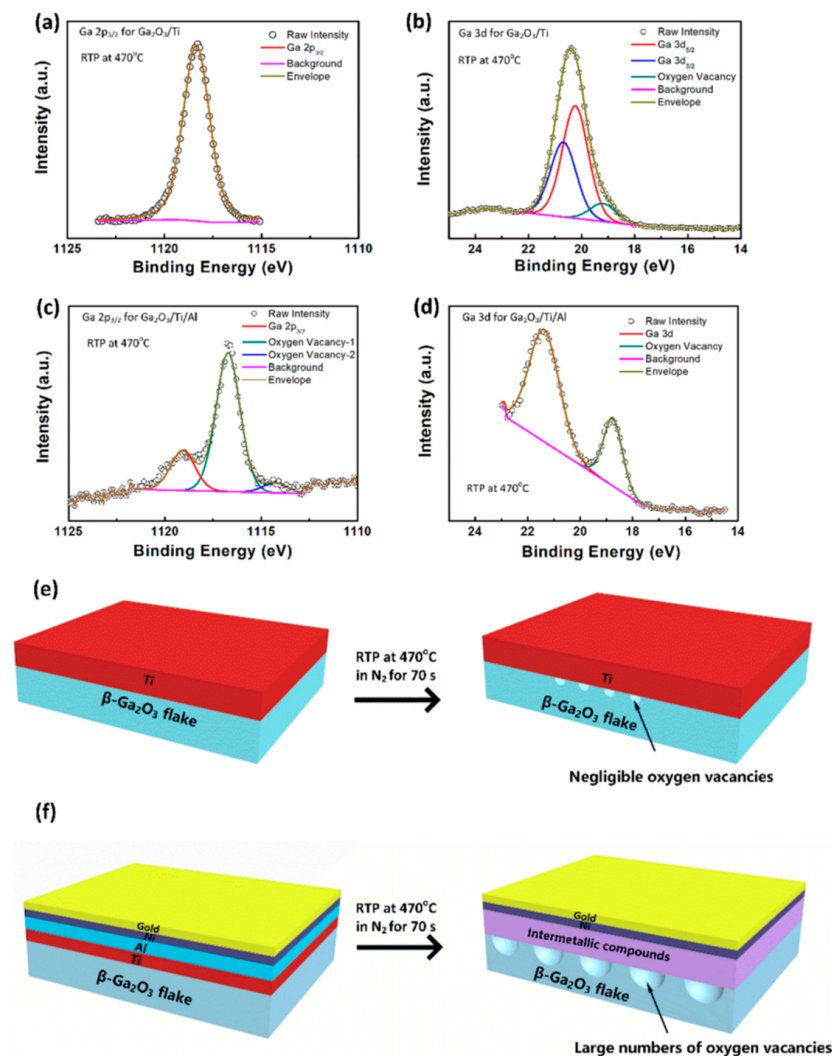


Figure 4. XPS results of (a) Ga 2p_{3/2} and (b) Ga 3d core-level spectra from the Ti-coated (~2.5 nm) β-Ga₂O₃ sample. (c) Ga 2p_{3/2} and (d) Ga 3d core-level spectra for the Ti/Al-coated (2/2 nm) β-Ga₂O₃ sample. (e) Schematic diagram of the role of Ti in the generation of oxygen vacancies. (f) Schematic of the formation process of oxygen vacancies at the interface of β-Ga₂O₃ and metal. Reproduced from Ref. [73].

In 2022, Tetzner et al. [76] used a TiW alloy instead of the traditional Ti/Au metal schemes, and a low ρ_c of $1.5 \times 10^{-5} \Omega \cdot \text{cm}^{-2}$ was extracted after a 700 °C RTA process. The temperature was 200 °C higher than that of the Ti/Au schemes. To understand the Ohmic contact formation mechanism, STEM HAADF and EDX were employed. The STEM HAADF image showed that a 3–5 nm TiO_x interlayer was formed, which was confirmed with the STEM EDX. They suspected that vacancies, defects, or Ga impurities that exist in the interlayer are beneficial for electrons flowing freely to reduce the R_C .

Thermal stability is another important index of contact quality. For Ti/Au electrodes, the most commonly used annealing temperatures are between 400 °C to 500 °C. Above 500 °C, Yao et al. [65] found that the Ohmic contacts degraded in their results. In 2022, Lee et al. [77] systematically investigated the influence of temperature on Ohmic contact quality. In their results, when the annealing temperature increased from 470 °C to 520 °C, aggressive Au diffused into the interface and reacted with Ga that diffused out, resulting in a much thicker Ti– TiO_x layer due to GaAu_2 formation, which accounted for the contact degradation. In Kim's [78] results, the R_C increased when the temperature changed from 400 °C to 500 °C or 600 °C. They deduced that this could have been due to an increased amount of Ti oxide. Related investigations have also been conducted and reported [79–81]. Therefore, more research into interfacial reactions for Ti/Au schemes and alternative metallization schemes, including Au-free electrodes, should be proposed to solve the instability issue of the Ti/ $\beta\text{-Ga}_2\text{O}_3$ interface using Ti/Au metal schemes. It should be noted that excellent Ohmic contact cannot be achieved just by selecting metal materials. Combined with other techniques, including surface treatment, ion implantation, epitaxial regrowth, adding an interlayer, etc., the contact quality can be improved and optimized.

3.2. Surface Treatment

A surface treatment before metal deposition can also help improve the Ohmic contact property (dry etching, plasma bombardment, etc.). In 2012, Higashiwaki et al. [82] compared the I–V results of Ga_2O_3 devices with and without the RIE treatment. The RIE process was implemented by using a BCl_3/Ar mixing gas for 1 min before Ti/Au (20/230 nm) deposition. The samples with the RIE treatment exhibited Ohmic contact characteristics, while without the RIE process the samples showed Schottky contact features. They speculated that the Ohmic contact formation was due to the large number of oxygen-vacancy surface defects formed during the RIE process. The defects acted as donors for Ohmic contact realization. Combined with Si ion implantation [83], they achieved a ρ_c of $4.6 \times 10^{-6} \Omega \cdot \text{cm}^{-2}$ with a doping concentration of $5 \times 10^{19} \text{ cm}^{-3}$. In addition, Zhou et al. [70] performed an Ar plasma bombardment process and optimized the duration of 30 s for generating oxygen vacancies, which are good for n-type surface doping. The mechanism was similar to that of the BCl_3/Ar RIE process. The R_C values in their results were as low as $0.95 \Omega \cdot \text{mm}$. Related results have also been reported by other groups [33,69,71,84–86].

Also, the annealing temperature and atmosphere may affect the interfacial reactions that dominate Ohmic contact formation. Bae et al. [87] compared the electrical results of the fabricated $\beta\text{-Ga}_2\text{O}_3$ nanobelts under different atmospheres with various temperatures. The samples treated under a N_2 atmosphere exhibited better characteristics than the ones treated in an air environment. Under an Ar atmosphere, Li et al. [88] reduced the R_C to $0.387 \Omega \cdot \text{mm}$ by optimizing the annealing temperature and the durations. In their results, a large drain current density of $\sim 3.1 \text{ mA}/\mu\text{m}$ ($V_{ds} = 100 \text{ V}$) was achieved due to the low R_C . To fully understand the influence of an Ar atmosphere on improving the $\beta\text{-Ga}_2\text{O}_3$ device's I–V characteristics, XPS was used to show the material changes during the RTA process. From the results, as can be seen in Figure 5, they deduced that Ti reduced $\beta\text{-Ga}_2\text{O}_3$ and generated large numbers of oxygen vacancies at the interface during the annealing process, which served as effective electron donors. For this reason, the depletion layer was narrower, resulting in Ohmic behavior and a low R_C for $\beta\text{-Ga}_2\text{O}_3$ FETs. The annealing temperature is another element that affects the interface reactions to determine the Ohmic contact property. In 2022, Lee et al. [77] systematically investigated the influence of temperature (from 370 °C

to 520 °C) on the Ohmic contact property. The lowest R_C occurred when temperature was 420 °C. When the temperature increased, the R_C increased as well. To investigate the reason for the degradation of the R_C with an increasing temperature, cross-sectional S/TEM was employed for a sample with an annealing temperature of 520 °C. Their results show that the thickness of the Ti-TiO_x layer (25–30 nm) increased due to the formation of GaAu₂ inclusions, which was caused by Au aggressively diffusing in and its reaction with Ga that had diffused out. In their early results [68], a thin Ti-TiO_x layer was beneficial for electron transport. The degradation of contact quality was the result of the increasing Ti-TiO_x layer thickness. Also, in earlier results, the degradation of contact characteristics was observed when the annealing process was performed above 500 °C [65]. Yao et al. speculated that Ti reduces Ga₂O₃, possibly forming an insulating oxide layer at the interface, which would account for the Ohmic contact degradation. In their results, the optimized annealing temperature was 400 °C, which achieved the lowest R_C value.

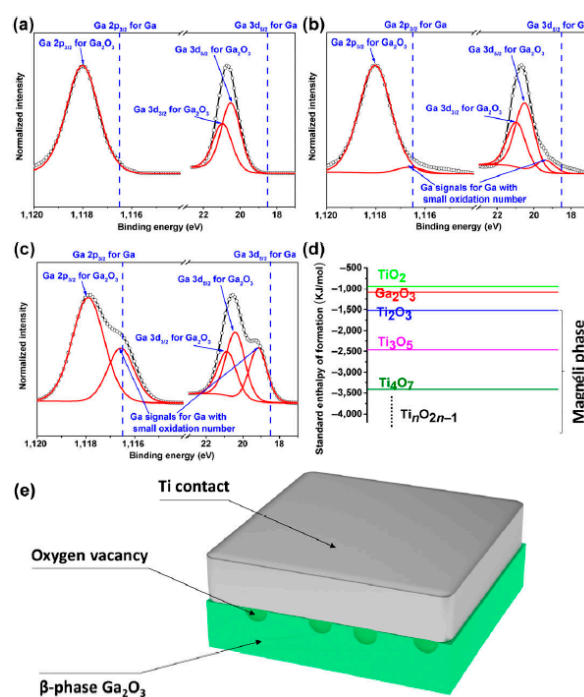


Figure 5. XPS results from β -Ga₂O₃. (a) Normalized Ga 2p_{3/2} XPS spectra and Ga 3d XPS spectra from pure β -Ga₂O₃, (b) β -Ga₂O₃ after annealing in argon at 300 °C for 180 min, and (c) Ti-coated (1 nm) β -Ga₂O₃ after annealing in argon at 300 °C for 180 min. Black dots show experimental data, and red curves show simulated fitting curves. (d) Free energy scheme of different metal oxides. (e) Schematic diagram of the proposed oxygen vacancy model at the Ti/ β -Ga₂O₃ interface. Reproduced from Ref. [88].

Surface treatment, including BCl₃/Ar RIE and Ar plasma bombardment, before metal deposition can help to reduce the R_C to a degree. During these processes, the accelerated high-energy ions react with Ga₂O₃ via physical and chemical methods, creating defects to form a highly damaged surface, which enables high recombination rates. However, excellent Ohmic contact cannot be achieved only using such methods. Techniques, including RIE, ion implantation, RTA, etc., are always used together to improve the Ohmic contact quality. In addition, the RIE technique is not always reproducible or practically applicable due to the undesired damage induced during semiconductor processing.

3.3. Ion Implantation

The ion-implantation doping technique (including Si, Sn, etc.) is another effective way for Ga₂O₃ to realize low-contact-resistance Ohmic electrodes by forming a heavily doped n⁺ region that facilitates electron flow. In 2013, Sasaki et al. [83] successfully fabricated Ohmic

electrodes with a low contact resistance via Si implantation, which requires the MOVPE method in β -Ga₂O₃. They optimized the Si doping concentration to $5 \times 10^{19} \text{ cm}^{-3}$, which was activated by annealing at a temperature of 950 °C. The R_C and ρ_c in their results were as low as $1.4 \text{ m}\Omega\cdot\text{cm}$ and $4.6 \times 10^{-6} \Omega\cdot\text{cm}^{-2}$, respectively. In other results, Zhou et al. [70] doped β -Ga₂O₃ with Sn at a concentration of $2.7 \times 10^{18} \text{ cm}^{-3}$. Combined with Ar plasma bombardment, the R_C was dramatically reduced to $0.95 \Omega\cdot\text{mm}$. The fabricated devices also exhibited an excellent on/off ratio and output characteristics and a low SS value. In addition, Ge and Sn were also studied for doping β -Ga₂O₃ [89]. In that study, the samples were treated under the same annealing condition (925 °C for 30 min). The efficiencies of Sn, Ge, and Si were calculated to be 28.2%, 40.3%, and 64.7%, respectively, using SIMS measurements. The same activation annealing condition for Ge and Sn with Si resulted in low activation efficiencies for Ge and Sn. The heavier Ge and Sn ions also created more implant damage than the Si ions due to the greater momentum transfer required to achieve the same implant depth, likely contributing to decreased implant activation and increasing both the contact and sheet resistances. In 2023, Tetzner et al. [90] analyzed the optimized annealing temperature for the activation of Ge-implanted β -Ga₂O₃ from 900 to 1200 °C using a pulsed RTA technique. The lowest recorded ρ_c value of $4.8 \times 10^{-7} \Omega\cdot\text{cm}^{-2}$ was achieved after a pulsed RTA at 1100 °C using 40 pulses. The activation efficiency was 14.2%. The measured R_C and ρ_c values at various annealing temperatures can be seen in Figure 6. Also, other representative studies related to the ion implantation technique have been reported [91–94].

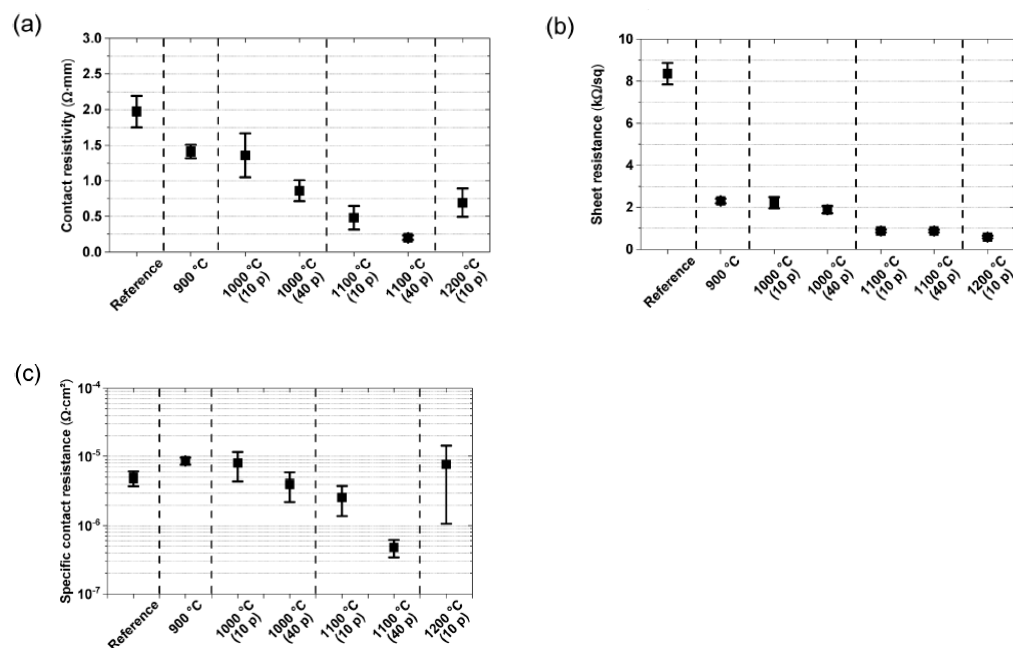


Figure 6. Measured contact resistivity (a), R_C (b), and specific contact resistance (c) as a function of the annealing conditions. Reproduced from Ref. [90].

Considering the high cost of ion implantation, the complicated steps, and the potential damage-induced diffusion of species, Zeng et al. [95] successfully proposed a Sn spin-on-glass (SOG) technique for β -Ga₂O₃ doping. A Sn-doped epitaxial layer with a doping density of $1 \times 10^{18} \text{ cm}^{-3}$ was formed on a Ga₂O₃ substrate. The obtained ρ_c was determined to be $2.1 \pm 1.4 \times 10^{-5} \Omega\cdot\text{cm}^{-2}$ in their results. As shown in Figure 7, the fabricated devices also exhibited improved output current, peak transconductance, on/off ratio, and breakdown voltage values. The SOG technique is an effective alternative to the simple, low-cost doping technique to make low- R_C Ohmic contact. Thus, based on the existing results using doping techniques, it is possible to form a heavily doped Ga₂O₃ layer and obtain ρ_c values from 10^{-5} to $10^{-7} \Omega\cdot\text{cm}^{-2}$.

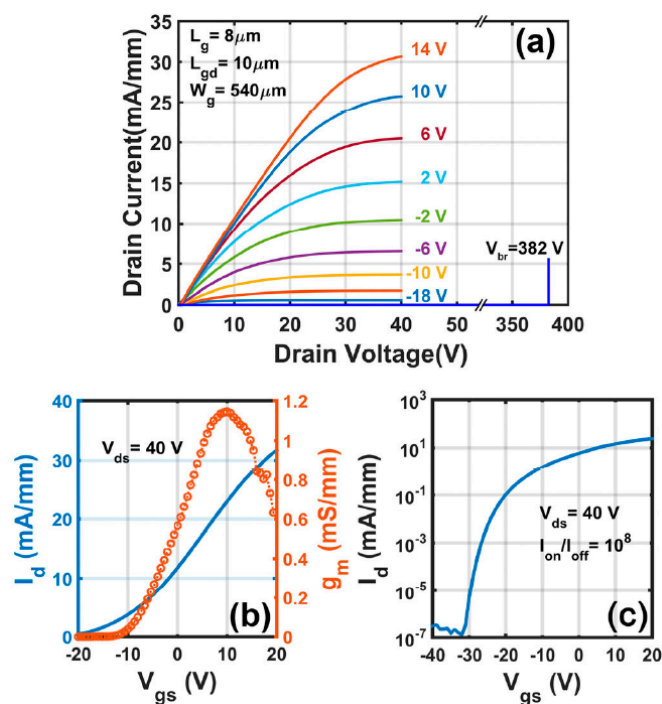


Figure 7. (a) Output characteristics of the SOG-doped MOSFET and (b,c) linear and log-scale transfer characteristics of the same device. Reproduced from Ref. [95].

Ion implantation, surface treatment, and post-RTA annealing are always used together to obtain a low R_C . Ion implantation can form a heavily doped interface to enhance electron tunneling. A surface treatment combined with RTA can generate oxygen vacancies that act as donors in Ga_2O_3 , resulting in a low R_C . For ion implantation, a high-temperature post-anneal is required to activate the implanted donor impurity and recover the induced crystalline damage. During the high-temperature process, dopant redistribution, residuals, crystalline defects, and incomplete activation should be noticed and optimized.

3.4. Epitaxial Regrowth

To further reduce the contact resistance, regrown contacts have been reported to fabricate Ohmic contacts. Ion implantation and spin-on-glass techniques need a high annealing temperature around 900–1200 °C and potentially deteriorate the material quality in the active region. However, the regrowth process, which is performed at a much lower temperature of about 600 °C can avoid this potential problem. In 2018, Xia et al. [32] used a molecular-beam epitaxy (MBE) method to form a heavily doped n-type Ga_2O_3 with a doping concentration of $2 \times 10^{20} \text{ cm}^{-3}$. The device's structure can be seen in Figure 8. An extracted R_C of $1.5 \Omega\text{-mm}$ was obtained from the TLM structure. The regrowth technique avoids gate recessing and potential damage associated with etching, which may degrade the carrier mobility. The fabricated devices exhibited a peak drain current of 140 mA/mm and an excellent transconductance of 34 mS/mm. Considering the advantage of high room-temperature electron mobility values (close to the theoretical limit) grown using metalorganic vapor phase epitaxy (MOVPE), Bhattacharyya et al. [36] proposed an MOVPE epitaxy approach to realize low-resistance regrown S/D contacts in a Ga_2O_3 lateral MESFET for the first time. As shown in Figure 9, the heavily Si-doped ($\sim 1.8 \times 10^{20} \text{ cm}^{-3}$) Ga_2O_3 was grown using MOVPE at a relatively low temperature of 600 °C. After that, an Ohmic metal stack of Ti/Au/Ni (20 nm/100 nm/30 nm) was evaporated, followed by 470 °C annealing in N_2 . From their testing results, an ultralow R_C of $80 \text{ m}\Omega\text{-mm}$ and a ρ_c of $8.3 \times 10^{-7} \Omega\text{-cm}^{-2}$ were achieved. In order to systematically study the mechanism of heavily doped $\beta\text{-Ga}_2\text{O}_3$ using MOVPE to achieve low contact resistance, in 2022 Alema et al. [96] optimized the doping concentration to $3.23 \times 10^{20} \text{ cm}^{-3}$, and the R_C and ρ_c values

were as low as $1.62 \times 10^{-7} \Omega \cdot \text{cm}^{-2}$ and $0.023 \Omega \cdot \text{mm}$. The ultralow contact characteristics had a significant impact, improving the RF devices' performance.

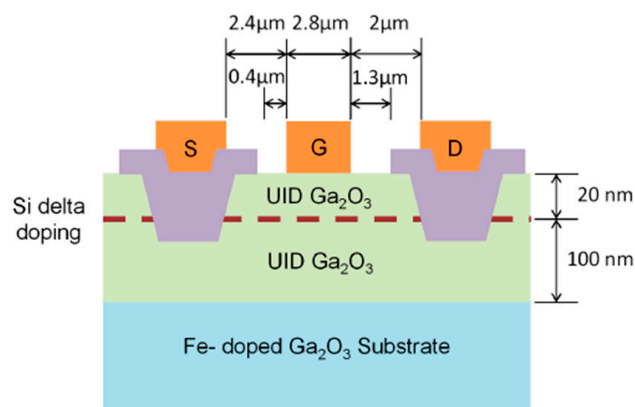


Figure 8. Device schematic of delta-doped $\beta\text{-Ga}_2\text{O}_3$ MESFET. Reproduced from Ref. [32].

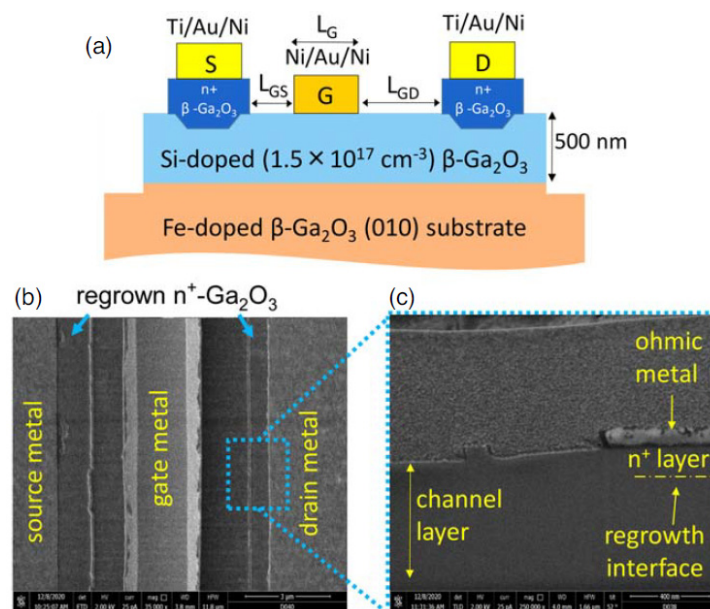


Figure 9. (a) Schematic of the fully MOVPE-grown Ga_2O_3 MESFET with regrown Ohmic contacts. (b) Top-view SEM image of the MESFET showing the regrown access regions. (c) Cross-sectional SEM image of the contact region showing the estimated regrowth interface. Reproduced from Ref. [36].

The existing results that have been reported in recent years demonstrate that regrown contact is an effective approach to achieve an ultralow R_C . Epitaxial regrowth obtains a high-quality crystalline film and can be versatile. However, there are also several constraints, such as low throughput, high expense, strict material compatibility, and the need for selective growth or subsequent etchings, as mentioned in Refs. [97,98].

3.5. Adding the Interlayer

The Ti/Au schemes always form a 3–5 nm interlayer, which facilitates electron transport for Ohmic contact formation. Another approach is inserting an intermediate semiconductor layer (ISL) with a low work function and a narrower bandgap. In 2016, Oshima et al. [99] proved the insertion of indium tin oxide (ITO) for forming Ohmic contact with $\beta\text{-Ga}_2\text{O}_3$. In their results, as shown in Figure 10, the ITO method exhibited Ohmic behavior at temperatures from 900 °C to 1150 °C. However, Pt/ $\beta\text{-Ga}_2\text{O}_3$ maintained Schottky contact, even at the RTA temperature of 500 °C. They also confirmed the existence of an intermediate semiconductor layer (ISL) at the interface using TEM and EDS analyses.

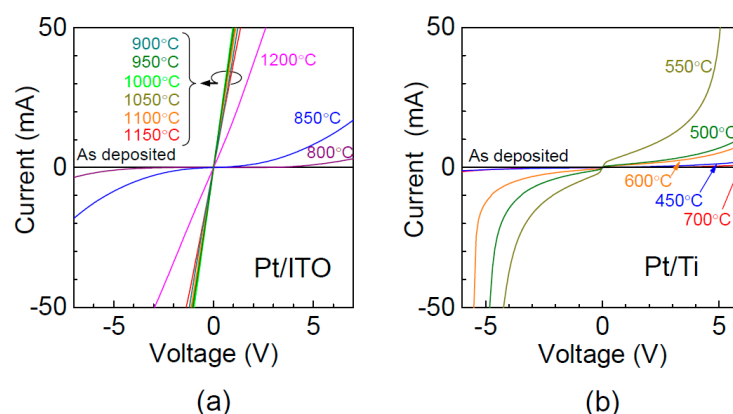


Figure 10. Typical I–V characteristics of (a) Pt/ITO and (b) Pt/Ti electrodes annealed at various temperatures. Reproduced from Ref. [99].

In 2017, considering the excellent conductivity property of ITO, by depositing an ITO layer before the metal deposition, Carey et al. created a Au/Ti/ITO/Si-doped Ga₂O₃ structure to form low- R_C contact. As shown in Figure 11, by optimizing the annealing temperature at 600 °C, the minimum R_C and ρ_c were determined to be 0.6 $\Omega \cdot \text{mm}$ and $6.3 \times 10^{-5} \Omega \cdot \text{cm}^{-2}$. A schematic of the band offset for Au/Ti/ITO on Ga₂O₃ and Au/Ti on Ga₂O₃ can be seen in Figure 12 [100]. The insertion of an ITO interlayer allows for reduced conduction band discontinuity between Ti and Ga₂O₃, which is beneficial for reducing R_C values. By inserting an aluminum zinc oxide (AZO) interlayer [101], Au/Ti/AZO/Ga₂O₃ schemes exhibit the minimum R_C and specific contact resistance values of 0.42 $\Omega \cdot \text{mm}$ and $2.82 \times 10^{-5} \text{ cm}^{-2}$, respectively. The optimized annealing temperature is 400 °C, as shown in Figure 13. In their results, samples without an AZO interlayer did not exhibit Ohmic I–V characteristics when varying the annealing temperature. The use of a thin layer of AZO, with a bandgap of 3.2 eV, can lower the barrier for electron transport and achieve a low R_C . A corresponding schematic of the band offset for AZO on Ga₂O₃ can be seen in Figure 14. Other related results have also been presented by other researchers [102–105]. It should be noted that different metal layers capping ITO layers are needed to prevent the degradation of the surface morphology.

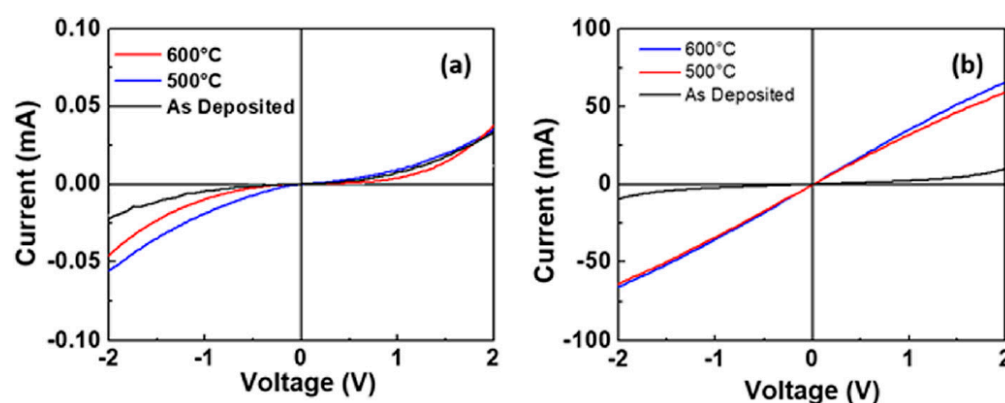


Figure 11. I–V curves of (a) Au/Ti/Ga₂O₃ and (b) Au/Ti/ITO/Ga₂O₃ contact stacks as a function of annealing temperature. Reproduced from Ref. [100].

Other elements such as substrate orientation have also been reported to influence the Ohmic contact property. To form Ohmic contact, Ti/Au contacts were deposited, followed by an RTA process at 450 °C for 5 min, which was employed on both ($\bar{2}01$) and (010) Sn-doped Ga₂O₃. The former sample exhibited Ohmic characteristics compared to the rectifying behavior of the (010) sample. Related content has also been investigated and reported by other groups [106–109].

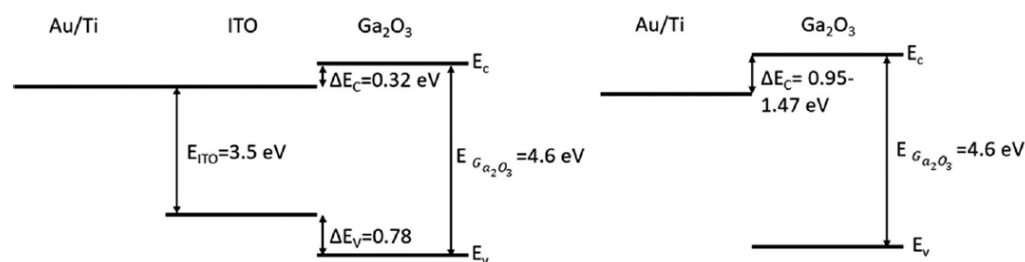


Figure 12. Schematics of band offset for Au/Ti/ITO on Ga₂O₃ and Au/Ti on Ga₂O₃. Reproduced from Ref. [100].

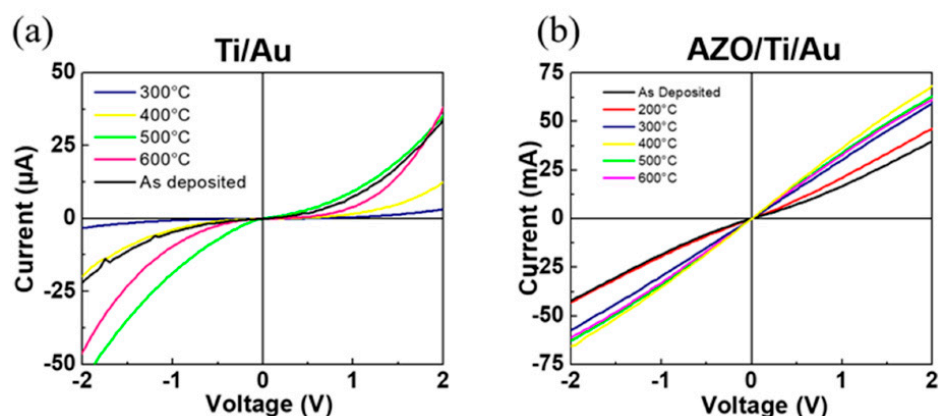


Figure 13. I–V curves of (a) Au/Ti/Ga₂O₃ and (b) Au/Ti/AZO/Ga₂O₃ contact stacks as a function of annealing temperature from as-deposited samples (black lines) to 600 °C (purple lines). The 200 °C data were similar to those of the as-deposited samples, and the contact resistance decreased with temperature in the AZO-based contacts. Reproduced from Ref. [101].

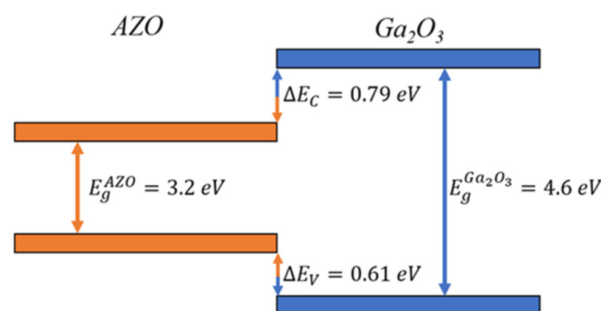


Figure 14. Schematic of band offset for AZO on Ga₂O₃. Reproduced from Ref. [101].

In recent years, researchers have investigated and optimized the Ohmic contact property of β -Ga₂O₃ by choosing a metal with a proper work function and investigating metal schemes, interfacial reactions between metal and semiconductors during the annealing process, and the doping concentration of Ga₂O₃ in the source/drain region, and they have achieved excellent results. Representative results with excellent Ohmic contact quality are summarized in Figure 15 [32,33,36,37,70,83,88,90,96,100]. Despite the significant improvement in the Ohmic contact techniques for β -Ga₂O₃, there are also some questions that need to be solved before commercializing the devices. (1) For power device applications, contact performance in high-temperature, -current, and -voltage environments is another concern. Failure analyses of the electrical stress/cycling of Ohmic electrodes have been investigated for other WBG semiconductor systems [110–112], while for β -Ga₂O₃, the research is lacking and efforts should be made to understand the degradation mechanism of Ohmic contacts under electrical stress. (2) To realize the integration of β -Ga₂O₃ semiconductors into Si CMOS technology, Au-free metal schemes should be investigated and proposed. The

Data Availability Statement: The authors declare that the data supporting the findings of this study are available within the article.

Conflicts of Interest: The authors declare no conflict of interest.

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