Analysis of the series resistance and interface state densities in metal semiconductor structures

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Abstract. The electrical properties of Co/n-Si metal-semiconductor (MS) Schottky structure investigated at room temperature using current-voltage (I-V) characteristics. The characteristic parameters of the structure such as barrier height, ideality factor and series resistance have been determined from the I-V measurements. The values of barrier height obtained from Norde’s function were compared with those from Cheung functions, and it was seen that there was a good agreement between barrier heights from both methods. The series resistance values calculated with Cheung’s two methods were compared and seen that there was an agreement with each other. However, the values of series resistance obtained from Cheung functions and Norde’s functions are not agreeing with each other. Because, Cheung functions are only applied to the non-linear region (high voltage region) of the forward bias I-V characteristics. Furthermore, the energy distribution of interface state density was determined from the forward bias I-V characteristics by taking into account the bias dependence of the effective barrier height. The results show that the presence of thin interfacial layer between the metal and semiconductor.

1. Introduction
The metal-semiconductor (MS) structures have an important role in modern electronics, and MS structures are one of the most widely used rectifying contacts in the electronics industry. Due to the performance and stability of metal semiconductor structures which are of great importance to the electronic devices [1-3]. Although these devices have been studied extensively, satisfactory understanding in all details has still not been achieved. Because there is a continuing need for faster and more complex systems for the information age, existing semiconductor devices are being studied for improvement, and new ones are being invented [1-5]. Due to technological importance of metal-semiconductor structures, a full understanding of the nature of the electrical characteristics of Schottky
barrier diodes in this system is of great interest. Electronic properties of a Schottky diode are characterized by its barrier height and ideality factor parameters. The interface states play an important role in determination of Schottky barrier height and other characteristic parameters and these can affect device performance, stability and reliability [3,6-8]. Thus, barrier height, ideality factor, series resistance (RS) and interface states density values (NSS) at metal-semiconductor structures play an important role in the determination of the main parameters of the structures. These parameters give useful information concerned with the nature of the device. When voltage is applied across the MS device, the combination of the interfacial insulator layer, depletion layer and the series resistance of the device will share applied voltage.

Usually, the forward bias I–V characteristics are linear in the semi-logarithmic scale at low voltages, but deviate considerably from linearity due to the effects of parameters such as the series resistance RS, the interfacial layer and interface states at sufficiently large applied voltage. The parameter RS is only effective in the downward-curvature region (non-linear region) of the forward I–V characteristics at sufficiently high applied voltage, but parameters such as the ideality factor n and barrier height $\Phi_b$, are effective in both the linear and non-linear regions of these characteristics, accompanying the change of the SBH [9,10]. The first studies on the interface layer in Schottky diodes were made by Cowley and Sze [11], who obtained their estimates from an analysis of barrier heights with different metallization as a function of the metal work function. Card and Rhoderick [12] examined the effects of the interface layer on the ideality factor of the forward bias I-V characteristics. Tseng and Wu [13] analysed the effect of the presence of an interfacial layer on the behaviour of Schottky barrier diodes.

It is well known that, unless specially fabricated, a Schottky barrier diode (SBD) possesses a thin interfacial native oxide layer between the metal and the semiconductor. The existence of such an insulating layer can have a strong influence on the diode characteristics as well as the interface states [1,3,14-16]. Therefore, the interfacial layer and the interface states play an important role in the determination of the barrier height. Consequently, it has been concluded that the barrier height determined from the I-V characteristics controlled by the interface states energy distribution in equilibrium with the semiconductor and the applied voltage under forward bias condition.

In the present study, we have investigated the electrical characteristics and interface states of the Co/n-Si Schottky structure. Au-Sb alloy and Co metal has been chosen as the ohmic contact and rectifier contact, respectively. The electronic parameters controlling the device performance, such as barrier height, ideality factor, series resistance and interface state energy distribution were evaluated by current–voltage measurements at room temperature and in the dark.

2. Experiment

The samples have been prepared using cleaned and polished n-Si (as received from the manufactured) with (100) orientation. The wafers were chemically cleaned using the RCA cleaning procedure [i.e., a 10 min boil in NH4OH+H2O2+6H2O followed by a 10 min boil in HCl+H2O2+6H2O]. The native oxide on the front surface of the substrates was removed in HF:H2O(1:10) solution and finally the wafer was rinsed in de-ionized water for 30 s. Then, low resistivity ohmic back barrier diode to n-type Si wafer was made by using Au-Sb alloy, followed by a temperature treatment at 420 oC for 3 min in N2 atmosphere. The Schottky barrier diode were formed on the front face of the n-Si as dots with diameter of about 1 mm by the galvanostatic electrodeposition of Co. Acid resistant adhesive tape was used to mask off all the substrate except for the deposition area. The electrodeposition of Co films on n-type Si substrate has been carried out at room temperature from an aqueous electrolyte containing 1M Co sulphate and 0.5M boric acid. The current–voltage characteristics were measured using a Keithley 487 Picoammeter/Voltage Source at room temperature and in the dark.
3. Results and discussion

3.1 Current-voltage (I-V) characteristics of Co/n-Si Schottky structure

The forward bias current-voltage characteristics of the Co/p-Si (MS) Schottky structure at 300 K (room temperature) are given in Fig. 1.

\[
I = I_o \exp \left( \frac{qV}{nkT} \right) \left[ 1 - \exp \left( -\frac{qV}{kT} \right) \right] \quad \text{(1)}
\]

where,

\[
I_o = AA^*T^2 \exp \left( -\frac{q\Phi_b}{kT} \right) \quad \text{(2)}
\]

is the saturation density, \( V \) is the definite forward-bias voltage, \( A \) is the effective diode area, \( k \) is the Boltzmann constant, \( T \) is the absolute temperature, \( A^* \) is the Richardson constant for n-type Si (\( A^* = 112 \text{ Acm}^{-2}\text{K}^{-2} \)) [1,18,19]. The barrier height was calculated using \( I_0 \) value and was found to be 0.70 eV. The ideality factor of Co/n-Si/AuSb Schottky contact from Eq. (1) is contained in the slope of straight line region of the forward-bias logarithmic characteristics of I-V through the relation;

\[
n = \frac{q}{kT} \frac{dV}{d(ln I)} \quad \text{(3)}
\]

where \( n \) is a measure of conformity of the diode to pure thermionic emission, and was found to be 1.19. For an ideal Schottky barrier diode \( n=1 \). However, \( n \) has usually a value greater than unity. This value indicates that the effect of the series resistance in the linear region is important. Fig. 1 show the dark forward bias I-V characteristics of one of the electrodeposited Co/n-Si Schottky contacts respectively. From Eq. (2) the barrier height, \( \Phi_b \) is given by;
Using Eqs (3) and (4), as explained above, the values of the barrier height ($\Phi_b$) and the ideality factor ($n$) of the Co/n-type Si Schottky contact were found as 0.70 eV and 1.19, respectively. Moreover, at high currents there is always a deviation which has been clearly shown to depend on parameters such as the interfacial layer thickness, the interface states density and series resistance, as one would expect [20,21].

The series resistance is a very important parameter of Schottky diode. The resistance of the Schottky contact is the sum total resistance value of the resistors in series and resistance in semiconductor device in the direction of current flow. The Schottky diode parameters as the barrier height $\Phi_b$, the ideality factor $n$ and the series resistance $R_s$ were also achieved using a method developed by Cheung and Cheung [22]. Cheung’s functions can be written as follows:

$$\frac{dV}{d(lnI)} = IR_s + \frac{n kT}{q}$$

and

$$H(I) = V - n \left( \frac{kT}{q} \right) \ln \left( \frac{I}{AA'T^2} \right)$$

where $\Phi_{bo}$ is the real barrier height extracted from the lower-voltage part of forward $I–V$ characteristics. The $dV/d(ln(I))$ plot is a straight line region where dominates the series resistance. Fig. 2 and Fig. 3, represent $H(I)$ (a) and $dV/dln(I)$ (b) vice versa current, respectively.

Figure 2. The experimental $H(I)$ vs $I$ plot obtained from forward bias current-voltage characteristics of the Co/n-Si Schottky structure.

Figure 3. The experimental $dV/dln(I)$ vs $I$ plot obtained from forward bias current-voltage characteristics of the Co/n-Si Schottky structure.
The values of barrier height and series resistance from Eq. 7 were found to be 0.71 eV and 205.95 Ω. In the same way, the values of ideality factor and series resistance from Eq. 5 were found as 1.34 and 193.62 Ω, respectively. Thus, it can clearly be seen that there is relatively difference between the values of $n$ obtained from the downward curvature regions of forward bias $I$–$V$ plots and from the linear regions of the same characteristics. The reason of this difference can be attributed to the existence of effects such as the series resistance and the bias dependence of the Schottky contact according to the voltage drop across the interfacial layer and change of the interface states with bias in this concave region of the $I$–$V$ plot. Furthermore, the $R_S$ values obtained from the Cheung functions are in agreement with each other due to consistency of Cheung functions.

Norde proposed an alternative method to determine values of the series resistance and barrier height [23]. Norde method was also employed [23] because high series resistance ($R_S$) can hinder an accurate evaluation of barrier height from the standard ln$I$–$V$ plot.

![Figure 4. F(V) vs. V plot obtained from forward bias current-voltage characteristics of the Co/n-type Si Schottky structure at room temperatures.](image)

The following function has been defined in the modified Norde’s method:

$$F(V) = \frac{V}{2} - \frac{kT}{q} \ln\left(\frac{l}{AA'T^2}\right)$$  \hspace{1cm} (8)

The effective Schottky barrier height is given by

$$\Phi_b = F(V_{min}) + \frac{V_{min}}{2} - \frac{kT}{q}$$  \hspace{1cm} (9)

and

$$R_s = \frac{kT}{qI_o}$$  \hspace{1cm} (10)

where $F(V_{min})$ is the minimum value of $F(V)$, $V_{min}$ is the corresponding voltage, and $I_o$ is the corresponding current at $V=V_{min}$, respectively. A plot of $F(V)$ versus $V$ for the Co/n-Si Schottky structure at room temperature is as shown in Fig. 4. From the $F(V)$–$V$ plot the values of $\Phi_b$ and $R_s$ of the structure have been determined as 0.72 eV and 257.16 Ω, respectively. It is noted that these values
are higher than those obtained by the $I-V$ method. This means that the value of series resistance indicates that the series resistance is a current-limiting factor for the Co/n-Si Schottky diode.

3.2 Interface state density properties of Co/n-Si Schottky structure

As can be seen from Fig. 5, the interface state density $N_{SS}$ has an exponential drop with bias from the midgap towards the top of the conduction band for Co/n-Si Schottky contact. The density distribution curves of the interface states can be thus obtained from experimental data of the forward bias $I-V$ in Fig. 1. For a real Schottky diode having interface states in equilibrium with the semiconductor, the ideality factor, $n$ becomes greater than unity as proposed by Card and Rhodercik [3,12] and is given by:

$$n = 1 + \frac{\delta}{\varepsilon_i} \left[ \frac{\varepsilon_i}{W} + qN_{SS}(V) \right]$$

(11)

where $N_{SS}$ is the density of interface states in equilibrium with the semiconductor, $W$ is the space charge width, $\varepsilon_i$ and $\varepsilon_s$ are the permittivity of the semiconductor and the interfacial layer, respectively.

In n-type semiconductors, the energy of the interface states $E_{ss}$ with respect to the bottom of the conduction band at the surface of the semiconductor is given by:

$$E_c - E_{ss} = q\Phi_e - qV$$

(12)

where $V$ is the applied voltage drop across the depletion layer and $\Phi_e$ is the effective barrier height. Eq. (11) can be used to obtain interface states densities ($N_{SS}$) values as a function of voltage. The interface states densities values were obtained from the Eq. (11) by obtaining the real parameters of the contact. As can be seen in Fig. 5, $N_{SS}$ value decreases with increasing $E_{SS}$ value. The increase in $N_{SS}$ values forms from mid gap towards the bottom of the conduction band. This increase is probably due to the increase in the series resistance ($R_s$). The potential drop across the interfacial layer varies with bias because of the change in the charge in the interface states and thus the interface state energy distribution, and it alerts the diffusion potential and therefore the depletion capacitance [1,3, 15,16 and 24].

Figure 5. Density of interface states $N_{SS}$ as a functions of $E_{SS}$-$E_{V}$ obtained from the $I-V$ measurements at room temperature.
4. Conclusion
In this study, we have investigated electrical properties of Co/n-type Si Schottky structure (MS) using current-voltage (I-V) measurement at room temperature. The values of diode parameters such as ideality factor \((n)\), series resistance \((R_s)\) and barrier height \((\Phi_{IV})\) were obtained from I-V measurements using Cheung and Norde’s method. The ideality factor and barrier height values calculated using Cheung functions with different methods were compared and seen that there was an agreement with each other. However, the parameters obtained from Cheung functions and Norde’s functions are not agreeing with each other. Because, Cheung functions are only applied to the non-linear region (high voltage region) of the forward bias I–V characteristics. Whereas, Norde’s functions are applied to the full forward bias I–V characteristics of the junctions. The interface state density has an exponential rise with bias from the midgap towards the top of the conduction band, and gives a peak about 0.446 eV. It is clear that ignoring the role of interfacial insulator layer, interface state density and series resistance can lead to significant errors in the electrical characteristics of devices.

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