Research Article

Temperature-dependent device properties of γ-CuI and β-Ga₂O₃ heterojunctions

Rama Venkata Krishna Rao¹ · Ajinkya K. Ranade² · Pradeep Desai² · Golap Kalita²,³ · Hiroo Suzuki¹ · Yasuhiko Hayashi¹

Received: 3 April 2021 / Accepted: 23 August 2021
Published online: 08 September 2021
© The Author(s) 2021

Abstract

Temperature-dependent studies of Ga₂O₃-based heterojunction devices are important in understanding its carrier transport mechanism, junction barrier potential, and stability at higher temperatures. In this study, we investigated the temperature-dependent device characteristics of the p-type γ-copper iodide (γ-CuI)/n-type β-gallium oxide (β-Ga₂O₃) heterojunctions, thereby revealing their interface properties. The fabricated γ-CuI/β-Ga₂O₃ heterojunction showed excellent diode characteristics with a high rectification ratio and low reverse saturation current at 298 K in the presence of a large barrier height (0.632 eV). The temperature-dependent device characteristics were studied in the temperature range 273–473 K to investigate the heterojunction interface. With an increase in temperature, a gradual decrease in the ideality factor and an increase in the barrier height were observed, indicating barrier inhomogeneity at the heterojunction interface. Furthermore, the current–voltage measurement showed electrical hysteresis for the reverse saturation current, although it was not observed for the forward bias current. The presence of electrical hysteresis for the reverse saturation current and of the barrier inhomogeneity in the temperature-dependent characteristics indicates the presence of some level of interface states for the γ-CuI/β-Ga₂O₃ heterojunction device. Thus, our study showed that the electrical hysteresis can be correlated with temperature-dependent electrical characteristics of the β-Ga₂O₃-based heterojunction device, which signifies the presence of surface defects and interface states.

Article Highlights

• We revealed the interface properties of p-type γ-copper iodide (γ-CuI) and n-type β-gallium oxide (β-Ga₂O₃) heterojunction.
• The developed heterostructure showed a large barrier height (0.632 eV) at the interface, which is stable at a temperature as high as 473 K.
• We confirmed the current transport mechanism at the interface of the heterojunction by analyzing the temperature dependent current–voltage characterization.

*Yasuhiko Hayashi, hayashi.yasuhiko@okayama-u.ac.jp | ¹Graduate School of Natural Science and Technology, Okayama University, 3-1-1 Tsushima-naka, Kita, Okayama 700-8530, Japan. ²Department of Physical Science and Engineering, Nagoya Institute of Technology, Gokiso-Cho, Showa-ku, Nagoya 466-8555, Japan. ³Frontier Research Institute for Material Science, Nagoya Institute of Technology, Nagoya, Japan.
Keywords Gallium oxide · γ-copper iodide · Heterojunction · Device · Temperature dependent

1 Introduction

Among ultra-wide bandgap semiconductors, gallium oxide (Ga$_2$O$_3$), with a bandgap of 4.5–4.9 eV, has attracted significant attention for deep ultraviolet (DUV) photonics and power electronic device applications [1, 2]. β-Ga$_2$O$_3$, with a monoclinic structure and lattice parameters of \( a = 12.22 \) Å, \( b = 3.0 \) Å, and \( c = 5.8 \) Å, is the most stable form among all the polymorphs of Ga$_2$O$_3$ at room temperature [3, 4]. It has been reported that electron mobility as high as 300 cm$^2$ V$^{-1}$ s$^{-1}$ can be achieved in β-Ga$_2$O$_3$ at room temperature. β-Ga$_2$O$_3$ possesses a critical field strength higher than that of Si, SiC, and GaN semiconducting materials. The predicted critical field (\( E_{br} \)) for β-Ga$_2$O$_3$ is 8 MV cm$^{-1}$, whereas the measured \( E_{br} \) is 3.8 MV cm$^{-1}$ [5]. Owing to its high chemical and mechanical stabilities (Young’s modulus of β-Ga$_2$O$_3$ = 232 GPa) and thermal stability (melting point 1820 °C), it is well suited for applications such as solar-blind photodetectors [6], light-emitting devices, and GaN semiconducting materials. 

Previously, Ranade et al. reported the integration of γ-CuI with gallium nitride (GaN), which is a III nitride wide-bandgap semiconductor, to form a p-n heterojunction with high-temperature stable photovoltaic action [18]. The successful fabrication of a γ-CuI/GaN heterojunction motivated us to explore the integration of p-type γ-CuI with β-Ga$_2$O$_3$. In our previous study, we reported the observation of a DUV radiation-induced photovoltaic action for the γ-CuI/β-Ga$_2$O$_3$ heterojunction. In contrast to our previous studies, herein, we revealed the behavior of the heterojunction interface in the γ-CuI/β-Ga$_2$O$_3$ material system, which is significant for understanding its defect states, current transport mechanism, and temperature stability [23]. The temperature-dependent device characteristics were studied in the temperature range 273–473 K to investigate the heterojunction interface. With an increase in temperature, a gradual decrease in the ideality factor and an increase in barrier height were observed, indicating a barrier inhomogeneity at the heterojunction interface. Interestingly, we can correlate the electrical hysteresis and barrier inhomogeneity behavior of the γ-CuI/β-Ga$_2$O$_3$ heterojunction device, thereby revealing the influence of the interface states on these parameters.
2 Materials and methods

Here, we used Sn-doped, n-type single-crystal β-Ga2O3 (thickness of 650 μm, donor concentration of 3 × 10¹⁸ cm⁻³) purchased from Tamura Corporation, Japan. Approximately 0.05 g of copper iodide (γ-Cul) powder (purity ~ 95%), purchased from Wako Pure Chemical Industries Ltd., was evaporated for 2 min in a vacuum chamber at a pressure of ~ 10⁻³ Pa and an applied current of 35 mA. The thickness of the γ-Cul layer was controlled by varying the deposition duration. Metal electrodes were deposited on the fabricated γ-Cul/β-Ga2O3 heterostructure to complete the device structure. Gold (Au) and indium (In) electrodes were deposited on top of the γ-Cul and backside of the β-Ga2O3, respectively, using a metal shadow mask with a thermal evaporator under a high vacuum (~ 10⁻³ Pa). The Cul/β-Ga2O3 heterostructure samples were characterized using X-ray diffraction (XRD), UV–Vis absorption spectroscopy, and Raman spectroscopy. XRD studies were carried out using a Rigaku Smart Lab SE with Cu Kα radiation as the X-ray source (av = 1.5406 Å). The surface of the heterostructure was analyzed using a JEOL JSM 5600 scanning electron microscope (SEM) at an accelerating voltage of 20 kV. Raman spectroscopy measurements on the β-Ga2O3 and deposited Cul film were performed using an NRS 3300 laser Raman spectrometer at a laser excitation wavelength of 532.08 nm. UV–Vis absorption spectroscopy analysis was performed using a JASCO V-670 K spectrophotometer. The Cul film and Au and In metal electrodes were deposited using a ULVAC VPC-260F thermal evaporator. Current density–voltage (J–V) measurements were carried out using a two-probe system and a Keithley 2401 source meter at different device temperatures. The J–V characteristics of the heterostructure were analyzed at different temperatures (298–473 K) on a hot plate using a digital temperature controller.

3 Results and discussion

Figure 1a shows the XRD spectra of the β-Ga2O3 substrate and the fabricated γ-Cul/β-Ga2O3 heterostructure. A strong diffraction peak at 61.01° corresponding to the (020) reflection phase of β-Ga2O3 was observed in both samples. Again, an additional high-intensity peak is observed at 26.06° corresponding to the (111) plane of the cubic-phase γ-Cul for the γ-Cul/β-Ga2O3 heterostructure sample, which is in accordance with the JCPDS Card number 06-0246 [24, 25]. The predominantly (111)-oriented cubic-phase γ-Cul was obtained on the monoclinic β-Ga2O3 single-crystal substrate, which is consistent with previously reported results [21, 22]. Figure 1b shows the Raman scattering spectra of the single-crystal β-Ga2O3 substrate and the γ-Cul/β-Ga2O3 heterostructure. The low-frequency Raman peaks at 146, 17, and 201 cm⁻¹ denote the liberation and translation of the tetrahedral/octahedral chains. The mid-frequency Raman peaks at 348, 417, and 476 cm⁻¹ are related to the distortion of the Ga2O6 octahedra. The high-frequency Raman peaks at 631, 654, and 767 cm⁻¹ indicate the stretching and bending of the GaO4 tetrahedra, as shown in Fig. 1b. The high-intensity A9 Raman mode at 200 cm⁻¹ signifies the high-quality crystalline nature of the β-Ga2O3 sample used for the device fabrication [20]. Further, by analyzing the Raman spectra of the fabricated heterostructure, we observed an additional peak at 119 cm⁻¹, corresponding to the deposited γ-Cul film on the β-Ga2O3 substrate. The XRD spectra of the β-Ga2O3 substrate and the γ-Cul/β-Ga2O3 sample can be correlated with the Raman analysis of the purity and crystalline nature of the prepared samples for the device fabrication. Figure 1c shows the UV absorption spectra of the γ-Cul film deposited on a glass substrate in comparison to the absorption spectra of β-Ga2O3. The γ-Cul film shows absorption peaks in the range of 350–400 nm, whereas the absorption for the β-Ga2O3 sample was obtained in the range of 190–280 nm. Thus, the bandgap width for the γ-Cul/β-Ga2O3 heterojunction was 190–400 nm. Figure 1d shows the Tauc plot for calculating the optical bandgap of the deposited γ-Cul film, which was computed as 3.02 eV, consistent with previously reported values [26]. A Tauc plot of the β-Ga2O3 sample was plotted for comparison with the Tauc plot of the γ-Cul film. The optical bandgap of β-Ga2O3 was computed as 4.6 eV, which agrees with the theoretical value [1, 27]. Furthermore, the optical absorption study and the obtained bandgap can be correlated with the highly crystalline β-Ga2O3 and γ-Cul/β-Ga2O3 heterostructure samples, as observed from the Raman and XRD analyses. Figure 1e shows the SEM image of the thermally evaporated γ-Cul film on β-Ga2O3. The thermally evaporated γ-Cul film on β-Ga2O3 showed a granular morphology, where the grain size of the γ-Cul and surface roughness may change with the deposition conditions. Figure 1f shows a tilted SEM image of the γ-Cul film on β-Ga2O3, presenting the thickness of γ-Cul around 1 μm. The thickness and uniformity of the film on the β-Ga2O3 substrate were controlled by the deposition rate, where the thickness and uniformity of the γ-Cul film can significantly differ with the deposition rate. A heterojunction device was fabricated with the as-deposited γ-Cul film, where a persistent diode characteristic was obtained, as discussed next, with a device structure of Au/γ-Cul/β-Ga2O3/In.

Figure 2a shows the cross-section stick and ball crystal structure of the γ-Cul and β-Ga2O3 device interface. The electron affinities of the n-type β-Ga2O3 and p-type γ-Cul were in the range of 4.0 and 2.1–2.2 eV, respectively, which
indicates the possibility of creating a large build-in field at the interface. The bandgaps of the two materials as calculated from the absorption spectra were 3.02 and 4.6 eV for γ-CuI and β-Ga2O3, respectively. As discussed here, owing to the large differences in the electron affinity and work function, a significant built-in field \((\varphi_{\text{Ga}_2\text{O}_3} - \varphi_{\text{CuI}} = V_{\text{bi}})\) can be obtained at the interface of the γ-CuI/β-Ga2O3 heterojunction [18, 28]. Figure 2b shows a schematic diagram of the fabricated γ-CuI/β-Ga2O3 vertical heterojunction device. The Au and In electrodes were deposited on γ-CuI and β-Ga2O3, respectively, to fabricate them. The Au electrode was deposited on γ-CuI considering the similar work function in the range of 5.1 eV. A work function in the range 4.08–4.12 eV was selected considering the electron affinity of n-type β-Ga2O3 to be approximately 4.0 eV [23, 29]. The fabricated Au/γ-CuI/β-Ga2O3/In vertical heterojunction device was analyzed for its J–V characteristics. First, the device was analyzed at room temperature (298 K). Figure 2c shows the J–V characteristics at 298 K in the voltage range of −2 to +2 V under dark conditions. Good rectifying diode behavior was observed with low series resistance and a high rectification ratio (≈106). Figure 2d shows the log plot of the J–V curve at room temperature. The diode characteristics can be compared with the previously reported results for γ-CuI/β-Ga2O3 and diamond/β-Ga2O3 heterojunction diodes [11, 20]. The diode ideality factor \((n)\), computed from the log plot, was found to be 3.5. The diode J–V characteristics can be expressed as follows, correlating the current and voltage with the ideality factor.

\[
J = J_0 \exp \left( \frac{qV}{nkT} \right) \exp \left( -\frac{q\varphi_B}{kT} \right),
\]

where \(J\) is the current density flowing through the diode, \(V\) is the voltage across the diode, \(J_0\) is the saturation current density, \(T\) is the temperature in Kelvin, \(q\) is the electron charge, \(k\) is the Boltzmann’s constant, and \(n\) is the ideality factor. The ideality factor is higher than some k electron charge, and \(\varphi_B\) is the effective barrier height.

Figure 3a shows the temperature-dependent J–V characteristics of the Au/γ-CuI/β-Ga2O3/In heterojunction under an applied bias voltage of −2 to +2 V in the temperature range 298–373 K. The temperature-dependent analysis of the γ-CuI/β-Ga2O3 heterostructure elucidated the interface properties and compatibility of the material system for device fabrication. The fabricated device showed consistent rectification diode characteristics as the temperature was increased to 373 K. Figure 3b shows the log plot with an increasing temperature. The forward current consistently increased with increase in temperature (Fig. 3a); however, the change in current was not significantly high, because the variation in the logarithm plot was not noticeably visible. The saturation current is significantly low, because of which a small change in current is pronounced in the logarithm plot in the reverse bias voltage. The reverse saturation current was slightly non-saturated at the reverse bias voltage for the measured temperature range. This can be attributed to the barrier inhomogeneity at the interface of γ-CuI/β-Ga2O3. Subsequently, the barrier height \((\varphi_{\text{Ga}_2\text{O}_3})\) was analyzed by changing the temperature for the J–V characteristic using the reverse saturation current density equation.

\[
J_0 = A* \cdot T^2 \cdot \exp \left( -\frac{q\varphi_{\text{Ga}_2\text{O}_3}}{kT} \right),
\]

where \(A^*\) is Richardson’s constant (41 A cm⁻² K⁻² for β-Ga2O3), \(A\) is the area, \(q\) is the electron charge, \(T\) is the temperature in Kelvin, \(k\) is the Boltzmann constant, and \(\varphi_{\text{Ga}_2\text{O}_3}\) is the effective barrier height.

Figure 3c shows the trends in \(n\) and \(\varphi_{\text{Ga}_2\text{O}_3}\) at various temperatures. \(n\) decreased, and \(\varphi_{\text{Ga}_2\text{O}_3}\) increased as the temperature increased from 298 to 373 K. The measured barrier height \((\varphi_{\text{Ga}_2\text{O}_3})\) at the interface between γ-CuI and β-Ga2O3 was approximately 0.632 eV at room temperature (298 K) from the J–V characteristics, which is relatively higher than those of other β-Ga2O3 heterojunction devices. However, the measured barrier height was smaller than the theoretical value, as mentioned earlier, which may be due to the presence of a tunneling component at the heterojunction interface in the presence of the interface states [24]. Furthermore, the interface quality of the Au/γ-CuI/β-Ga2O3/In heterojunction was investigated. The J–V characteristics of the forward and reverse sweeps were measured to analyze the occurrence of electrical hysteresis under dark conditions. Figure 4a shows the forward and reverse sweeps under a bias voltage of ±2 V. The measured J–V curve showed no hysteresis effect for the forward bias voltage. Figure 4b shows the logarithmic plot of the J–V characteristics with a small electrical hysteresis in the reverse saturation current. As the reverse saturation current is much smaller, the electrical hysteresis becomes more prominent. The presence of electrical hysteresis in the reverse saturation current indicates some level of interface states for the fabricated γ-CuI/β-Ga2O3 heterojunction [29, 30]. Figure 4c shows the J–V characteristics of the fabricated device at 473 K, which still showed excellent rectification diode characteristics at a rectification ratio of...
Further, the J–V characteristic was also measured at 523 K; however, the device properties were not consistent, as a dark color appeared around the Au electrode due to oxidation. The study of the high-temperature stability of the γ-CuI/β-Ga₂O₃ device is an important aspect to confirm the suitability of the fabricated heterojunction device. Figure 4d shows the probable energy band diagram for the γ-CuI/β-Ga₂O₃ heterojunction device at equilibrium. The energy band diagram was configured from the electron affinity and bandgap values of n-type β-Ga₂O₃ (χ = 4.0 eV; \( E_g = 3.02 \) eV) and p-type γ-CuI (χ = 2.1–2.2 eV; \( E_g = 4.6 \) eV). Because the electron affinities of the two semiconductors are significantly different, a large band bending as well as a large barrier potential at the heterojunction interface can be estimated [24, 35–37]. The band diagram also represents the suitability of both the semiconductors for heterojunction device applications, where the formation of an interface with the deposition process can significantly affect the device performance. From the temperature-dependent analysis, it can be observed that the γ-CuI/β-Ga₂O₃ heterojunction is quite stable with consistent highly rectifying diode characteristics. Most importantly,
Fig. 2  a cross-section stick and ball crystal structure of γ-CuI and β-Ga₂O₃;  b schematic of the fabricated vertical heterojunction device of γ-CuI and β-Ga₂O₃;  c J–V characteristics; and  d log plot of the J–V curve of the fabricated device for a voltage range of –2 V to 2 V

Fig. 3  a J–V characteristics in the temperature range 298–373 K and voltage range of –2 to 2 V;  b Logarithm plot in the voltage range of –2 to 2 V, representing the current transport behavior for the Au/γ-CuI/β-Ga₂O₃/In heterojunction device for the temperature range 298–373 K;  c Variation in the ideality factor (n) and barrier height (φ) with an applied temperature in the range 298–373 K
the experimental results suggest that the observed barrier inhomogeneity from the temperature-dependent J–V analysis can be correlated with the electrical hysteresis of the diode characteristics, which signifies the presence of surface defects and interface states.

4 Conclusions

We investigated the temperature-dependent device characteristics of the p-type γ-Cul and n-type β-Ga₂O₃ heterojunctions, thereby analyzing the interface properties. A predominantly (111)-oriented cubic-phase γ-Cul was deposited on a β-Ga₂O₃ substrate by evaporation. The fabricated γ-Cul/β-Ga₂O₃ heterojunction showed excellent diode characteristics with a high rectification ratio and low reverse saturation current at 298 K, in the presence of a large barrier height of 0.632 eV. A decrease in the ideality factor and an increase in barrier height were observed when the temperature was increased from 298 to 373 K, indicating a barrier inhomogeneity at the heterojunction interface due to the surface defects present there. The electrical analysis also showed a small hysteresis effect on the reverse saturation current for the fabricated γ-Cul/β-Ga₂O₃ heterojunction. The presence of electrical hysteresis for the reverse saturation current and the barrier inhomogeneity in the temperature-dependent characteristics indicates the presence of some level of interface states. Irrespective of the existence of surface defects and interface states, a rectifying diode characteristic was obtained at temperatures as high as 473 K for the fabricated γ-Cul/β-Ga₂O₃ heterojunction. Our study revealed that the electrical hysteresis and temperature-dependent electrical characteristics of the β-Ga₂O₃-based heterojunction device could be significant and correlated in identifying interface properties.

Acknowledgements We would like to thank Editage (www.editage.com) for English language editing.

Declarations

Conflict of interest The authors declare that there is no possible conflict of interest.

Consent for publication All authors has given the consent for publication of research.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not
References

1. Baldini M, Galazka Z, Wagner G (2018) Recent progress in the growth of β-Ga2O3 for power electronics applications. Mater Sci Semiconductor Process 78:132–146

2. Chabak KD, McCandless JP, Moser NA, Green AJ, Mahalingam K, Crespo A, Hendricks N, Howe BM, Tetlak SE, Leedy K, Fitch RC, Wakimoto D, Sasaki K, Kuramata A, Jessen GH (2018) Recessed-gate enhancement-mode β-Ga2O3 MOSFETs. IEEE Electron Dev Lett 39:67–70

3. Oishi T, Koga Y, Harada K, Kasu M (2015) High-mobility β-Ga2O3(201) single crystals grown by edge-defined film-fed growth method and their Schottky barrier diodes with Ni contact. Appl Phys Express 8:031101

4. Ma N, Tanen N, Verma A, Guo Z, Luo T, Xing HG, Jena D (2016) Intrinsic electron mobility limits in β-Ga2O3. Appl Phys Lett 109:212101

5. Kim M, Geo JK, Singisetti U, Ma Z (2017) Recent advances in free-standing single crystalline wide band-gap semiconductors and their applications: GaN, SiC, ZnO, β-Ga2O3, and diamond. Mater Chem C 5:8338

6. Xu J, Zheng W, Hwang F (2019) Gallium oxide solar-blind ultraviolet photodetectors: a review. J Mater Chem C 7:8753–8770

7. Pratiyuah AS, Krishnamoorthy S, Muralidharan R, Rajan S, Nath DN (2019) 16: Advances in Ga2O3 solar-blind UV photodetectors, gallium oxide technology, devices and applications, metal oxide. OSA Publications China, pp 365–399

8. Higashimaki M, Murakami H, Kumagai Y, Kuramata A (2016) Current status of Ga2O3 power devices. J Appl Phys 55:1202

9. Oshima T, Okuno T, Arae N, Suzuki N, Ohira S, Fujita S (2008) Vertical solar-blind deep-ultraviolet Schottky photodetectors based on β-Ga2O3 substrates. Appl Phys Express 1:011102

10. Jia M, Wang F, Tang L, Xiang J, Teng KS, Lau SP (2020) High-performance deep ultraviolet photodetector based on NiO/β-Ga2O3 heterojunction. Nanoscale Res Lett 15:47

11. Kim H, Tarelkin S, Polyakov A, Troschiev S, Nosukhin S, Kuznetsova M, Kim J (2020) Ultrawide-bandgap p-n heterojunction of diamond/β-Ga2O3 for a solar-blind photodiode. ECS J Solid State Sci Technol 9:045004

12. Farzana E, Ren F, Hays DC, Gila BP, Tadjer M, Hobart KD, Pearl SJ (2018) Valence band offsets for CuI on (021) bulk Ga2O3 and epitaxial (010) (Al0.14Ga0.86)2O3. Appl Phys Lett 113:182101

13. Yamada N, Kondo Y, Ino R (2019) Low-temperature fabrication and performance of polycrystalline cu films as transparent p-type semiconductors. Phys Status Solidi 216:1700782

14. Yang C, Souchay D, Kneiß M, Bogner M, Wei HM, Lorenz O, Oekler O, Benstetter G, Yu QY, Grundmann M (2017) Transparent flexible thermoelectric material based on non-toxic earth-abundant p-type copper iodide thin film. Nat Commun 8:1–7

15. Kalita G, Mahyavanshi RD, Desai P, Kato M, Tanemura M, Kalita G (2019) Ultrafast light induced electrical hysteresis effect in graphene-Ga2O3 heterojunction. Appl Phys Lett 114:151102

16. Fares C, Ren F, Hays DC, Gila BP, Tadjer M, Hobart KD, Pearl SJ (2018) Valence band offsets for CuI on (021) bulk Ga2O3 and epitaxial (010) (Al0.14Ga0.86)2O3. Appl Phys Lett 113:182101

17. Michaelson HB (1977) The work function of the elements and its periodicity. J Appl Phys 48:4729–4733

18. Kalita G, Shaarin MD, Paudel B, Mahyavanshi R, Tanemura M (2017) Temperature dependent diode and photocathodic characteristics of graphene-Ga2O3 heterojunction with deep-ultraviolet irradiation. Appl Phys Express 10:110102

19. Alonso M, Cimino R, Horn K (1990) Surface photovoltage effects in photoemission from metal-GaP(110) interfaces: importance of its periodicity. J Appl Phys 48:4729–4733

20. Fares C, Ren F, Hays DC, Gila BP, Tadjer M, Hobart KD, Pearl SJ (2018) Valence band offsets for CuI on (021) bulk Ga2O3 and epitaxial (010) (Al0.14Ga0.86)2O3. Appl Phys Lett 113:182101

21. Zhang ZW, Lin RC, Li TT, Zhang ZJ, Huang F (2018) High quality β-Ga2O3 film grown with N2O for high sensitivity solar-blind-ultraviolet photodetector with fast response speed. J Alloys Compd 735:150–154

22. Alonso M, Cimino R, Horn K (1990) Surface photovoltage effects in photoemission from metal-GaP(110) interfaces: importance of its periodicity. J Appl Phys 48:4729–4733

23. Alonso M, Cimino R, Horn K (1990) Surface photovoltage effects in photoemission from metal-GaP(110) interfaces: importance of its periodicity. J Appl Phys 48:4729–4733

24. Woodall JM, Islam MS, Kaya A, Dryden DM, Mao H, Alhalaibi B (2017) Oxidation of GaAs substrates to enable β-Ga2O3 films for sensors and optoelectronic devices. In: Matin M, Dutta AK, Chowdhury S (eds) Wide bandgap power devices and application II. SPIE, p 11
35. Mohamed M, Irmscher K, Janowitz C, Galazka Z, Manzke R, Fornari R (2012) Schottky barrier height of Au on the transparent semiconducting oxide $\beta$-Ga$_2$O$_3$. Appl Phys Lett 101:132106
36. Schein FL, Von Wenckstern H, Grundmann M (2013) Transparent p-Cul/n-ZnO heterojunction diodes. Appl Phys Lett 102:92109
37. Motaung DE, Mhlongo GH, Makgwane PR, Dhonge BP, Cummings FR, Swart HC, Ray SS (2018) Ultra-high sensitive and selective H$_2$ gas sensor manifested by interface of n-n heterostructure of CeO$_2$-SnO$_2$. Sens Actuator B Chem 254:984–995

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.