P-type semiconductors in gallium oxide electronics

Kentaro Kaneko[*1,2], Shu Takemoto[2], Shin-ichi Kan[2], Takashi Shinohe[3], and Shizuo Fujita[2,4]

[1] Engineering Education Research Center, Kyoto University, Katsura, Kyoto 615-8530, Japan
[2] Department of Electronic Science and Engineering, Kyoto University, Katsura, Nishikyo-ku, Kyoto, 615-8510, Japan
[3] FLOSFIA Inc., Kyodai-Katsura Venture Plaza, Katsura, Nishikyo-ku, Kyoto 615-8245, Japan
[4] Photonics and Electronics Science and Engineering Center, Kyoto University, Katsura, Kyoto 615-8520, Japan
ken-kaneko@kuee.kyoto-u.ac.jp, Phone: +81-75-383-3039

Keywords: Gallium oxide, Ga_2O_3, Corundum, Power device, Mist CVD, MIST DRY®

Abstract

Corundum-structured gallium oxide (α-Ga_2O_3) has a huge band gap of 5.61 eV and it shows n-type conductivity by doping with Si, Ge or Sn ions. α-Ga_2O_3 SBDs and MOSFETs show lowest on-resistance of 0.1 mΩ·cm^2 and normally-off operations, respectively. Additionally, it can tune bad gaps by alloying with α-In_2O_3 (3.7 eV) and α-Al_2O_3 (9.0 eV) and consist a pn heterojunction with p-type α-Ir_2O_3. α-Ga_2O_3 has much potentials to expand its power device applications.

INTRODUCTION

Gallium oxides (Ga_2O_3) has been gathering much attentions for their huge band gaps of 5.61 eV (α-Ga_2O_3) [1] and 4.48 eV (β-Ga_2O_3) [2]. Ga_2O_3 takes 5 types of crystal polymorph, among these, corundum-structured α-Ga_2O_3 is attractive in view of bandgap tuning from 3.7 to 9.0 eV by alloying with same crystal structured oxides of α-In_2O_3 and α-Al_2O_3 accompanying high crystallinity[3][4]. Besides α-Ga_2O_3 Schottky barrier diodes (SBDs) show extremely low on-resistance of 0.1 mΩ·cm^2 [5] and normally-off operations[6].

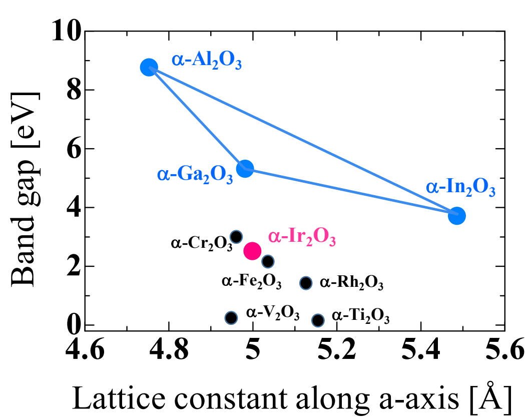

Fig. 1. A relationship between energy band gaps and average bond lengths of corundum-structured oxides. A triangle consists with α-Al_2O_3, α-Ga_2O_3, α-In_2O_3 is an alloy system with band gaps from 3.7 to 9.0 eV [4].

However, the lack of p-type oxide semiconductors acting as a counterpart of both α-Ga_2O_3 and β-Ga_2O_3 has obstructed high-performance power devices based on Ga_2O_3.

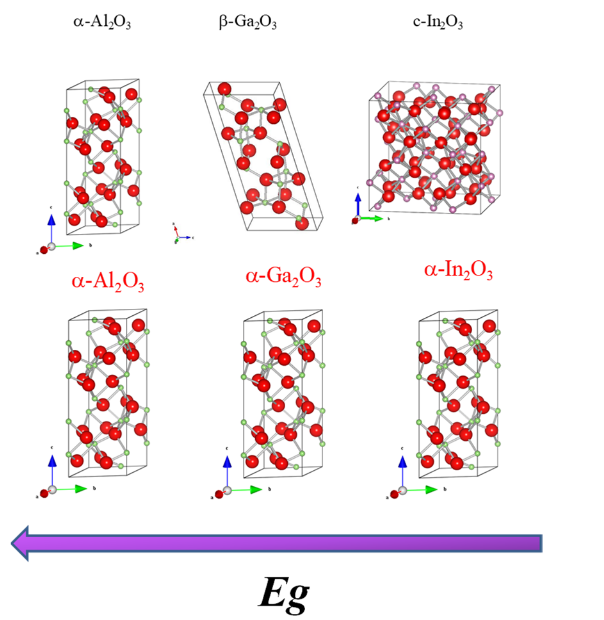

Fig. 2. Schmatic images of crystal structures of β-Ga_2O_3 and α-Ga_2O_3 alloy systems. From the view of band gap tuning, β-Ga_2O_3 (β-gallia) has to alloy with different crystal-structured oxides of α-Al_2O_3 (corundum) and c-In_2O_3(bixbyite). On the other hand, an α-Ga_2O_3 alloy system consists of only corundum-structured oxides.

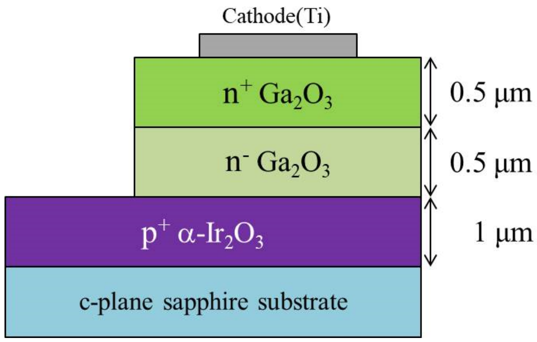

Fig. 3. Schematic cross-section of α-Ir_2O_3 /α-Ga_2O_3 pn diode [11].

Experiment

We have been focusing on corundum-structured α-Rh_2O_3 and α-Ir_2O_3, which were reported to show p-type conductivity by Seebeck effect and thermoelectric power measurement, respectively [7-10]. However, carrier densities and hole mobilities calculated from Hall effect measurements were not reported due to their low Hall voltages. Making of single-phased α-Rh_2O_3 and α-Ir_2O_3 thin films is a key to control hole concentrations. First attempts were done to grow and characterize α-Rh_2O_3, leading to small Hall coefficients and high hole concentrations. This was attributed to that the Fermi-level was located at the energy higher than the bottom of conduction band at *E-k* dispersion in α-Rh_2O_3 and the electron conduction vailed the hole conduction. Therefore, in order to tune the Fermi-level, we fabricated an alloy of α-Rh_2O_3 and α-Ga_2O_3 on α-Al_2O_3 substrates. An α-$(Rh,Ga)_2O_3$ thin film showed clear p-type conductivity by Hall effect with the hole mobility of 1.0 cm^2/Vs and the hole concentration of 7.6×10^{17} cm^3[4]. Single-phase α-Ir_2O_3 thin films were also fabricated and we observed p-type conductivity by Hall-effect measurements. These results pave the way to fabricate pn junctions. Highly-doped α-Ga_2O_3 (n+) and α-Ga_2O_3 (n-) layers were fabricated on α-Ir_2O_3 (p+) thin films on sapphire substrates. They showed well-defined rectifying current-voltage characteristics with the turn-on voltage of about 2.0 V [11]. We are confident that the present approach is bloomed for future evolution of p-type oxide semiconductors applicable in electronics based on Ga_2O_3.

Acknowledgements

Part of this work was supported by "Strategic Innovation Program for Energy Conservation Technologies" of the New Energy and Industrial Technology Development Organization (NEDO).

References

[1] A. Segura *et al*., Phys. Rev. Mat. **1**, 024604 (2017).

[2] T. Onuma *et al*., Jpn. J. Appl. Phys. **54**, 112601 (2015).

[3] K. Kaneko *et al*., J. Appl. Phys. **113**, 233901 (2013)

[4] K. Kaneko *et al*., Jpn. J. Appl. Phys. **57**, 02CB18 (2018)

[5] M. Oda *et al*., Appl. Phys. Express **9**, 021101 (2016).

[6] Press Release from FLOSFIA INC.; http://flosfia.com/20180713/

[7] F. P. Koffyberg. J. Phys. Chem. Solids **53,** 1285 (1992).

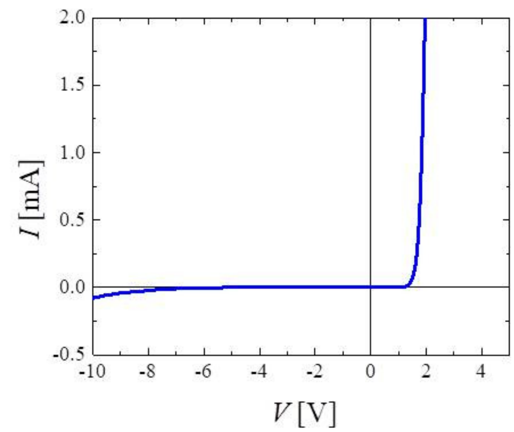

Fig. 4. Current-voltage characteristics of the α-Ir_2O_3/α-Ga_2O_3 pn heterojunction diode [11].

[8] R. K. Kawar, *et al* *Appl. Surf. Science,* **206**, 90 (2003).

[9] Y. B. He, *et al* , J. Phys. Chem. C **112**, 11946 (2008).

[10] W.H. Chung, *et al* , Surf. Scinece. **606**, 1965 (2012).

[11] S. Kan, *et al* , Appl. Phys. Lett. **113**, 212104 (2018)