Study of Temperature-dependent Conduction Mechanisms in Au/0.8nm-GaN/n-GaAs Schottky Diode

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Study of temperature-dependent conduction mechanisms in Au/0.8nm-GaN/n-GaAs Schottky diode

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Abstract

Passivation of interface states in the Schottky barrier is an approach to enhance the properties of the Schottky devices. In this work, Au/0.8nm-GaN/n-GaAs Schottky structure is studied electrically in a wide temperature range. With increasing temperature, the reverse current I_{inv} increases from 1×10^{-7} A to 1×10^{-5} A, and the saturation current I_s increases from 1×10^{-32} A to 5×10^{-7}A. The series resistance R_s decreases with increasing temperature from 13.44 Ω to 4.25 Ω. The ideality factor n decreases from 10.64 to 1.15. The barrier height ϕ_b increases abnormally with increasing temperature from 0.54 eV at 80 K to 1.03 eV at 180 K, then decreases to 0.82 eV at 420 K. The abnormal behavior of ϕ_b and the high values of n in low temperature are due to the tunnel mechanisms effects, such as FE and TFE currents. FE mechanism is the dominant process at low temperatures (80-300 K) and TFE mechanism is the dominant one at high temperatures (300-420K). Finally, our structure presents an inhomogeneous barrier height, maybe caused by the thin GaN interface layer.

Keywords: nitridation; GaN/n-GaAs; Schottky diode; I-V-T; conduction mechanisms; barrier height;

Introduction

Metal-semiconductor (MS) contacts are very important in microelectronics [1-4]. Such as optoelectronic devices, bipolar integrated circuits, high-temperature, and high-frequency applications [5, 6]. The thermionic emission (TE) theory is the

principal theory used to determine the parameters of the Schottky contact. However, some anomalies were reported at low temperatures and found that the Schottky barrier height and the ideality factor extracted from the current-voltage (I-V) characteristics are evolved with temperature [5, 7-10]. This implies that there is a deviation of the thermionic emission theory induced by other mechanisms, such as the thermionic field emission TFE and the emission field FE currents [5, 11]. The presence of these anomalies is confirmed by the spatial barrier inhomogeneities [7, 12-15], which were proved by ballistic electron emission microscopy studies [16, 17]. Many researchers described the spatial barrier inhomogeneities by Gaussian distribution function and this approach is widely accepted to analyze the experimental data [12, 18-24]. In addition, the abnormal behavior can also be due to the existence of interface states [7, 25], which act as recombination centers and generate local electric fields, causing random metallic paths, reducing carrier lifetime, and inducing large leakage current [26, 27]. These interface states come from surface dislocations and surface contaminations incorporated during the elaboration process [27-29]. Also, the Schottky metallization step generally causes interfacial modifications [29-32]. So, the interface quality has an essential impact on device behavior and performance. In this context, surface passivation is the best method to control the defective states [27-29, 33-37]. Many studies have been done to improve the interface properties by nitridation of GaAs surface [27, 28, 35, 36, 38-41]. The nitride layers have good stability against the formation of amorphous surface oxides, high electronegativity, and thermal stability [27, 42]. In this work, we report a study on the current transport mechanism in Au/0.8 nm-GaN/n-GaAs Schottky diode using a glow discharge plasma source (GDS) as nitridation processes. The I–V characterizations and the extracted electrical parameters are investigated in a temperature range of (80–420 K).

Experimental part

The Schottky contacts are elaborated using commercially available Si-doped n-GaAs (100) substrates, of a thickness of 400 μm and doping density $N_d = 4.9 \times 10^{15} cm^{-3}$. The surface cleaning, the Schottky contacts, and the ohmic contacts processes were carried out as described in refs. [28, 38]. After surface cleaning, the substrates heated at 500 C° were nitrided using a glow discharge nitrogen plasma source, running at 5 W for 30 min in an ultra-high vacuum chamber. This process allows for creating a 0.8 nm-thick undoped GaN layer. Following the nitridation step, the substrate was annealed at 620 °C for 1 hour in view to crystallize the GaN layer [37, 43, 44]. The current-voltage measurements were investigated under different temperatures (80–420 K), using an automatic standard apparatus based on a current source Keithely 220, a high impedance voltmeter Agilent 34401 A, and a liquid nitrogen cryostat Janis VPF 400.

Results part

Figure 1 shows the semi-logarithmic scale and linear scale of I-V characteristics of Au/0.8nm-GaN/n-GaAs structure, in (80-420 K) temperature range.

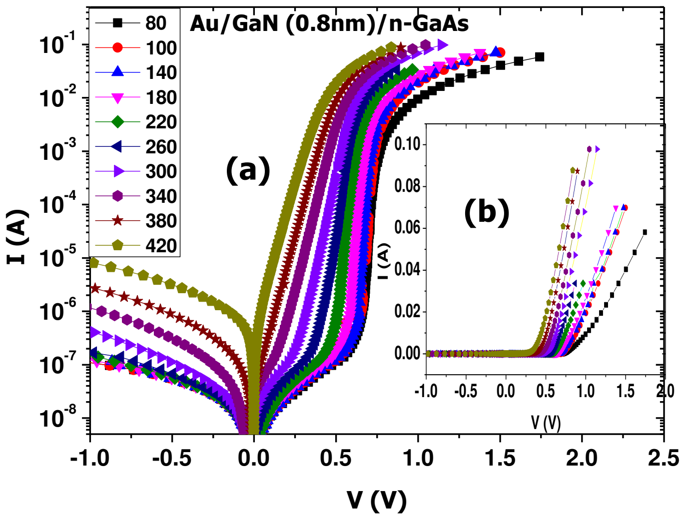

Figure 1: I-V measurements of Au/0.8nm-GaN/n-GaAs structure at different temperatures, (a) semi-logarithmic scale and (b) linear scale.

As can be seen, from the semi-logarithmic scale, in low bias voltages the current varies linearly with increasing bias voltage and decreases with decreasing of temperature. The reverse current I_{inv} increases with increasing temperature, from 1×10^{-7} A for 80 K to 1×10^{-5} A for 420 K. In the linear scale, the threshold voltage V_0 increases with decreasing temperature.

The expression of the current for non-ideal Schottky diodes is expressed as [45]:

$$I=I_s\left(exp\left(\frac{q(V-IR_s)}{nkT}\right)-1\right) \quad (1)$$

$$I_s= AA^*T^2\, exp\left(-\frac{q\Phi_b}{kT}\right) \quad (2)$$

where I_s is the saturation current, R_s is the series resistance, n is the ideality factor, k is the Boltzmann constant, A is the effective diode area, A^* is the effective Richardson constant and Φ_b is the barrier height.

The slope and y-axis intercept of ln(I) versus V give the values of n and I_s respectively, where,

$$ln(I) = \frac{q}{nkT}V+ln(I_s) \quad (3)$$

and Φ_b is calculated by:

$$\Phi_b = \frac{kT}{q}\, ln\left(\frac{AA^*T^2}{I_s}\right) \quad (4)$$

The values of R_s are extracted using Cheung and Cheung method [45] which is based on :

$$G(I) = \frac{\partial V}{\partial(lnI)} = R_sI + \frac{nkT}{q} \quad (5)$$

Figures 2 and 3 show the variations of the series resistance R_s and the saturation current I_s versus temperature.

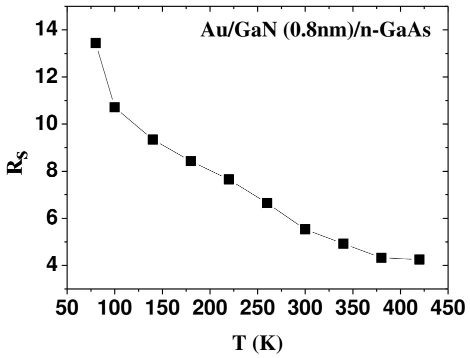

Figure 2: The variation of R_s versus temperature.

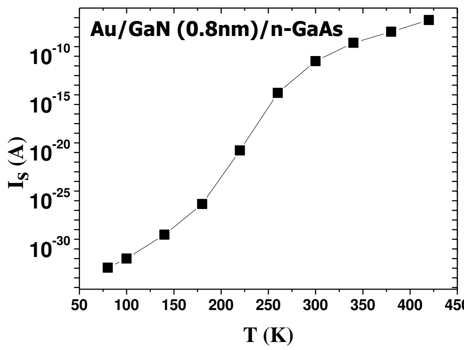

Figure 3: The variation of I_s versus temperature.

As can be seen, the structure exhibits low resistance series R_s which decreases from 13.44 Ω at 80 K to 4.25 Ω at 420 K, showing the good quality of the interface, improved by the nitridation process. In addition, I_s increases with temperature from 1.11×10^{-32} A at 80 K to 5.57×10^{-7}A at 420 K.

The extracted values of the ideality factor and barrier height are plotted in figure 4.

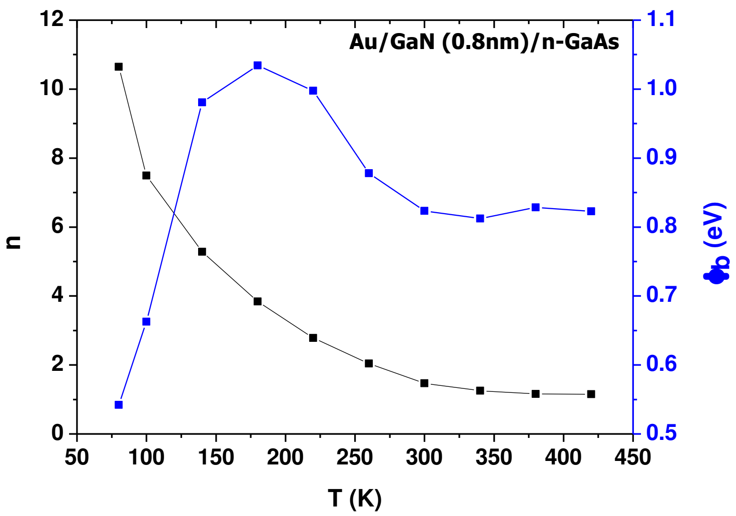

Figure 4: n and ϕ_b extracted for different temperatures.

In this figure, n decreases with increasing temperature from 10.64 at 80 K to 1.15 at 420 K, in accordance with the literature [5-7, 11, 26]. ϕ_b increases abnormally with increasing temperature from 0.54 eV at 80 K to 1.03 eV at 180 K and then decreases to 0.82 eV at 420 K. These results are similar to several studies [7, 12, 20, 46-48]. For Schottky contacts, the barrier height should decrease with increasing temperature, in accordance with the variation of the bandgap with temperature [1, 2, 7, 45, 47, 49-51]. The abnormal behavior of ϕ_b and the high values of n in low temperature can be

explained by the effect of the tunnel mechanisms, such as thermionic field emission (TFE) current and emission field (FE) current [5, 11].

The tunneling current can be expressed as following [1, 12, 52, 53]:

$$I = I_{tun}\left[exp(\frac{q(V-IR_S)}{E_0}) - 1\right] \quad (6)$$

$$\frac{E_0}{kT} = \frac{E_{00}}{kT} cot\,h\left(\frac{E_{00}}{kT}\right) \quad (7)$$

$$E_{00} = \frac{h}{4\pi}\left(\frac{N_D}{m_e^* \varepsilon_S}\right)^{\frac{1}{2}} \quad (8)$$

where E_{00} is the characteristic tunneling energy, h is the Planck constant, m_e^* is the effective mass of electron and ε_S is the dielectric constant of GaAs.
Figure 5 shows the variation of ($E_0 = nkT/q$) versus kT/q.

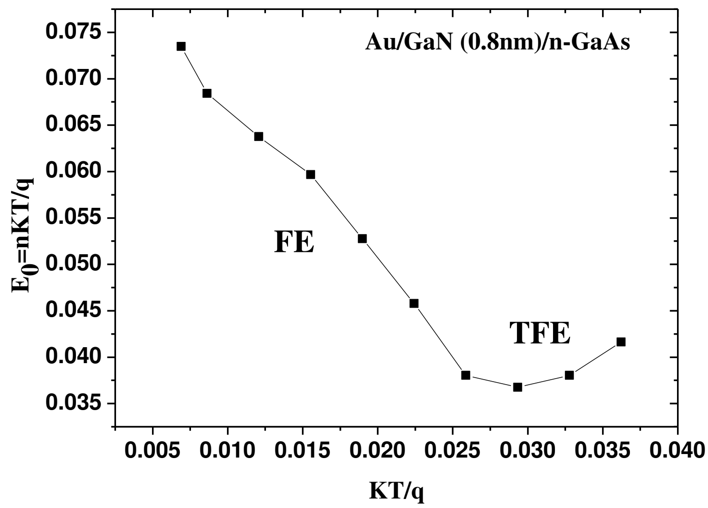

Figure 5: The variation of E_0 (nkT/q) versus kT/q.

From figure 5, E_0 is approximately 2 to 10 times higher than kT/q, in the temperature range of 80 K-300 K. This indicates that the dominant current is the FE mechanism at low temperatures [5]. In the temperature range 300 K-420 K, E_0 remains almost equal to kT/q. This confirms that the TFE mechanism is dominant in high temperatures [5]. These results are in good agreement with a simulation study of Au/1nm-GaN/n-GaAs structure [5].

To further study the abnormal behavior of the barrier height, the Richardson characteristic $ln(I_s/T^2)$ versus q/kT is presented in figure 6.

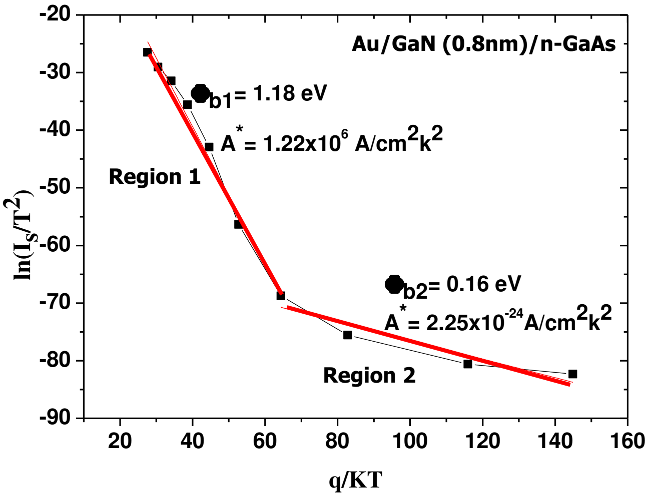

Figure 6: variation of Richardson characteristic $ln(I_s/T^2)$ versus q/kT. Red lines are linear fits of experimental data according to the root mean square method.

Figure 6 gives two linear regions which due to the inhomogeneity of the barrier height of the structure [12]. $\phi_b$and A^* are estimated at *1.18 eV* and $1.22\times10^6\,Acm^{-2}K^{-2}$ in region 1 and at *0.16 eV* and $2.25\times10^{-24}\,Acm^{-2}K^{-2}$ in region 2, respectively. The extracted values of A^* are very far from the theoretical value for n-GaAs, which is equal to $8.16\,Acm^{-2}K^{-2}$ [49].

Figure 7 presents the variation of ϕ_b versus n.

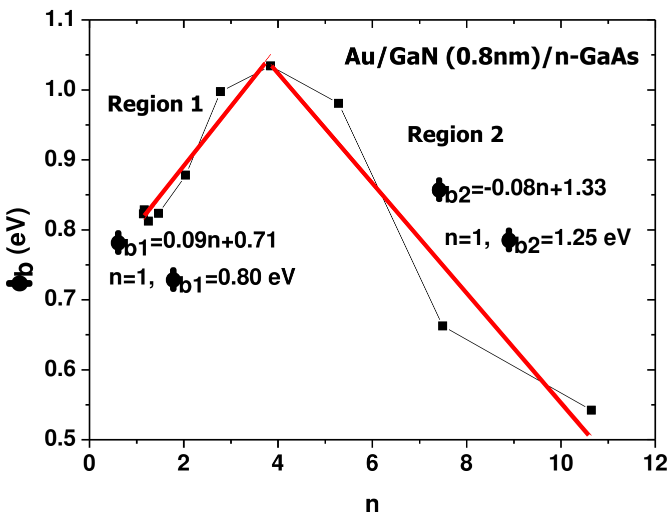

Figure 7: plot of ϕ_b versus n.

The structure has two linear regions, which are explained by the inhomogeneity of the barrier height [54, 55]. By extrapolation, the values of ϕ_b for $n=1$ is equal to 0.80 eV, in region 1 and equal to 1.25 eV, in region 2. These results are in good agreement with Richardson's characteristics.

The inhomogeneity of the barrier height showed in the Richardson characteristics and in the plot ϕ_b versus n, is probably due to the presence of the 0.8 nm GaN interfacial layer. Helal et al. [5] have studied in simulation work, Au/n-GaAs Schottky in a wide temperature range 80 K-400K, with and without thin GaN (1 nm) interfacial layer. They found that Au/n-GaAs shows a homogeneous barrier height and Au/1nm-GaN/n-GaAs structure shows an inhomogeneous one.

Conclusion

In this paper, the current-voltage of an Au/0.8nm-GaN/n-GaAs structure is measured, in (80-420 K). With increasing temperature, the reverse current I_{inv} increases, and the ideality factor n decreases. The barrier height ϕ_b increases abnormally with increasing temperature from 0.54 eV at 80 K to 1.03 eV at 180 K and then decreases to 0.82 eV at 420 K. We explained the abnormal behavior of ϕ_b and the high n values in low temperature, by the tunnel mechanisms effects, such as FE and TFE currents. Finally, the structure presents an inhomogeneous barrier height, caused probably by the thin GaN interface layer.

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Figures

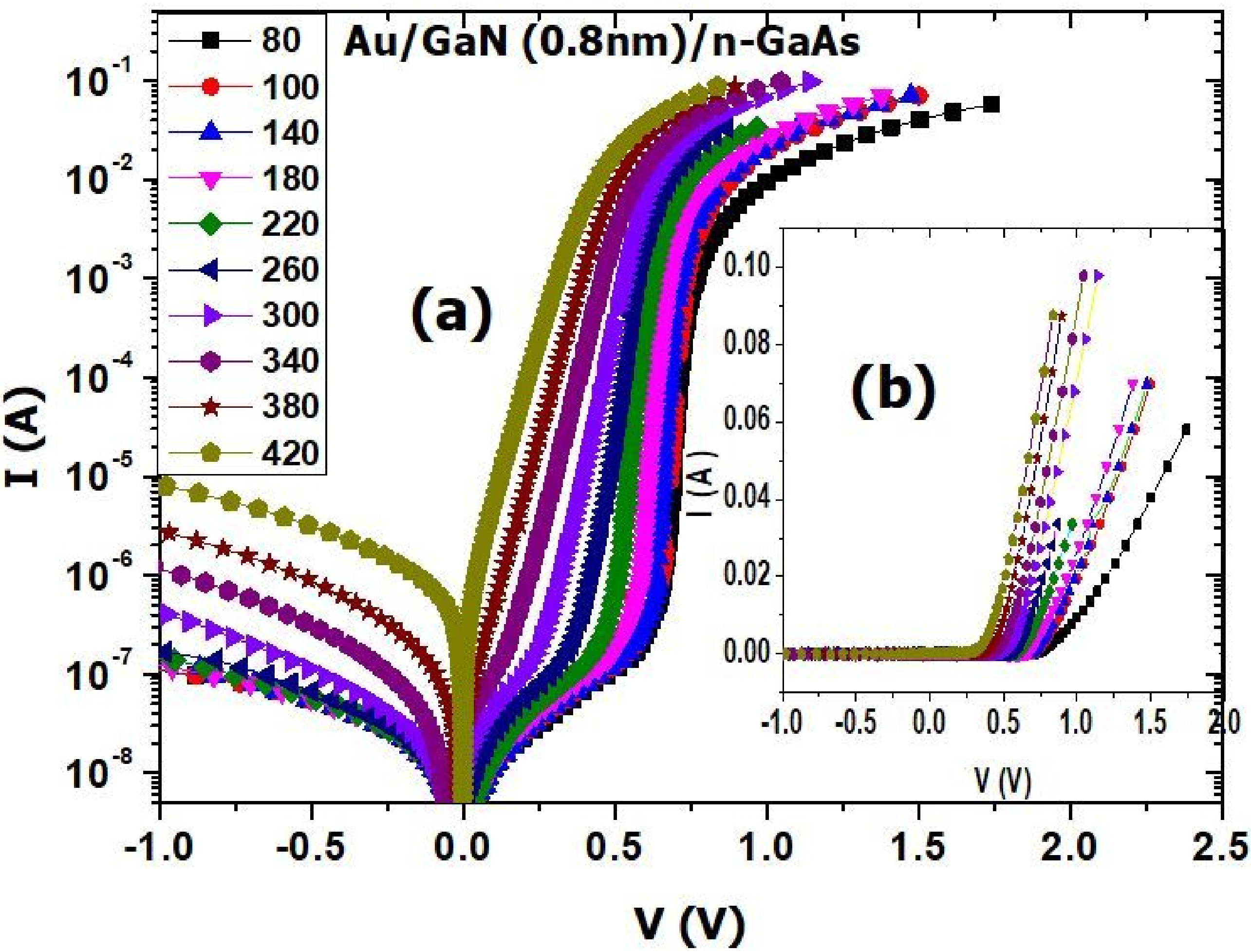

Figure 1

I-V measurements of Au/0.8nm-GaN/n-GaAs structure at different temperatures, (a) semi-logarithmic scale and (b) linear scale.

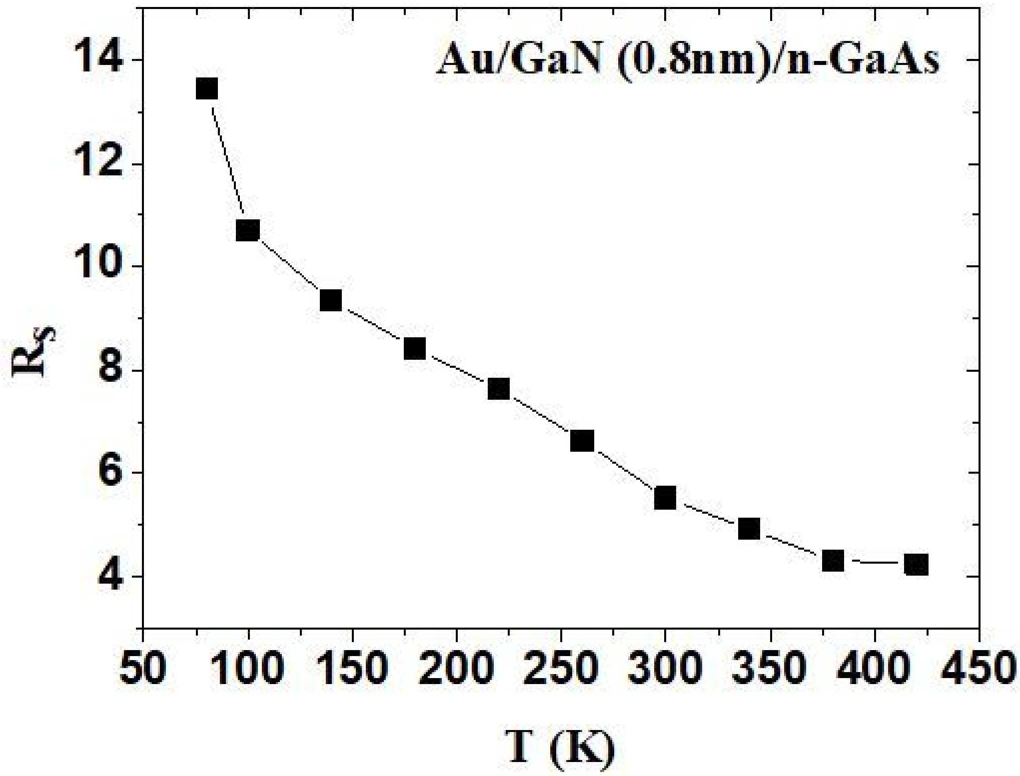

Figure 2

The variation of Rs versus temperature.

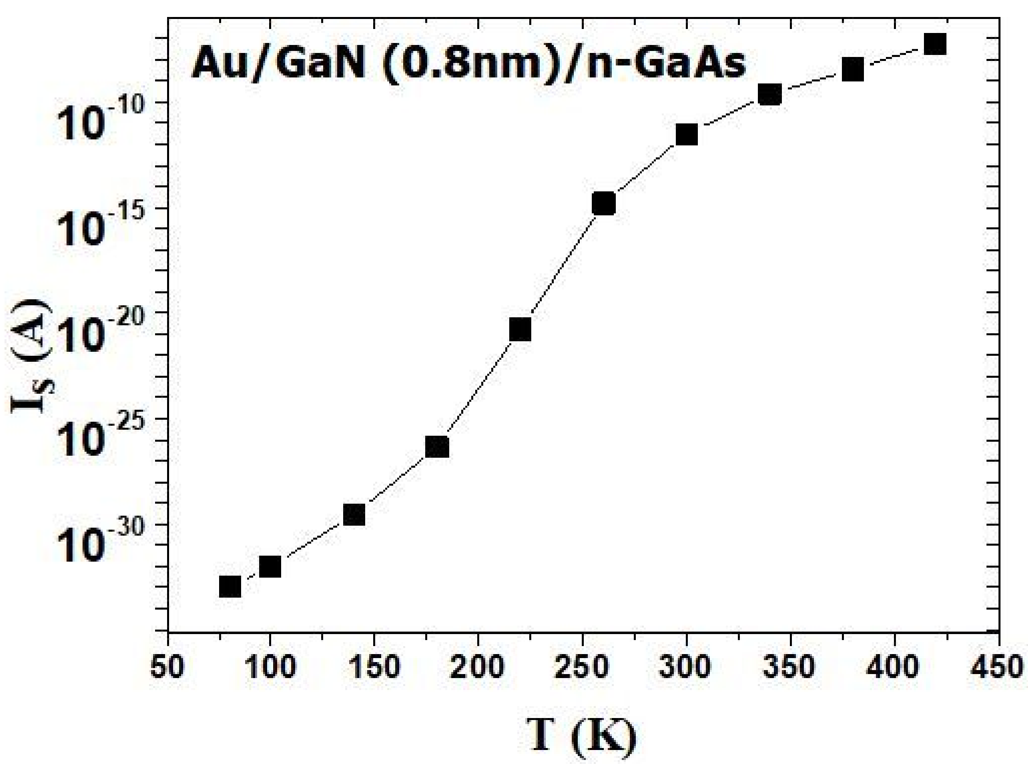

Figure 3

The variation of Is versus temperature.

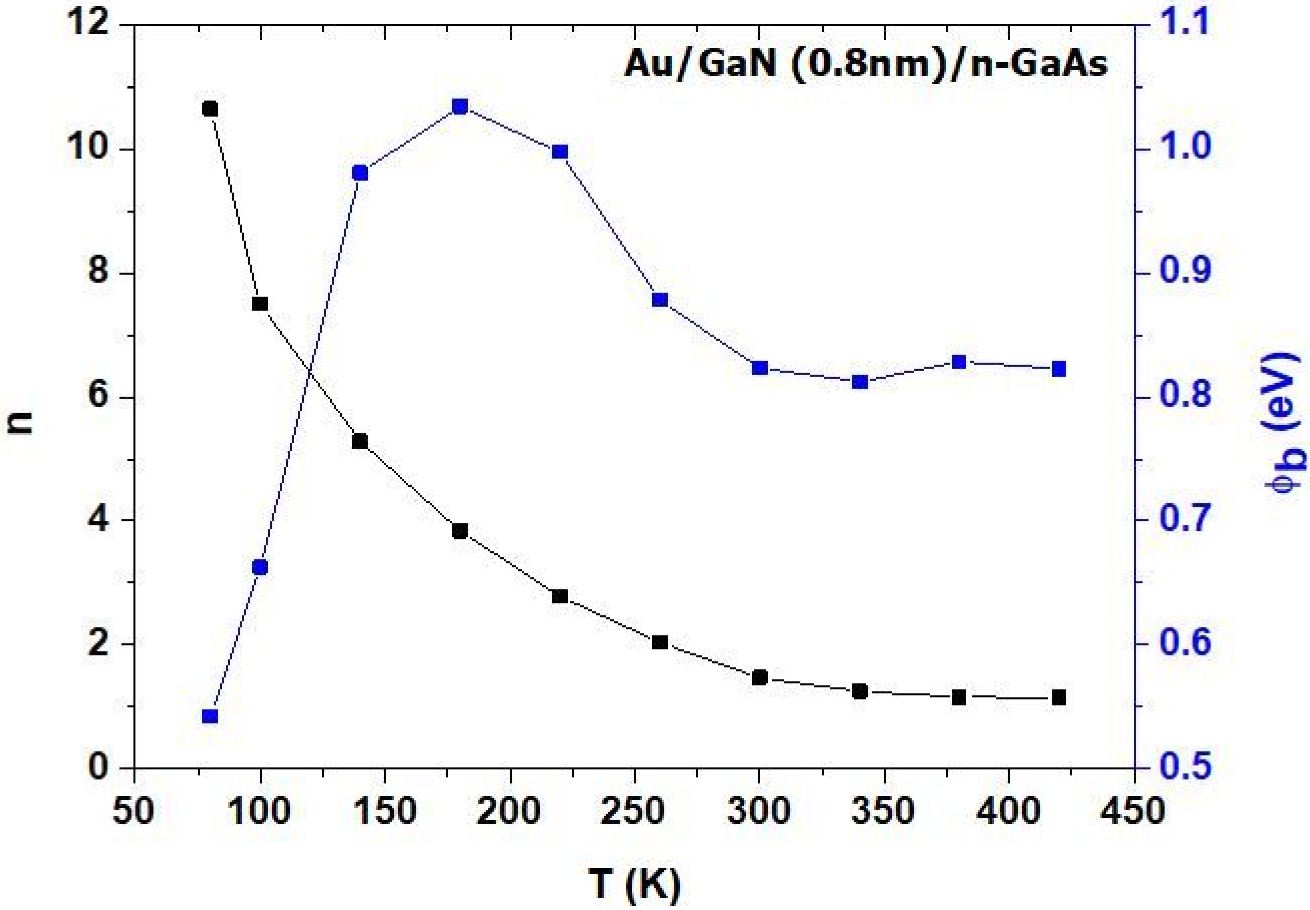

Figure 4

n and b extracted for different temperatures.

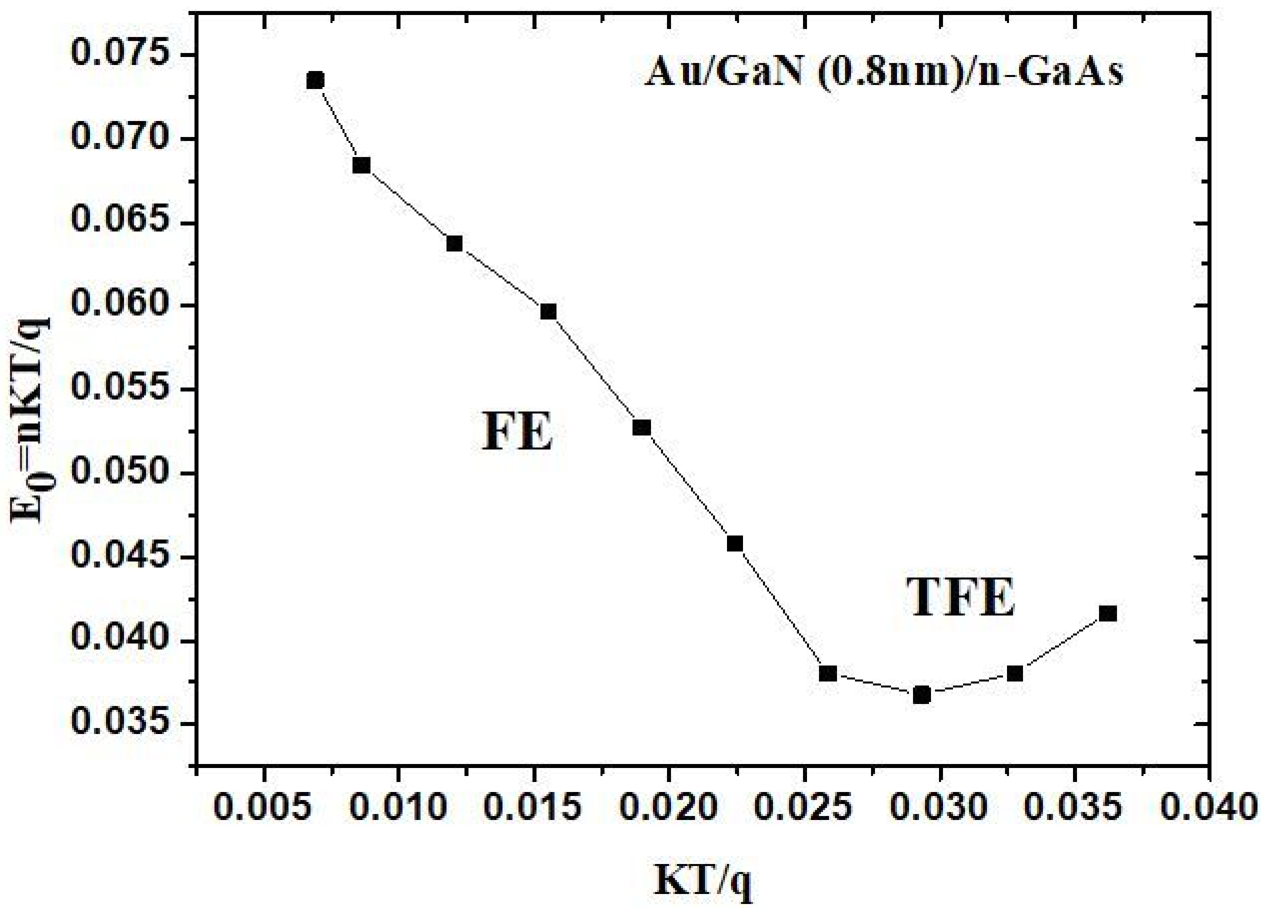

Figure 5

The variation of E0 (nkT/q) versus kT/q.

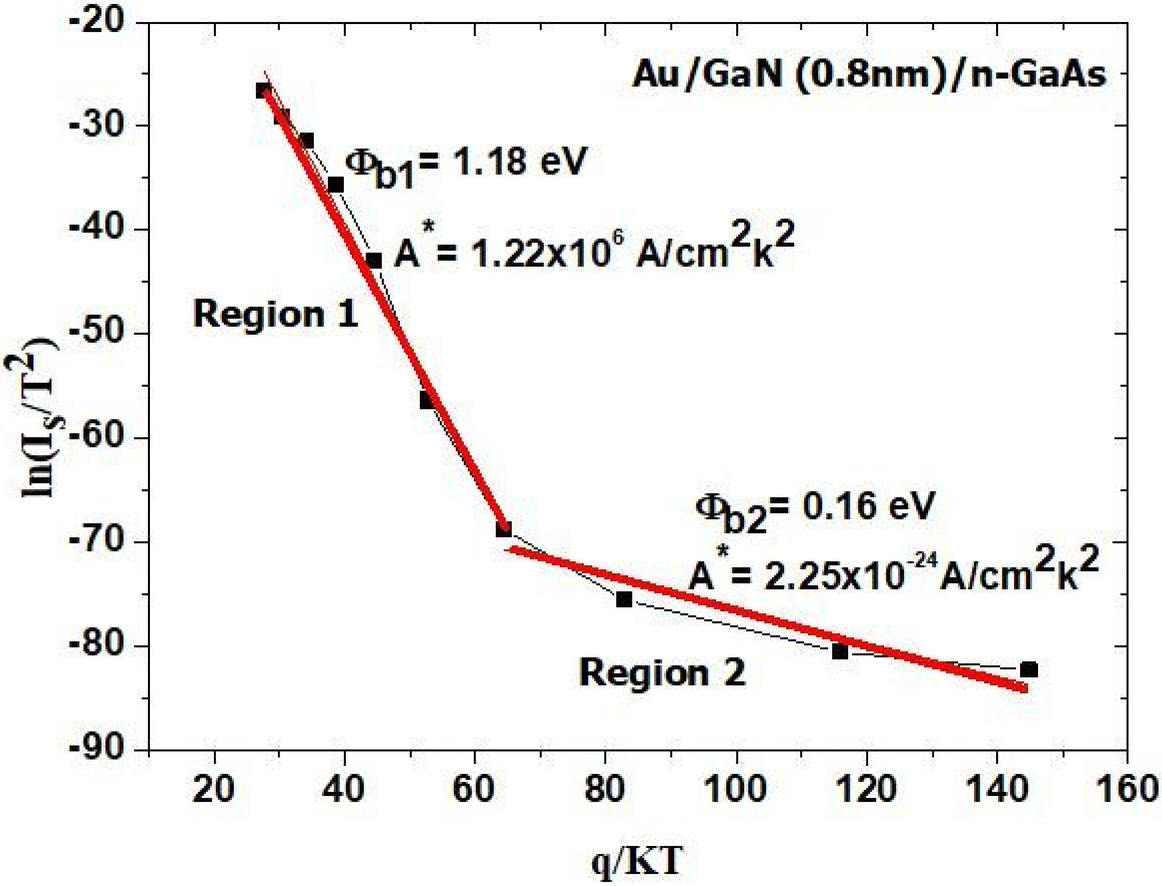

Figure 6

variation of Richardson characteristic ln(I_s/T^2) versus q/kT. Red lines are linear fits of experimental data according to the root mean square method.

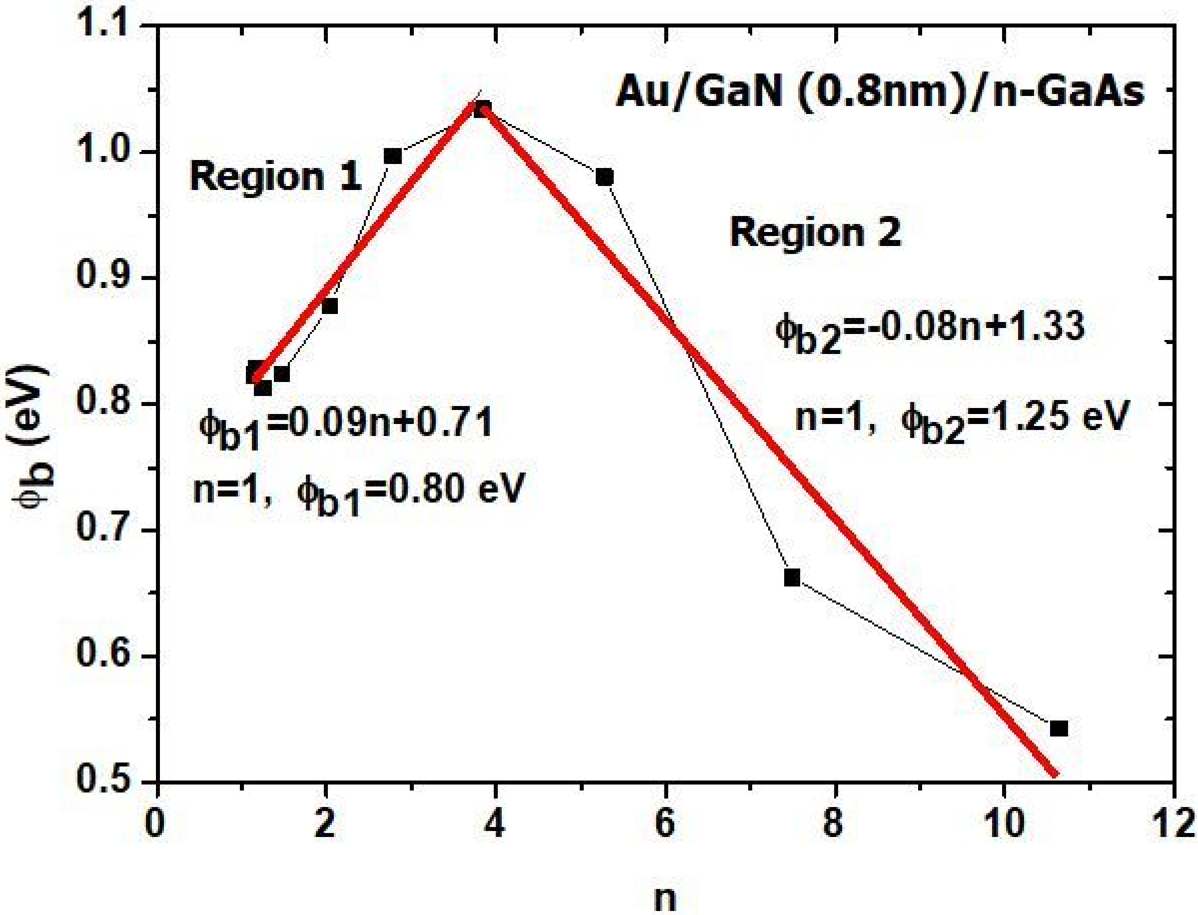

Figure 7

plot of b versus n.