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Temperature dependence of current–voltage characteristics of an In/p-GaSe:Gd/Au–Sb Schottky barrier diode

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Abstract
In/p-GaSe:Gd/Au–Sb Schottky barrier diodes (SBDs) have been fabricated and characterized by the current–voltage (*I–V*) technique as a function of temperature. The forward *I–V* characteristics have been analysed on the basis of standard thermionic emission (TE) theory and the assumption of a single Gaussian distribution of the barrier heights (BHs), and the characteristic parameters of the SBD such as barrier height, ideality factor and series resistance have been determined from the *I–V* measurements. The modified Richardson plot, according to inhomogeneity of the BHs, has good linearity over the temperature range. The value of the Richardson constant has been found to be 310 A cm^{-2} K^{-2}, which is close to the theoretical value of 247 A cm^{-2} K^{-2} for p-GaSe.

1. Introduction

A gallium selenide (GaSe) crystal belonging to $A^{III}B^{VI}$ semiconductor compounds has a layered structure [1]. The low density of dangling bonds on the surface because of the almost complete chemical bonds within the layer, the intercalation and mechanical weakness due to the weak van der Waals force among the layers are the typical characteristics of the layered semiconductor. Thus, it is possible to form heterojunction devices with a low interface density of states and to alter the electrical properties of the semiconductor, which is convenient in device processing [2].

Layered semiconductors have received considerable attention owing to their numerous potential applications such as the production of optical switching devices [3] and photodetectors [4, 5], light emitting diodes working in the visible region of the electromagnetic spectra [6, 7], a radiation detector operating at room temperature [8, 9] and a photoelectric analyser of polarized light [10].

Metal–semiconductor (MS) structures are important research tools in the characterization of semiconductor materials. At the same time, the fabrication of these structures plays a crucial role in the construction of some useful devices [11]. In the literature, very few experimental studies are available on the current–voltage (*I–V*) characteristics as a function of temperature for layered semiconductors. The current–voltage characteristic parameters of the metal/p-GaSe:Gd Schottky barrier diode (SBD) in the wide temperature range have not yet been reported.

In this study, the *I–V* measurements of the In/p-GaSe:Gd/Au–Sb SBD are reported for the first time, to our knowledge. Temperature dependences of the ideality factor and barrier height of the diode have been analysed by the thermionic emission (TE) mechanism in the light of the inhomogeneity model. The series resistance effect has been observed from the forward-bias region of the *I–V* characteristics. Therefore, Norde's functions have been used to determine some contact parameters such as the barrier height (BH) and value of series resistance of the In/p-GaSe:Gd/Au–Sb SBD.

2. Experimental details

A p-GaSe:Gd monocrystal was grown in our crystal growth laboratory by using a modified Bridgman–Stockbarger

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method. The sample used in this work was gently cleaved with a razor blade from the grown ingots, and it was immediately inserted into the deposition chamber. Neither further polishing nor cleaning treatment was required because of the natural mirror-like cleavage faces of the grown sample. Ohmic contact on the backside of the sample was formed by thermally evaporating indium (In) and then annealing at 300 °C for 2 min in a nitrogen atmosphere. The Schottky contacts with diameters of about 1 mm by means of a shadow mask were formed by evaporating an Au–Sb alloy on the front of the p-GaSe:Gd sample. All evaporation processes were carried out in a vacuum coating unit at about 10^{-6} Torr. The *I*–*V* measurements of the diode were performed using a Keithley 487 picoammeter/voltage source and a Leybold Heraeus closed-cycle helium cryostat in the temperature range of 120–320 K with a temperature step of 20 K ($\Delta K = 20$ K) under dark conditions.

3. Results and discussion

An ideal Schottky contact current can be described by the well-known TE theory given as follows [12]:

$$I = I_0\left[\exp\left(\frac{qV}{nkT}\right) - 1\right], \tag{1}$$

where I_o is the saturation current derived from the straight line intercept of ln$I$ at $V = 0$ and is given by

$$I_0 = AA^*T^2 \exp\left(-\frac{q\Phi_{ap}}{kT}\right). \tag{2}$$

The quantities V, A, T, k, q and Φ_{ap} are the forward-bias voltage, diode area, temperature in kelvin, Boltzmann's constant, electronic charge and zero bias apparent (experimental) BH, respectively. A^* is the Richardson constant of 247 A cm^{-2} K^2 for p-GaSe [13].

From equation (1), n is the ideality factor and is a measure of the uniformity of the diode to pure TE and is given by the following relation:

$$n = \frac{q}{kT}\left(\frac{\mathrm{d}V}{\mathrm{d}\ln I}\right). \tag{3}$$

The reverse- and forward-bias *I*–*V* plots of the In/p-GaSe:Gd/Au–Sb SBD in the temperature range of 120–320 K are given in figure 1. As can be seen, a change of both forward and reverse characteristics has occurred with temperature. The reverse-bias current of the In/p-GaSe:Gd/Au–Sb SBD has increased with increasing temperature.

The value of the ideality factor of the In/p-GaSe:Gd/Au–Sb SBD was calculated from the slopes of the linear regions of the semi-log forward-biased *I*–*V* curves (figure 1) at each temperature, using equation (3). I_0 was obtained by extrapolating the linear region of the semi-log forward *I*–*V* curves and Φ_{ap} was determined by using equation (2). The determined values of n and Φ_{ap} are presented in figure 2 as a function of temperature. As can be seen from figure 2, the ideality factor (n) and Φ_{ap} values obtained by analysing the forward-biased *I*–*V* characteristic based on the TE mechanism indicated that, although the ideality factor values have slightly increased, the Φ_{ap} values have decreased

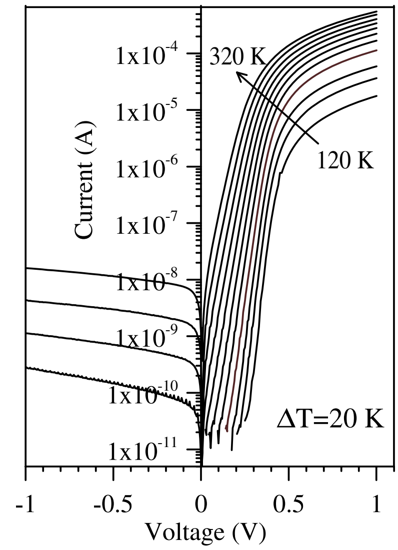

Figure 1. Current–voltage characteristics of the In/p-GaSe:Gd/Au–Sb Schottky barrier diode at various temperatures.

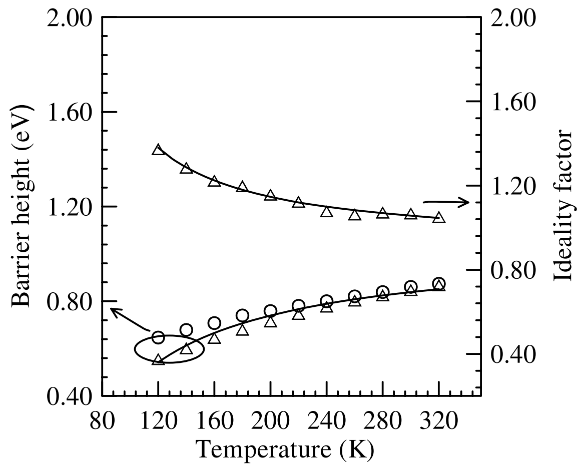

Figure 2. Temperature dependence of the barrier height and ideality factor (triangles) for the In/p-GaSe:Gd/Au–Sb Schottky barrier diode. The solid lines show calculated values of the ideality factor and barrier height obtained using equations (5) and (6), and the circles show the barrier height values obtained from the Norde method [25].

with decreasing temperature. The experimental values of Φ_{ap} for the SBD range from 0.56 eV (at 120 K) to 0.87 eV (at 320 K). This is likely due to the laterally inhomogeneous barrier height causing deviations from thermionic emission which become more pronounced as the temperature decreases [14, 15]. Because the electrons possess a weak kinetic energy kT at low temperature, they prefer to pass the low barrier [16]. Since the current transport across the MS interface is a temperature-activated process at low temperatures, it will be dominated by current flowing through the patches of the lower SBH and larger ideality factor. The dominant BH will increase with the increasing temperature and bias voltage [17–24].

There are certainly sources for SBH inhomogeneity. For example, there may be a mixture of different metallic

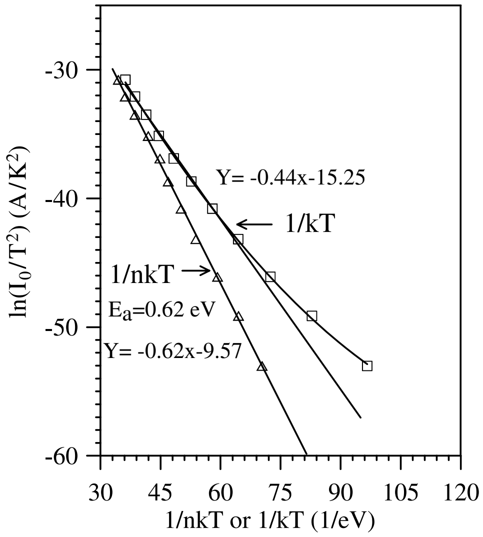

Figure 3. The Richardson plot of $\ln(I_0/T^2)$ versus $1/nkT$ or $1/kT$ for the In/p-GaSe:Gd/Au–Sb Schottky barrier diode.

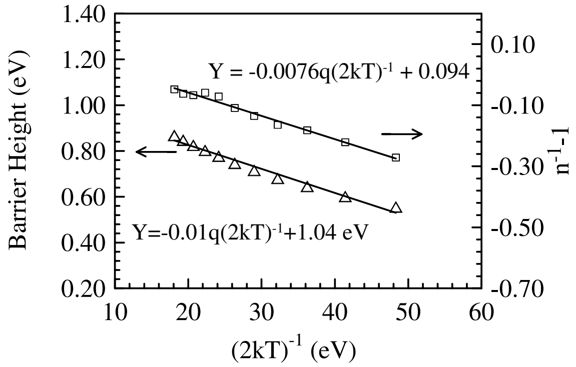

Figure 4. The barrier height and ideality factor versus $1/2\,kT$ curves of a In/p-GaSe:Gd/Au–Sb Schottky barrier diode according to Gaussian distribution of the barrier heights.

phases with different SBHs at a MS interface due to an incomplete interfacial reaction. Additionally, there may be doping inhomogeneity at the MS interface, dopant clustering. Contamination at the MS interface, whether particulates or undesirable reaction products, is often present at the MS interfaces of diodes prepared by the routine processing methods used in the semiconductor electronics industries. These contaminants may act directly to introduce inhomogeneity or they may simply promote inhomogeneity through the generation of defects, additional interfacial chemical phases, etc. Even in the absence of a chemical contaminant, SBH inhomogeneity may be present. Finally, there are numerous structural defects, grain boundaries, dislocations, stacking faults at MS interfaces, and these may contribute to SBH inhomogeneity [24].

In a different way, equation (2) can be rewritten as follows to determine the barrier height by means of the 'conventional' Richardson plot:

$$\ln\left(\frac{I_0}{T^2}\right) = \ln(AA^*) - \frac{q\Phi_b}{kT}. \tag{4}$$

The Richardson constant is usually determined from the intercept of the $\ln(I_0/T^2)$ versus $1/kT$ plot. By using the values of n determined from equation (3), the Richardson plot of $\ln(I_0/T^2)$ versus $1/kT$ or $1/knT$ for the In/p-GaSe:Gd/Au–Sb SBD was obtained as is shown in figure 3. The conventional $\ln(I_0/T^2)$ versus $1/kT$ Richardson plot is nonlinear (figure 3). This nonlinearity is caused by the temperature dependence of the barrier height and ideality factor, especially at lower temperature. Similar results have also been found by several authors [11, 17, 19–21, 23, 24, 26–28].

The Richardson constant value of $A^* = 3.04 \times 10^{-5}$ A cm^{-2} K^{-2} is determined from the intercept at the ordinate of this experimental plot, which is much lower than the known value for holes in p-GaSe (247 A cm^{-2} K^{-2}). This deviation may be attributed to the spatial inhomogeneous barrier heights and potential fluctuations at the interface that consist of low and high barrier areas [17–19, 21, 22, 27, 29, 30]. The formation of a laterally inhomogeneous Schottky barrier may result into an effective area for the current conduction lower than the total area of the diode [31].

The dependence of $\ln(I_0/T^2)$ versus $1/nkT$ is linear in the temperature range 120–320 K with a slope giving an activation energy of 0.62 eV and a value of 8.89×10^{-3} A cm^{-2} K^{-2} for the Richardson constant as shown in figure 3. This value of A^* is still significantly lower than the theoretical prediction of 247 A cm^{-2} K^{-2}. Such a large deviation in the Richardson constant has also been observed for the Ag/SnSe SBD by Tugluoglu *et al* [11] and Pt/GaN SBD by Iucolano *et al* [31].

For the temperature dependence of the barrier height and ideality factor, spatial inhomogeneities are assumed to model the interface of the Schottky diode which, for the case of a Gaussian distribution, lead to equations (5) and (6) for Φ_{ap} and n_{ap}, respectively [32]. The decrease in the barrier height with a decrease in temperature can be explained by the lateral distribution of the BH if the BH has a Gaussian distribution of the BH values over the Schottky contact area with the mean BH $\bar{\Phi}_{b0}$ and standard deviation σ_s. The standard deviation is a measure of the barrier homogeneity. The Gaussian distribution of the BHs yields the following expression for the BH [23, 33–36]:

$$\Phi_{ap} = \bar{\Phi}_{b0} - \frac{q\sigma_s^2}{2kT}, \tag{5}$$

where Φ_{ap} is the apparent BH measured experimentally, $\bar{\Phi}_{b0}$ stands for the mean BH and σ_s is the standard deviation, at zero bias. The temperature dependence of σ_s is usually small and can be ignored [37]. Thus, the plots of Φ_b versus $1/2\,kT$ (figure 4) should be a straight line that gives $\bar{\Phi}_{b0}$ and σ_s from the intercept and slope, respectively.

The observed variation of the ideality factor with temperature in the model is given by [34]

$$\left(\frac{1}{n_{ap}} - 1\right) = -\rho_2 + \frac{q\rho_3}{2kT}, \tag{6}$$

where n_{ap} is the apparent ideality factor (experimental data) and ρ_2 and ρ_3 quantify the voltage deformation of the BH distribution. The temperature dependence of the ideality factor can be understood on the basis of equation (6), which indicates that the $(1/n) - 1$ versus $1/2\ kT$ plot should give a straight

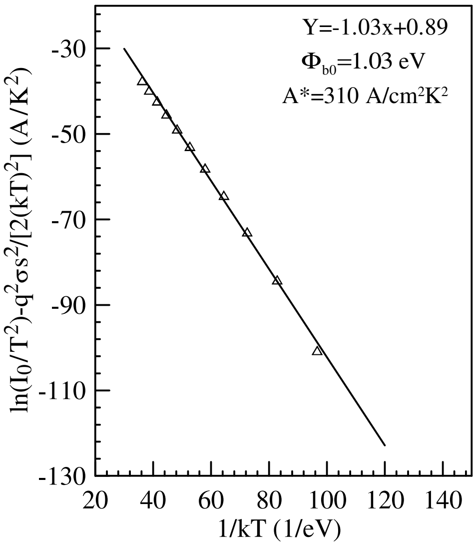

Figure 5. The modified Richardson plot $\ln(I_0/T^2) - (q^2\sigma_s^2/2k^2T^2)$ versus $1/kT$ plot for the In/p-GaSe:Gd/Au–Sb Schottky barrier diode according to Gaussian distribution of barrier heights.

line with an intercept and a slope dependence on the voltage coefficients ρ_1 and ρ_2, respectively. The values of $\rho_2 = -0.094$ and $\rho_3 = -0.0076$ V were obtained from the $((1/n) - 1)$ versus $1/2\ kT$ plot (figure 4). The continuous solid line in figure 2 represents data-estimated values of the ideality factor and BH obtained using equations (5) and (6). These results fit very well with the experimental results represented in figure 2.

The Richardson plot can be modified by combining equations (2) and (5) and using the experimental I_0 data and can be written as

$$\ln\left(\frac{I_0}{T^2}\right) - \left(\frac{q^2\sigma_s^2}{2k^2T^2}\right) = \ln(AA^*) - \frac{q\bar{\Phi}_{b0}}{kT}. \qquad (7)$$

A modified $\ln(I_0/T^2) - \left(q^2\sigma_s^2/2k^2T^2\right)$ versus $1/kT$ plot gives $\bar{\Phi}_{b0}$ and A^* as 1.03 eV and 310 A cm^{-2} K^{-2}, respectively (figure 5). As can be seen, the value of $\bar{\Phi}_{b0} = 1.03$ eV obtained from this plot is in agreement with the value of 1.04 eV obtained from the BH plot versus $1/kT$ plot. The agreement between the theoretical effective Richardson constant and the value obtained from this plot is the evidence for the presence of barrier inhomogeneity (the model of Gaussian distribution) SBHs in the In/p-GaSe:Gd/Au–Sb SBD.

In order to provide evidence for the presence of barrier inhomogeneity, the temperature dependence of the ideality factor can be reported in the form of a plot of nkT versus kT [24, 38]. The high values of the ideality factor show that there is a deviation from the TE theory for the current mechanism. The increase in the ideality factor with decreasing temperature is known as the T_0 effect [39]. The temperature dependence of the ideality factor observed and given in figure 2 is found to have the form $n = 1 + (T_0/T)$, where T_0 is a constant, independent of temperature. This behaviour is typical of a real Schottky contact, i.e. a contact with a distribution of barrier inhomogeneities. Figure 6 shows the nkT versus kT plot for the SBD in the temperature range of 120–320 K, respectively.

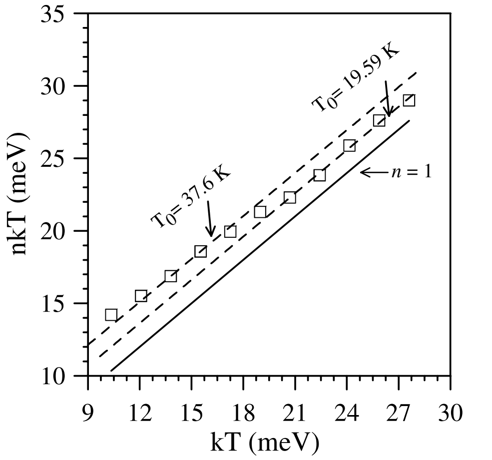

Figure 6. The nkT versus kT plot for the In/p-type GaSe:Gd/Au–Sb Schottky barrier diode.

In this figure, the solid line represents the ideal behaviour ($n = 1$) and the experimental data (open squares) could be fitted by a straight line which is parallel to that of the ideal Schottky contact behaviour ($n = 1$) in the temperature ranges of 120–220 K and 240–320 K.

The value of T_0 for the In/p-GaSe:Gd/Au–Sb SBD has been found to be 37.60 K in the temperature range of 120–220 K and 19.59 K in the temperature range of 240–320 K from the linear fit to experimental data, respectively (figure 6). Similar results were reported in the literature [15, 38].

This behaviour was explained with the presence of a distribution of low barriers combined with a large uniform area of higher SBHs [24].

It has been observed that the voltage drop caused non-ideal behaviour at all temperatures at a high voltage region (series resistance region). According to the thermionic emission theory, the forward-bias *I–V* characteristics of a SBD with the series resistance can be expressed as [12]

$$I = I_0 \exp\left[\frac{q(V - IR_s)}{nkT}\right], \qquad (8)$$

where R_s is the series resistance and the IR_s term is the voltage drop across the series resistance of the diode. Norde's function [25] $F(V)$ has been used to obtain the values of the BH and the series resistance. The $F(V)$ function is defined as

$$F(V) = \frac{V}{2} - \frac{kT}{q}\ln\left(\frac{I(V)}{AA^*T^2}\right), \qquad (9)$$

where $I(V)$ is the current obtained from the *I–V* curve. A plot of $F(V)$ versus V for the diode at different temperatures is shown in figure 7.

The value of the barrier height of a diode can be determined as follows (by using Norde's functions):

$$\Phi = F(V_{\min}) + \frac{V_{\min}}{2} - \frac{kT}{q}, \qquad (10)$$

where $F(V_{\min})$ is the minimum value of $F(V)$ and $V_{\min}$ is the corresponding voltage [40]. The estimated SBH of the In/GaSe:Gd/Au–Sb SBD obtained by the Norde method is 0.87 eV at 300 K and has been given in figure 2. This value is consistent with the value obtained by the *I–V* method.

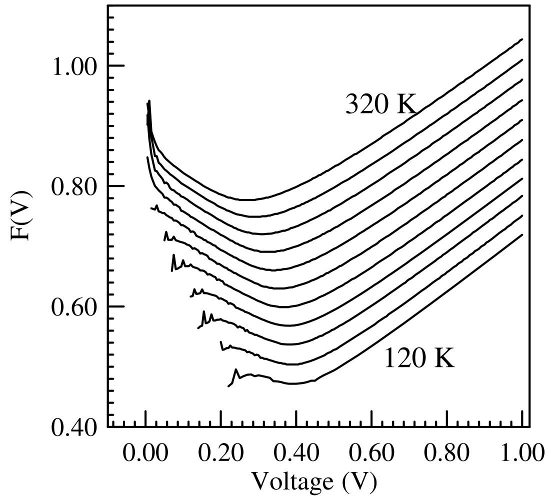

Figure 7. The $F(V)$ versus V plot of the In/p-GaSe:Gd/Au–Sb Schottky barrier diode at various temperatures.

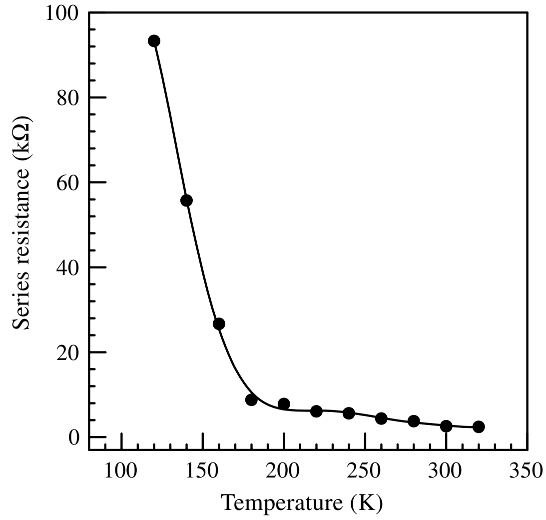

Figure 8. Temperature dependence of the series resistance from Norde's functions of the In/p-GaSe:Gd/Au–Sb Schottky barrier diode.

For real contacts ($n > 1$), the series resistance can be expressed as [41, 42]

$$R_s = \frac{(2-n)kT}{qI_{\min}}, \tag{11}$$

where $I_{\min}$ is the value of the forward current at the voltage $V_{\min}$ where the function $F(V)$ exhibits a minimum. From the $F(V) - V$ plots, the values of the series resistance (R_s) of the SBD given in figure 8 have been determined as 2.44 kΩ at 320 K and 93.31 kΩ at 120 K, respectively.

The SBH has decreased and series resistance has increased with decreasing temperature. Temperature-dependent Hall measurements indicated that the resistivity of the GaSe:Gd sample increases with increasing temperature [43]. The increase of the GaSe:Gd resistivity causes an increase of R_s, which leads to a downward *I–V* curve at high voltages. The high value of the series resistance can be attributed to the freeze-out of carriers at low temperatures.

4. Conclusion

The *I–V* characteristics of the In/p-GaSe:Gd/Au–Sb SBD were measured in the temperature range 120–320 K for the first time. The *I–V* characteristics of the GaSe-based Schottky diodes over a wide temperature range have been modelled on the basis of the thermionic emission mechanism by assuming the presence of single Gaussian distributions of barrier heights. The basic diode parameters such as the ideality factor, barrier height and series resistance were extracted from electrical measurements of the In/p-GaSe:Gd/Au–Sb SBD. The sample has displayed a good ideality factor which remains nearly unchanged with increasing temperature above 240 K. But below 240 K, the ideality factor has increased as the temperature has been lowered, reaching a value of 1.37 at 120 K. However, Φ_{ap} has decreased with decreasing temperature. The experimental results of the BH and ideality factor fit very well with the theoretical equations related to the Gaussian distribution of Φ_{ap} and n_{ap}. The Richardson constant was determined to be 310 A cm^{-2} K^{-2}, in agreement with the theoretical value.

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