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Tunneling via surface dislocation in W/β-Ga_2O_3 Schottky barrier diodes

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Abstract: In this work, W/β-Ga_2O_3 Schottky barrier diodes, prepared using a confined magnetic field-based sputtering method, were analyzed at different operation temperatures. Firstly, Schottky barrier height increased with increasing temperature from 100 to 300 K and reached 1.03 eV at room temperature. The ideality factor decreased with increasing temperature and it was higher than 2 at 100 K. This apparent high value was related to the tunneling effect. Secondly, the series and on-resistances decreased with increasing operation temperature. Finally, the interfacial dislocation was extracted from the tunneling current. A high dislocation density was found, which indicates the domination of tunneling through dislocation in the transport mechanism. These findings are evidently helpful in designing better performance devices.

Key words: β-Ga_2O_3; SBD; SBD paramatters; tungsten; low temperature; tunneling via dislocation

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1. Introduction

Ultrawide bandgap (UWBG) semiconductors represent a growing new area of research including materials, physics, technologies, and applications. This new semiconductor class is promising for future generation devices especially the devices used in harsh-environment applications. Among these UWBG are AlGaN, AlN, diamond and Ga_2O_3. Compared with other UWBG semiconductors, Ga_2O_3 has a bandgap of about 4.8 eV with a high breakdown electrical field[1, 2]. In contrast to the other UWBG, Ga_2O_3 is directly obtainable from melt by scalable growth methods such as Czochralski[3], optical floating zone[4] and vertical Bridgman[5] etc. therefore, Ga_2O_3 is comparatively low cost[2]. The monoclinic β-Ga_2O_3 is the most thermodynamically stable[2, 6] in comparison with other polymorphs (α, β, γ, δ, ε, and k)[2]. Currently β-Ga_2O_3 is therefore mainly used in unipolar devices while p–n heterojunctions require different semiconductors because of the challenge to obtain stable p-type β-Ga_2O_3[7]. For Schottky barrier diode (SBD) formation with β-Ga_2O_3, different metals are used such as Au[8], Ni[9], Pt[8] and W[10]. Interpreting and understanding the temperature dependant β-Ga_2O_3 SBD characteristics and the dominate conduction mechanisms are very important for improving SBD performance[11]. The most important transport mechanism for this type of SBD is the thermionic emission (TE) current[12, 13]. However, at low temperature other transport mechanisms dominate such as tunneling[11] and tunneling via dislocations[14]. Labed *et al.*[11] have demonstrated the domination of tunneling at low temperature for Ni/β-Ga_2O_3 SBD and with increasing temperature, the tunneling current decreases. Fillali *et al.*[15] also demonstrated this fact for GaAs/AlGaAs MQW SBDs. Arslan *et al.*[14] showed the domination of tunnelling via dislocations current in the depletion region at low temperatures for an (Ni/Au)/AlInN/AlN/GaN SBD. β-Ga_2O_3 power-switching devices performance and reliability depend in great part on dislocations, therefore, their presence in β-Ga_2O_3 materials have to be reduced. Dislocations are induced by the substrate's surface state and its polishing and etching, or dislocations that directly originate from stacking faults in the substrate[16]. In addition to their negative effects on leakage current and breakdown[14, 17], dislocations may act as nucleation sites for other types of defects[17] and their density may be as high as 1×10^5 cm^{-2} [17, 18]. Yao *et al.*[17] estimated the dislocation density in the range of 6×10^4–1×10^6 cm^{-2} for bulk β-Ga_2O_3. Yang *et al.*[19] fabricated Schottky barrier diodes on β-Ga_2O_3 substrates with dislocation density of about 1×10^6 cm^{-2}. The dislocation density is affected by interfacial traps, plasma and diffusion of metal atoms into the surface of β-Ga_2O_3[1, 9]. Therefore, tunneling via dislocation is expected to dominate at this type of device, especially at low temperature. Furthermore, in the last few years there is a high interest for tungsten (W) for Schottky contact with β-Ga_2O_3[20, 21]. This interest is related to several reasons: it has a high thermal stability, a lower temperature-dependent contact characteristics with β-Ga_2O_3, and a work function of 4.5 eV so that a modest barrier height with potentially better temperature endurance is anticipated. Furthermore, tungsten is at a lower cost with comparison with gold and platinum.

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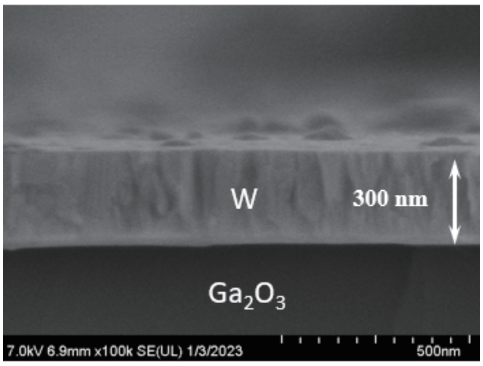

Fig. 1. An SEM cross section image of W/β-Ga_2O_3 SBD.

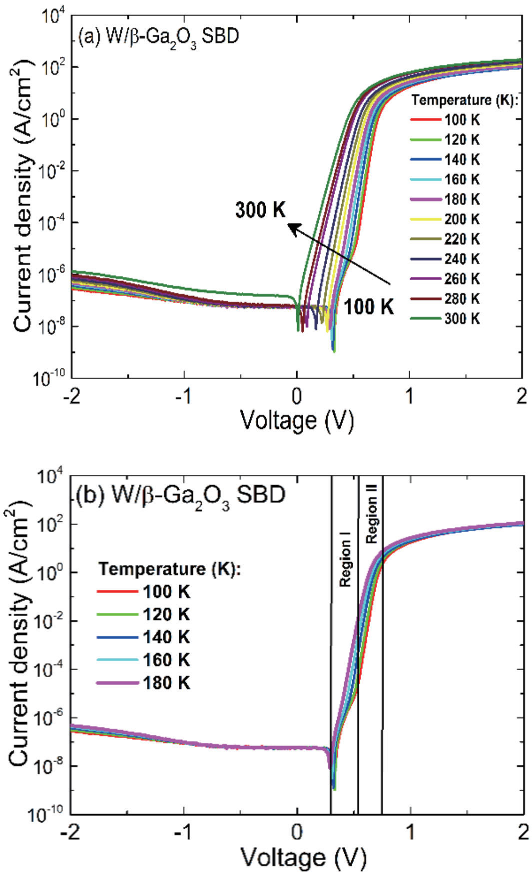

Fig. 2. (Color online) (a) Measured J–V of W/β-Ga_2O_3 SBDs at different temperatures (100–300 K) and (b) shows the double regions at low voltage domain at low temperatures (100–180 K).

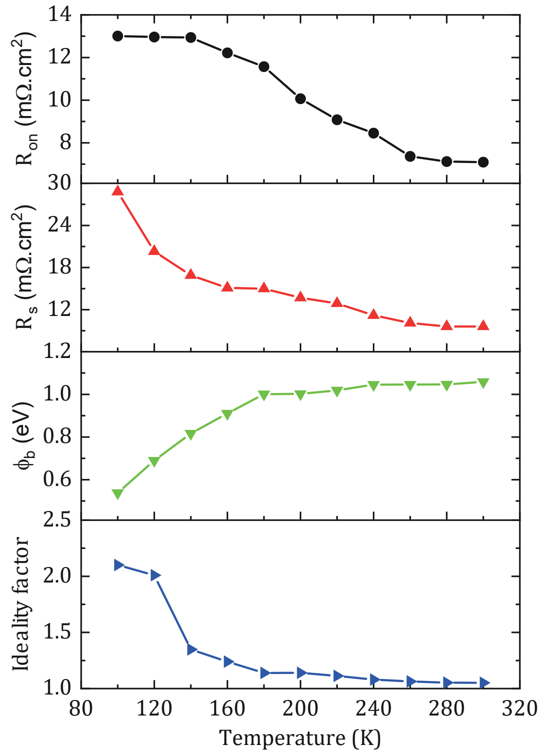

Fig. 3. (Color online) Temperature dependent ideality factor, ϕ_b, R_s and R_{on}.

In this work, the W/β-Ga_2O_3 Schottky barrier diode (SBD) deposited by CMFS is studied and analyzed in a temperature domain from 100 to 300 K to unveil the conduction mechanism at low temperatures. The aim is to study the possibility of tunneling via dislocation transport mechanism and to extract the interfacial dislocation density.

2. Materials and fabrication method

The active layer of the SBD is a Si-doped β-Ga_2O_3 film, grown by halide vapor phase epitaxy on the Sn-doped β-Ga_2O_3 substrate at 1×10^{18} cm^{-3}. The edge-defined film-fed growth (EFG) is used to prepare the substrate, which has an orientation of (001), by Novel Crystal (Japan). The donor concentration in the β-Ga_2O_3 epitaxial film is 3×10^{16} cm^{-3}. The ohmic contacts, consisting of Ti/Au electrodes (10 nm/40 nm), were then deposited by E-beam evaporation. A tungsten (W) film (300 nm) is used for the Schottky contact, and is deposited on the Si-doped β-Ga_2O_3 active layer by confined magnetic field based sputtering method (CMFS). The fabricated SBD was annealed at 400 °C. An SEM cross section image of the fabricated β-Ga_2O_3 SBD is shown in Fig. 1.

3. Results and discussion

3.1. Temperature-dependent current density

The W/β-Ga_2O_3 semi-logarithmic temperature dependent J–V characteristics are shown in Fig. 2(a). The forward bias of the structure current is an exponential function of the applied bias voltage only for temperatures higher than 180 K. However, for temperatures lower than 180 K, double regions were observed which can be clearly seen in Fig. 2(b). The double regions at low voltage domain are believed to a non-negligeable tunneling current contribution to the total current[11]. The leakage current, at room temperature (300 K) at –2 V, is of about ~10^{-6} A/cm^2 and is nearly independent on temperature. The forward current is about 192 A/cm^2 at 2 V forward bias at room temperature and is also nearly independent on temperature.

3.2. Temperature dependent SBD parameters

Schottky barrier height ($\phi_b(T)$), serie resistance (R_s) and ideality factor (η) were extracted as presented in Fig. 3. $\phi_b(T)$ and R_s versus temperature are determined by the Sato and Yasumura method[22] in which, from the current–voltage equation, a function $F(V, T)$ is defined as[22]:

$$F(V,T) = \frac{V}{2} - \frac{K_B T}{q}\ln\frac{J}{A^* T^2} = \phi_b + \frac{JR_s}{n} + V\left(\frac{1}{\eta} - \frac{1}{2}\right). \quad (1)$$

From Eq. (1), it can be shown that the barrier height

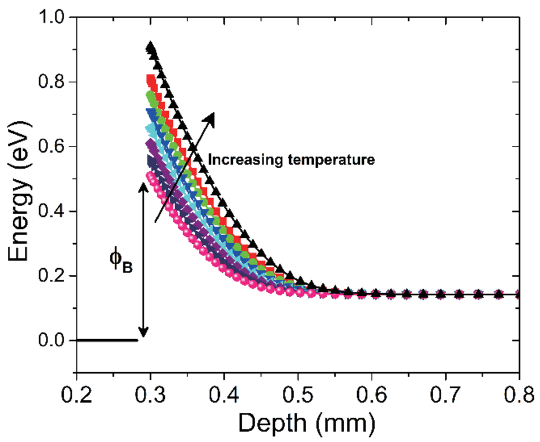

Fig. 4. (Color online) Extracted band diagram shows barrier height at different temperatures.

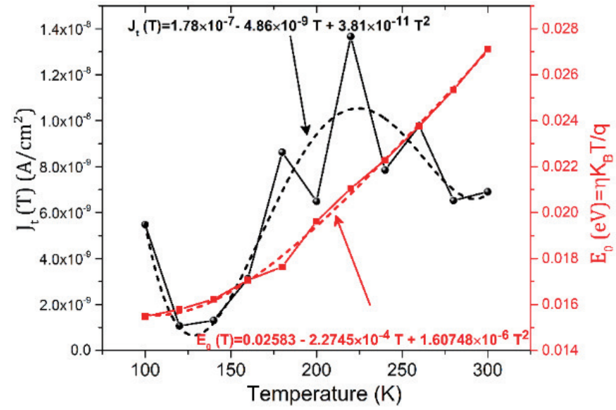

Fig. 5. (Color online) Extracted saturation current (J_t) and tunneling parameter E_0 at different operation temperatures and their polynomial extrapolation equations.

$\phi_b\,(T)$ and R_s are given by[22]:

$$\phi_b\,(T) = F_{min}\,(V,T) - \left(\frac{2}{\eta}-1\right)\frac{K_B T}{q} + V\,(F_{min})\left(\frac{1}{\eta}-\frac{1}{2}\right), \quad (2)$$

$$R_s = \frac{(2-\eta)K_B T}{qJ\,(F_{min})}, \quad (3)$$

where $J(F_{min})$ is the current when $F(V,T)$ is at its minimum at a fixed temperature.

The slope of the linear region of the $\ln(J-V)$ plot at low voltage is proportional to the ideality factor η. This relation is expressed as[23]:

$$\eta = \frac{q}{K_B T}\frac{dV}{d\,(\ln\,(J))}. \quad (4)$$

With increasing temperature from 100 to 300 K, η decreases from 2.1 to 1.05. The high value at low temperature is often related to the tunneling current[11]. The decreasing η is due to the effect of thermionic emission transport process. The Schottky barrier height (SBH) (ϕ_b) increased from 0.54 to 1.03 eV with increasing temperature from 100 to 200 K, then a saturation in ϕ_b for temperatures higher than 200 K. This behavior of η and ϕ_b could be due to barrier inhomogeneity at the W/β-Ga_2O_3 interface[19, 24]. Furthermore, for temperatures lower than 200 K, low energy electrons can be transferred to tungsten by tunnelling through the barrier. When the temperature increases from 200 K, other electrons at higher energies surmount the barrier using a thermionic emission mechanism and the barrier appears to be higher and the band diagram extracted using Silvaco TCAD at different temperatures explains the increasing in ϕ_b with increasing temperature as shown in Fig. 4. Clearly, a high ϕ_b at room temperature was obtained when tungsten is deposited by CMFS. This result may be related to high tungsten workfunction or to the β-Ga_2O_3 electron affinity being lower than 4 eV. The first maybe due to the tungsten atom diffusion into the surface of β-Ga_2O_3, which is similar to Nickel diffusion[1].

Finally, as shown in Fig. 3, R_s and R_{on} decreased with increasing temperature. These decreases are related to the β-Ga_2O_3 resistivity decrease which could be due to the excitation and transition of electrons under the influence of lattice thermal vibration, as the operating temperature increases[24].

A high ideality factor and a high leakage current indicate the domination of tunneling current at 100 K. Among the expected tunneling mechanisms are tunneling via dislocation and traps (oxygen and gallium vacancies) assisted tunneling. In most publications, a high dislocation density is observed in bulk β-Ga_2O_3[19, 25]. In addition, one of the expected dislocation source is vacancy condensation[26]. In addition, the diffusion of tungsten into the surface of β-Ga_2O_3 and the formation of the Ga–W–O ternary compound at the W/β-Ga_2O_3 interface after annealing is expected[27]. The formation of this compound leads to a lattice mismatch between the Ga–W–O ternary compound and β-Ga_2O_3 and the result is the formation of an interfacial dislocation in addition to bulk β-Ga_2O_3 dislocation which will affect the W/β-Ga_2O_3 SBD performance and transport mechanism.

Generally, the tunneling current through a barrier is given by[11, 14]:

$$J_{Tu} = J_t\left\{\exp\left[\frac{q\,(V-R_s J)}{E_0}\right]-1\right\}, \quad (5)$$

where J_t is the tunneling saturation current and E_0 is the tunneling parameter. E_0 can be defined as[11, 28]:

$$E_0 = E_{00}\coth\frac{E_{00}}{K_B T}. \quad (6)$$

With the consideration of the domination of tunneling via dislocations, the saturation current J_t is given by[14, 29]:

$$J_t = qD_{dis}v_D\exp(-qV_k/E_0), \quad (7)$$

where D is the dislocation density, $v_D \approx 3.024\times10^{12}\ s^{-1}$ is the Debye frequency for β-Ga_2O_3[30] and $qV_k \approx \phi_b$[14].

Using Eq. (5), J_t and E_0 are determined from measured J–V characteristics of Fig. 2 and knowing $qV_k(0)$, the dislocation density can be extracted from the following equation[14]:

$$D_{dis} = \frac{J_t\,(0)}{qv_D}\exp\frac{qV_k\,(0)}{E_0\,(0)}, \quad (8)$$

where $J_t\,(0)$ and $E_0\,(0)$ can be obtained by polynomial extrapolation of $J_t\,(T)$ and $E_0\,(T)$ to 0 K. The polynomial fitting equations are given in the legend of Fig. 5. The value of $qV_k\,(0)$ approximate to $\phi_b(0)$ which is obtained by extrapolation of ϕ_b to zero. The dislocation density for W/Ga-W-O/β-Ga_2O_3

SBD is extracted by using $J_t(0)$ =1.78 × 10^{-7} A/cm^2, $E_0(0)$ = 25.83 meV, and $qV_k(0)$ = 0.47 eV. A dislocation density of about ~ 3.56 × 10^7 cm^{-2} is obtained. In Ga_2O_3, two types of dislocation, which are screw and edge are expected[31]. The high dislocation demonstrates the possibility of tunneling via dislocation dominated transport mechanism especially at low temperatures.

4. Conclusions

In conclusion, the parameters of W/β-Ga_2O_3 Schottky barrier diode (SBD), deposited by CMFS, were extracted and analyzed at different temperatures. The ideality factor decreases from 2.1 to 1.05 with increasing temperature from 100 to 300 K. The high ideality factor is interpreted by the tunneling current domination at low temperature. The barrier height increased from 0.54 to 1.03 eV with increasing temperature. These variations are related to the Gaussian distribution of ϕ_b in the interfacial layer. The high ϕ_b value at room temperature when CMFS used for tungsten deposition may be related to the high tungsten workfunction. R_s and R_{on} decreased with increasing temperature which was related to β-Ga_2O_3 resistivity. Finally, a 3.56 × 10^7 cm^{-2} dislocation density was extracted from the tunneling current. This high density demonstrated the domination of tunneling, via dislocation, transport mechanism especially at low temperatures.

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