Electrical Characteristics and Annealing Effect on Al/n-GaSb Schottky Diode Doped Using DMTe (Dimethyltellurium)

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Abstract

The electrical properties of Al/n-GaSb Schottky diodes, doped with 1.4×10^{18} cm^{-3} (tellurium) were examined. C-V (capacitance-voltage) measurements at 300 K show barrier heights of 0.63 eV, compared to 0.59 eV determined from room temperature I-V (current-voltage) measurements. The voltage and frequency dependence on the capacitance is due to the ideality factor of the Schottky barrier and due to a high series resistance. At low frequency the measured capacitance is dominated by the depletion capacitance of the Al/n-GaSb Schottky diode which is bias-dependent and frequency-dependent. The diode shows a strong temperature dependence of ideality factor from approximately 3.6 at room temperature to as high as 6.7 at 140 K. There may be a small portion of the device nonideality attributable to generation-recombination currents due to deep levels in GaSb. The barrier height decreased from 0.57 eV to 0.35 eV for the sample annealed at 300ºC for 1 minute.

Keywords: Schottky diode, Electrical properties, Annealing, Doping DMTe(Dimethyltellurium)

Abstrak

Sifat-sifat listrik dari diode Schottky Al/n-GaSb yang didadah dengan tellurium 1.4×10^{18} cm^{-3} dikaji dalam penelitian ini. Pengukuran C-V (kapasitansi-tegangan) pada suhu 300 K menunjukkan bahwa besarnya energi halang (barrier height) sebesar 0,63 dan dibandingkan dengan hasil pengukuran I-V (arus-tegangan) pada suhu kamar adalah sebesar 0,59 eV. Ketergantungan kapasitansi terhadap tegangan dan frekuensi adalah disebabkan oleh factor idealitas (ideality factor) energi halang dari diode Schottky dan juga disebabkan oleh resistansi seri yang tinggi. Pada frekuensi rendah kapasitansi yang terukur didominasi oleh kapasitansi deplesi dari diode Schottky Al/n-GaSb yang tergantung dari tegangan bias dan frekuensi. Faktor idealitas diode menunjukkan ketergantungan yang sangat kuat terhadap suhu, dari sekitar 3,6 pada suhu kamar sampai sebesar 6,7 untuk suhu 140^o. Ketidak-idelan divais munculnya dari arus generasi-rekombinasi karena tingkatan energy dalam GaSb. Energi halangnya menurun dari 0,57 eV menjadi 0,35 eV untuk sampel dianil pada suhu 300ºC selama 1 menit.

Kata kunci : Diode Schottky, Sifat listrik, Penganilan, Pendadahan DMTe(Dimethyltellurium)

1. Introduction

In a perfect metal-semiconductor contact, charge carriers can flow in either direction without experiencing any resistance at the interface. In reality, however, a potential barrier is always formed at the interface. The formation of the so called Schottky barrier has been modelled by several workers. The first model of the barrier formation was developed by Schottky (Schottky, 1938) and Mott (Mott, 1938). They suggested that, in the absence of interface states, the barrier is mainly due to the difference in the work function of the metal and semiconductor. When the metal is brought into contact with the semiconductor, in the case where the work function of the metal is larger than that of the semiconductor, electrons will be transferred from the semiconductor to the metal. The process will continue until the Fermi levels of the two materials line up. This process leads to an energy band bending within the semiconductor, forming a space charge depletion region.

Schottky barrier diodes are a basic structures for semiconductor characterisation and technology. Schottky barrier contacts can be used for investigating the physical and electrical properties of a semiconductor material and its surface, for example, a Schottky diode can be used to study bulk defects and interface properties of a metal-semiconductor system. Therefore, it is important to obtain a better understanding of the fundamental physical and electrical properties of the metal-semiconductor interface so that technologies for preparing Schottky contacts can be developed for device applications.

Schottky diodes obtained by evaporating various metals (Al, Au, Ag, Ni, Sb, Pd) on (100) n-GaSb (Te doped with density in the range of 1-2x10^{17} cm^{-3}) have been reported (Milnes *et al.*, 1993; Liu *et al.*, 2004; Ahmetoglu *et al.*, 2007) different barrier height values (depending also on the surface treatment) were found : for example, $q\phi_B$ ranges between 0.38-0.44, 0.64-0.84, and 0.43-0.46 eV, respectively, for silver, gold, and nickel deposited on vacuum cleaved GaSb. However, more recently it has been shown that pinning of the Fermi level near the top of the valence band (Dimoulas *et al.*, 2006; Li *et al.*, 2010) is responsible for an almost independent Schottky barrier height compared to the work function of the metal utilised (Polyakov *et al.*, 1992; Ait Kaci *et al.*, 2001). In fact, with a direct band gap equal to 0.7525 eV at 300 K, GaSb shows one of the highest Schottky barrier heights which deviates from the simple rule $q\phi_B = 2/3E_g$ (Mead, 1966). However, the achievement of an ideal GaSb Schottky barrier has proved to be difficult because an oxidised film inhomogeneously grows on the GaSb surfaces and if the latter is not stabilised by a passivating process, the oxide layer degrades the rectifying properties of any metal contact deposited on the surface. In fact, the highest barrier heights have been obtained on vacuum cleaved GaSb crystals (Pole *et al.*, 1987; Walters and Williams, 1988) or by evaporating in situ Al metal contact on molecular beam epitaxy grown n-GaSb layers (Perotin *et al.*, 1994).

In this paper, we investigate the electrical properties of Al/n-GaSb Te-doped epilayers grown by MOCVD and the effect of thermal treatment on the properties of the Schottky diodes.

2. Experimental Details

2.1 Device Fabrication

n-GaSb Te-doped epilayers were grown in a horizontal quartz atmospheric pressure MOCVD reactor. Six IR lamps were used to heat the graphite susceptor. TMGa (trimethylgallium) and TMSb (trimethylantimony) were used as metalorganic sources and kept at a constant bath temperature of -9 and 0°C, respectively which correspond to a molar flow of 2.53 and 1.82 μmol/min respectively, for 1 sccm hydrogen flows through the metalorganics. DMTe (dimethyltellurium) was used as dopant precursor and kept at a constant temperature of 27°C. High purity H_2 was passed through a proprietary metal hydride filter made by Ultra Pure Systems. The growth temperature was 540°C and the total flow rate of H_2 was 8 l/min. Substrates used were semi insulating (SI) GaAs (100) from Freiberger (Germany). Prior to the growth, substrates were immersed for 5 min in each of trichloroethylene at a temperature of 100°C, acetone and methanol and then etched in H_2SO_4:H_2O_2:H_2O=1:1:8 solution for 30 seconds followed by a DI water rinse. The substrate were then blown dry by N_2, before being loaded into the reactor.

Al/n-GaSb Schottky diodes were fabricated on (100) Te-doped *n*-GaSb epilayers with a doping concentration of 1.4 × 10^{18} cm^{-3} grown on Semi Insulating (SI)-GaAs substrates. The layers were first degreased for 5 min in boiling trichloroethylene and rinsed by ultrasonic vibration in acetone and methanol to remove organic contaminations, then etched with an H_2SO_4:H_2O_2:H_2O=1:1:8 solution to remove the surface damage layer and rinsed with deionised water. Before loading the samples into the evaporation chamber, the HCl:H_2O=1:1 solution was used to remove the native oxide layer on the GaSb surface. All etching was stopped in deionised H_2O (18 MΩ) and high purity nitrogen was used to dry the samples. The crystals were inserted into a metal evaporation unit immediately after the etching process. Low resistance ohmic contacts were formed by evaporation of Au-Ge-Ni followed by annealing at 350°C for 5 min in an N_2 atmosphere.

Standard photolithography techniques were used for Schottky contact formation. Before forming the Schottky contacts, the samples were dipped in dilute HCl for about 30 s to remove any native thin oxide layer on the surface and then rinsed in deionised water. Al was used as the Schottky contact and the diodes had dimensions of 580x580 μm^2. The evaporating processes were carried out in a vacuum coating unit at 10^{-6} Torr. After formation of the Schottky diodes, the samples were annealed in a quartz tube furnace from 200 to 500°C for 1 min in flowing N_2. The I-V characteristics were measured using a Keithley 487 Picoammeter/Voltage Source at room temperature and low temperature measurements were conducted using a Cryostat system.

2.2 Measurement Set Up

The I-V measurements were taken using a Wentworth Lab. Ltd. probe station equipped with a needle probe which was capable of making well defined pressure contact on areas of approximately 50 x 50 μm^2. A Keithley 595 controlled by a computer was used to simultaneously supply the bias and read the current. The I-V was measured at low temperatures using a cryogenic system. A similar circuit was used for capacitance-current (C-V) measurements by employing a HP LF4129A network analyser which could be operated from 100 Hz to 10 MHz.

3. Results and Discussion

3.1 I-V and C-V Analysis of Schottky Diode

Forward bias current-voltage characteristics can be used to determine the barrier height of metal-semiconductor contacts. In the case where the current transport is dominated by thermionic emission process, the I-V relationship is described by (Sze, 1981)

$$J = J_o \left(\frac{qV}{\eta kT} \right) \left[1 - \exp\left(-\frac{qV}{kT} \right) \right] , \tag{1}$$

$$J_o = A^* T^2 \exp\left(-\frac{q\phi_B}{kT} \right) , \tag{2}$$

where $\phi_B = (\phi_{Bo} - \Delta\phi_o)$ is the effective barrier height at zero bias. A* is the effective Richardson constant given by. $A^* = (4\pi m^* q k^3 / H^3)$. For a first order approximation, only electrons in the direct Γ band are considered to contribute to the current transport. The value of $A^* = 5.4 Acm^{-2}\ K^{-2}$) is used which is independent of temperature (Crowell and Sze, 1966). The effective barrier height at zero bias is thus given by

$$\phi_b = \frac{kT}{q} \ln\left(\frac{A_d A^* T^2}{I_o} \right) , \tag{3}$$

where A_d is the Schottky contact area, I_o is the saturation current at zero bias.

Extrapolating a plot of forward bias *vs* ln(I)/[1-exp(-qV/kT)] gives the saturation current at zero bias I_o, from which the barrier height at zero bias can then be extracted, while the slope of this plot gives the value of the ideality factor, η, given by

$$\frac{1}{\eta} = \frac{kT}{q} \frac{d}{dV} \ln\left[\frac{J}{\{1 - \exp(-qV/kT)\}} \right] , \tag{4}$$

or, for V > 3kT/q,

$$\frac{1}{\eta} = \frac{kT}{q} \frac{d(\ln J)}{dV} . \tag{5}$$

A reverse-biased Schottky diode can also be used to determine the barrier parameters. The existence of charges in the barrier region makes the depletion region behave like a parallel plate capacitor. There are three sources of charge in the barrier region of an *n*-type semiconductor. These are (i) due to uncompensated donors, (ii) holes in valence band, and (iii) electrons in the metal surface (Sze, 1981). The space charge per unit area, Q_{SC}, and the capacitance of the depletion layer per unit area are given by (Rhoderick and Williams, 1988)

$$Q_{SC} = [2q\varepsilon_s N_D (V_{bi} - V_r - kT)]^{1/2} , \tag{6}$$

and

$$C = \left[\frac{q\varepsilon_s N_D}{2} \right]^{1/2} \left[V_{bi} - V_r - \frac{kT}{q} \right]^{-1/2} , \tag{7}$$

or

$$\frac{1}{C^2} = \frac{2\left(V_{bi} - V_r - \frac{kT}{q} \right)}{q\varepsilon_s N_D} , \tag{8}$$

where V_{bi} is the built-in potential, and ε_s the dielectric constant of the semiconductor (1.39×10^{-10} F/cm for GaSb). Equation 8 shows that a plot of $1/C^2$ vs V should give a straight line with a slope of $2/q\varepsilon_s N_D$ and an intercept with the horizontal axis at

$$V_I = V_{bi} - \frac{kT}{q} \tag{9}$$

The barrier height is then determined by

$$\phi_{Bn} = V_{bi} + \xi = V_I + \frac{kT}{q} + \xi , \tag{10}$$

where ξ is given by

$$\xi = \left(\frac{kT}{q} \right) \ln\left(\frac{N_C}{N_D} \right) , \tag{11}$$

with N_C the effective density of states in the conduction band.

3.2 C-V Measurements

Figure 1 shows a plot of the inverse capacitance per unit area squared versus reverse bias at room temperature. The capacitance was measured at 1 MHz. The doping density calculated from this graph of n = 1.5×10^{18} cm^{-3} is in good agreement with the Hall data. This is the highest doping density reported for this material. From the C-V measurement data, the intercept voltage (V_i) was found to be 0.63 eV and the barrier height is calculated using Equation (10) to be 0.64 eV. This value is comparable to that found for Schottky diodes formed by Al deposition on Te-doped GaSb grown using different metalorganic sources (Poole *et al.*, 1987; Roteli *et al.*, 1997; Chen *et al.*, 1996).

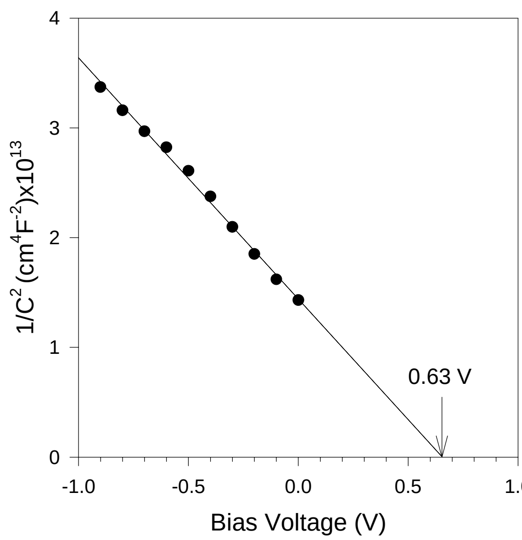

Figure 1. Inverse capacitance vs reverse bias at room temperature.

3.3 Frequency Dependent C-V Measurements

Frequency dependent C-V measurement were performed on the Schottky diode as a function of bias. Figure 2 shows typical response curves for a GaSb Schottky diode which indicate that the measured capacitance is dependent on the reverse bias voltage and frequency. The voltage and frequency dependence is due to the ideality factor of the Schottky barrier and due to a high series resistance (Sahin *et al.*, 2005; Tararoglu and Altindal, 2006). At low frequency the measured capacitance is dominated by the depletion capacitance of the Al/n-GaSb Schottky diode which is bias-dependent and frequency-dependent. As the frequency is increased, the total diode capacitance is affected not only by the depletion capacitance but tunnelling which renders the device susceptible to stray inductances (Butcher *et al.*, 1996). Because of these effects, the capacitance-bias dependence becomes less pronounced or disappears. The frequency dependence is weakened for high reverse voltages.

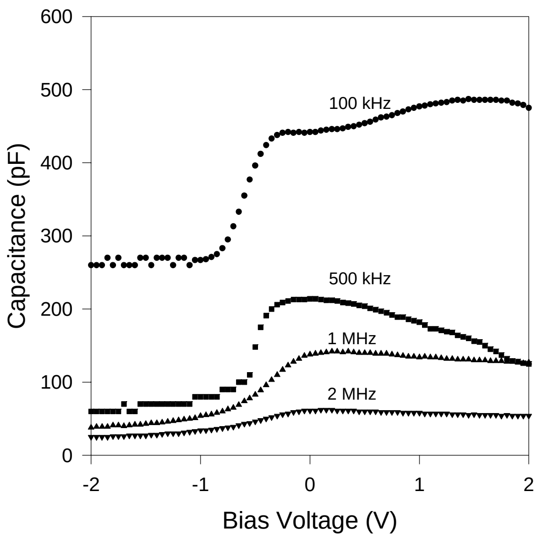

Figure 2. The frequency dependence of the capacitance of the Al/n-GaSb Schottky diode at room temperature.

3.4 I-V Characteristics and Ideality Factor

Low-temperature I-V measurements were conducted using a Cryostat system. A semilogarithmic plot of the I-V-T characteristics of a typical Al/n-GaSb diode over a temperature range of 140 - 320K and the linear part of the forward bias plot are shown in Figures 3 and 4 respectively. As shown in Figure 4, the saturation current density J_o (equation 1) is the intercept on the current axis at zero bias. J_o at 300 K was found to be $1.45x10^{-4}$ A/cm^2. The room temperature value of barrier height for the diode determined using equation (2) and was found to be 0.57 eV. The temperature dependence of the barrier height ϕ_B for the same sample is shown in Figure 5, where the barrier height of ϕ_B gradually decreases when the temperature is lowered. Temperature dependence, of η and ϕ_B, similar to that of Figure 5 indicates inhomogeneity at the metal-semiconductor interface (Tyagi, 1984; Saxana, 1969; Werner and Guttler 1991). Literature reports on the temperature dependence of ϕ_B are conflicting. Polyakov *et al.* (1992) showed that the ϕ_B for an Au Schottky barrier on GaSb was a decreasing function of temperature with temperature dependence identical to that of the band gap (E_g). Walters and Williams (1988) found that ϕ_B for an Au Schottky barrier on GaSb decreased more or less linearly with increasing temperature with a temperature coefficient of about $-0.3x10^{-4}$ eV/K. This result is similar to the temperature dependence of ϕ_B of Figure 5 with a temperature coefficient of about $-0.2x10^{-4}$ eV/K. On the other hand, Spicer *et al.* (1985) observe that the temperature dependence of ϕ_B for a Pd Schottky barrier on GaSb was much less than that of E_g. On theoretical grounds one would expect a temperature dependence of E_g to result in a temperature dependence of ϕ_B, because of a change in E_g-ϕ_o where ϕ_0 is the neutral level for surface states. It is also expected that ϕ_B and χ_S, would change with temperature. The interpretation of the temperature dependence of ϕ_B is not clear.

The difference in barrier height as obtained from capacitance-voltage (C-V) and current-voltage (I-V) measurements on Al/*n*-GaSb Schottky barriers can be explained as follows: when comparing the values obtained for ϕ_B, 0.63 and 0.59 eV by C-V characteristics and I-V-T characteristics, respectively, the effects of an insulating layer or charges existing at the semiconductor-metal interface must be considered. Most Schottky diodes have a thin oxide or insulating layer at the metal-semiconductor junction unless all the processing is done in a vacuum. In the case of C-V measurements, an interface layer of several monolayers or so can significantly enlarge the value V_o determined at $1/C^2 = 0$ and the measured barrier potential. Also, deep levels occurring in the GaSb band gap can affect capacitance measurements if they emit carriers to the conduction band at a rate comparable to the testing signal frequency of the capacitance meter.

The effective value of the Richardson coefficient that was used in this analysis, 5.4 A cm^{-2}K^{-2}, is very small compared to that determined theoretically based on the effective mass, 26 A cm^{-2}K^{-2} using $A^*=(4\pi m^* qk^3/h^3)$ (Tyagi, 1984). This would indicate the presence of a barrier through which the electrons must tunnel. The ideality factor η, however, is near unity indicating that the potential in the insulating layer remains constant with voltage. Rhoderick and Williams (1988) showed that for very thin insulating layers on silicon, charged states which exist in equilibrium with the metal tend to hold the barrier height constant, thus the ideality factor η remains low. The present tests indicates that a very thin barrier exists at the junction through which the electrons must tunnel, but the potential drop across it remains fairly constant with applied voltage. The electric potential across this layer, or charges it contains, is a probable cause of the difference in the measured barrier heights by capacitance-voltage and current-voltage techniques.

The ideality factor (η) can be calculated from the linear part of the I-V curves as shown in Figure 4, according to equation (4). The diode shows a strong temperature dependence of ideality factor from approximately 3.6 at room temperature to as high as 6.7 at 140 K. There may be a small portion of the device nonideality attributable to generation-recombination currents due to deep levels in GaSb. Similar results have been reported by Chen *et al.*, (1996). However tunnelling mechanisms probably provide a greater contribution to both the high device currents and device nonideality. Another possibility for the high leakage current is due to oxide layer on the GaSb epilayer as reported by Perotin *et al.*, (1994) on Au/n-GaSb Schottky diode. Even though the removal of oxide layer during Schottky diode fabrication has been conducted, the exposure from the atmosphere was unavoided resulting a native oxide on n-GaSb surface. The oxide layer degraded the rectifying properties of metal contact deposited on the surface.

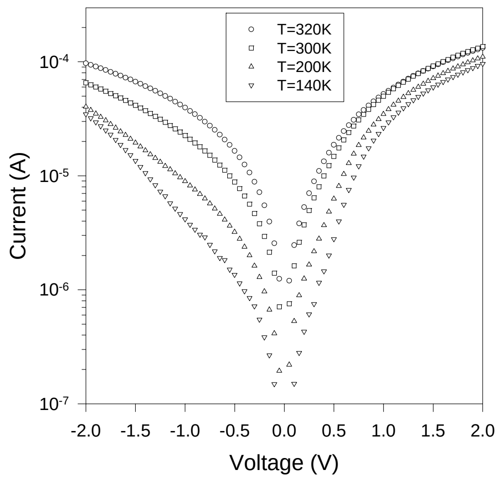

Figure 3. I-V-T characteristics of Al/n-GaSb Schottky diode.

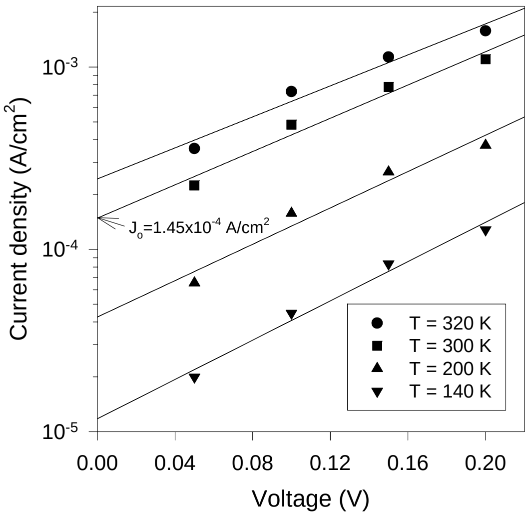

Figure 4. Plot of current density as a function forward bias in the temperature range 140 320 K.

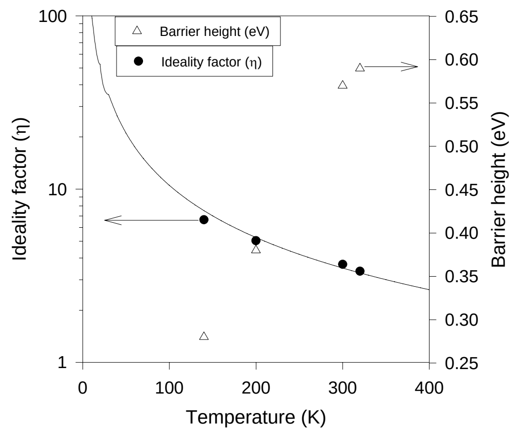

Figure 5. Plot of ideality factor and barrier height *versus* temperature. Points are experimental data, the solid line is predicted by equation 13.

For materials with low doping level, nearly ideal diodes with ideality factors close to unity may be expected. In this case, η is insensitive to the temperature. A strong deviation of η from unity is evident for the Al/*n*-GaSb diodes prepared in this work because the starting material has a moderately high doping level. This is an indication that the tunnelling mechanism is involved in the current transport mechanism and the I-V relationship of equation 1 can then be rewritten in the form

$$J=J_s \exp\left(\frac{qV}{\eta kT}\right)\left[1-\exp\left(-\frac{qV}{kT}\right)\right], \qquad (12)$$

where the ideality factor, η, now can be shown to be of the form (Padovani and Stratton, 1966)

$$\eta = \zeta \coth \zeta \text{ with} \zeta = \frac{q\hbar}{2kT}\sqrt{\frac{N_D}{\varepsilon m^*}} , \qquad (13)$$

where ħ is the reduced Planck constant, ε is the dielectric constant equal to 1.38×10^{-10} Fcm^{-1} for GaSb, m* is the electron effective mass equal to 0.38×10^{31} kg for GaSb and N_D is the donor concentration. The ideality factor as a function of temperature predicted by equation (13) for the Al/*n*-GaSb Schottky diode is presented in Figure 5 (solid line). The data fit well for an assumed donor density of 2.1×10^{18} cm^{-3}. This value is slightly higher than the value obtained from C-V measurements (see Figure 1). This is not surprising since the tunnelling current penetrates the tip of the barrier, which lies within a few monolayers of the interface where the local donor density may be higher than that in the bulk.

3.5 Sample Annealing

The electrical properties of Al/n-GaSb Schottky barriers were compared following annealing under various conditions. The effect of annealing is clearly observed. The room temperature I-V characteristics of an Al/n-GaSb Schottky diode following different annealing temperature treatments is shown in Figure 6. At room temperature, the diode shows a relatively good forward and reverse characteristics. The I-V characteristic becomes more ohmic with higher annealing temperatures and higher current currents are evident. The barrier height measured from the I-V characteristics, as a function of the annealing temperature, for an Al/n-GaSb diode is shown in Figure 7. The barrier height decreased from 0.57 eV to 0.35 eV for the sample annealed at 300ºC for 1 minute. In general, the barrier height was found to decrease with increasing annealing time. The barrier lowering may be partly due to an increase in doping concentration at the metal-semiconductor interface caused by metal in diffusion from the metal barrier. This is confirmed by C-V measurements. Finally, the Schottky diodes become completely ohmic as the annealing temperature is raised to 400ºC for 1 minute due to interaction of metal and semiconductor (Su *et al.,* 1990).

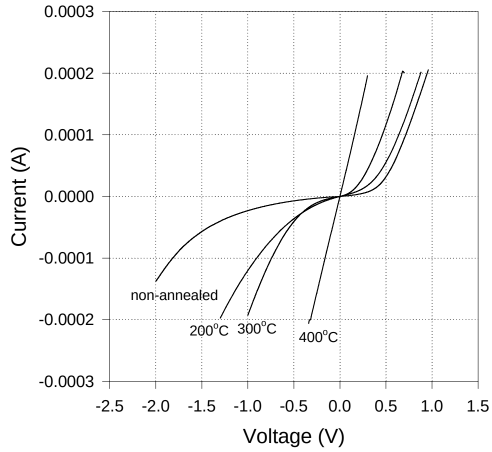

Figure 6. I-V characteristics of the Al/n-GaSb Schottky diode at different annealing temperatures.

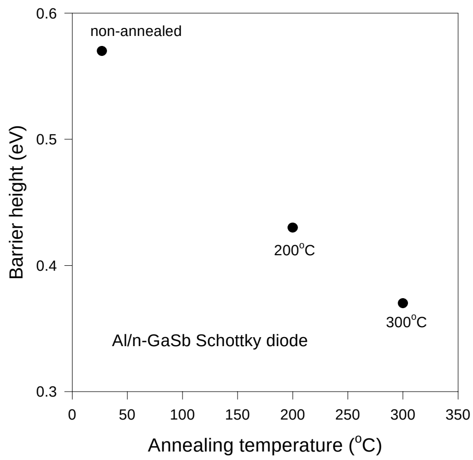

Figure 7. The barrier height as a function of annealing temperature (annealing time at 1 minute).

4. Conclusions

Aluminium Schottky contact to n-GaSb have been studied. Al/n-GaSb Schottky diodes have been fabricated using Te-doped n-GaSb grown on GaAs substrates by MOCVD. GaSb with n-type doping density of 1.4×10^{18} cm^{-3} was used. It was found that room-temperature barrier heights for Al/n-GaSb Schottky diodes were equal to 0.59 eV and 0.63 eV determined using both I-V and C-V measurements, respectively. Room temperature (RT) ideality factor of Al/n-GaSb Schottky diodes is approximately 3.6. The doping density $n = 1.5 \times 10^{18}$ cm^{-3} calculated from C-V measurement is in good agreement with Hall data. The model of thermally-assisted tunnelling provides a quantitative fit with experiment. Fit is achieved with a slightly higher donor concentration at the semiconductor surface than found at the depletion region edge by C-V measurements. The Schottky diode capacitance is dependent on the reverse bias voltage and frequency. As the frequency is increased, the total diode capacitance is affected not only by the depletion capacitance but tunnelling which renders the device susceptible to stray inductances. After annealing, the barrier height decreased from 0.57 eV to 0.35 eV for an Al/n-GaSb sample annealed at 300^{o}C for 1 minute. The barrier lowering may be partly due to an increase in doping concentration at the metal-semiconductor interface.

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