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Determination of the values of ideality factor, barrier height and saturation current for three different Schottky combinations via Conventional $I-V$ and Modified Cheung's models.

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ABSTRACT
In this work, the values of the electrical properties of some metal – semiconductor contacts was studied using modified cheungs model. Three metals were considered; they are chromium, Tungsten and Molybdenum, while n-type silicon and n-type germanium were used as the semiconductors. Values of certain parameters were simulated into some relevant equations to calculate and extract the values of the electrical parameters. The result shows that values of some of these electrical parameters are altered with the introduction of interfacial layer. These altered values enhances the performance of the Schottky diode. In terms of performance, Cr/I/n-Si offers a better performance as regards the high value of ideality factor, low series resistance, and moderate barrier height.
Keywords: *Ideality-factor, Barrier-height, Saturation-current, Modified Cheungs Model*

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I. Introduction:

The Schottky diode is a special type of diode with very low forward voltage drop and a very fast switching action. This low voltage drop is approximately 0.15-0.45 V, and thus translates into higher system efficiency. For this reason, they do not have recovery time as there is nothing to recover from i.e there lies a charge carrier depletion region at the junction. Schottky diode also known as metal-semiconductor junctions, plays a very important role in electronic devices.

The current versus voltage for a Schottky barrier diode is given by the following well known equation named the Richardson equation of Schottky diode given by. The junction parameters are barrier height, ideality factor, and series resistance. For a Schottky barrier diode, the relationship between the applied forward bias voltage and current is given by Lee (2002):

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

where n is the ideality factor. The Richardson equation for current – voltage for a Schottky diode is given by (Yeganeh and Rahmatollahpur, 2010) as

$$I = I_o\left[\exp\left(\frac{q(V-IR_S)}{nkT}\right)-1\right] \quad (2)$$

$V > 3KT/q$) given as (Ahmad and Sayyad, 2009) equation 3 can be written as

$$I = I_o \exp\left(\frac{qV}{nKT}\right) \quad (3)$$

where in both case, I_o is the saturation current given as

$$I_o = AA^{\bullet}T^2 \exp\left(\frac{-q\Phi_B}{kT}\right) \quad (4)$$

where A is the effective diode area, A* is the effective Richardson constant, T is the absolute temperature, K is the Boltzmann constant, q is the electronic charge and Φ_b is the barrier height.
The Barrier Height is defined as the barrier against electrons flow from the metal to the n-type semiconductor. It controls the electron transport across the metal – semiconductor interface.
Gholami and Khakbaz (2011) describe the series resistance as the total resistance of bulk of the semiconductor contact wires and ohmic contacts Performance of Schottky diode is based on choice of metals, choice of temperature and the values of the electrical parameters which are saturation current, barrier height, series resistance and ideality factor. The choice of metal depends on the work function of the metals, the choice of temperature depends on the voltage values starting from $V > \frac{3KT}{q}$, where T lies between 23 – 45℃ . The electrical parameters are extracted from an equation computed and a plot of the I-V characteristics using Cheung model, and modified Cheung's model developed. The values of metal work function and the effect of interfacial-layer plays a vital role in the formation of a good Schottky contact (Tung, 1993). Many authors such Gholami and Khakbaz (2011) studied the I-V characteristics of PtSi/p-Si Schottky barrier diode at low temperatures, using three different models to extract the electrical parameters. Mikhelashvili and Sekar (2000) studied the electrical characterization of Schottky diode using only n-type silicon with only one type of metal.
Yeganeh and Rahmatollahpur (2010) extracted the barrier height and ideality factor from both I-V and C-V characteristics plot on Au/P-Si Schottky diode. The effects of Schottky diode area and presence of interlayer between the metal and the semiconductor were neglected. Most of the models by many authors did not consider all the electrical parameters as point of interest.
Most of the researches conducted on Schottky barrier diode formation are on extrinsic semiconductors. We felt it will be appropriate to conduct similar research on intrinsic semiconductors, i.e Si and Ge.
The use of different models in this work also brings out more options when dealing with physics of Schottky barrier diode. The Cheung's models were further modified by the introduction of interfacial layer.

Basic Operational Terms in Schottky Diode Formation
Schottky diode has some basic operational terms that are used to characterized its electrical properties. When a junction is formed between a metal and a semiconductor, the Fermi levels on both sides get aligned and a barrier (to electron flow) is formed due to energy difference between work function of the metal and electron affinity of the semiconductor Timtere(2019). Based on this theory, these parameters are defined.

Work Function, Φ_m (in eV); Metals have work function that is defined as the minimum energy required for an electron to escape from the Fermi level into the vacuum. It is a very important figure of merit in Schottky diode formation. The value of the work function compared with the value electron affinity of a semiconductor determines whether the contact is Ohmic or rectifying.

Electron Affinity, χ_s (in eV); the electron affinity is peculiar to semiconductors. It is the energy difference between vacuum level and the bottom of the conduction band.

Saturation Current, I_o (in A); the saturation current is the limiting or maximum current in a diode such that further increase of voltage produces no further increase in current. It is regarded as the fully conducting state in a metal – semiconductor junction. In Schottky diode, it gives the zero bias barrier height, and the voltage dependence of barrier height in the presence of series resistance [8]. It is a function of absolute temperature and barrier height.

Barrier Height, Φ_B (in eV); the barrier height is defined as the barrier against electron flow from the metal to the semiconductor. The barrier height controls the electron transport across the metal – semiconductor interface, hence, it is an important electrical parameter to the successful operation of Schottky diode Boulgamh (2005). Measured barrier height values depend on the metal species and the diode size distribution Chawanda (2011) and Yu et al (2005). It is related to the metal work function and electron affinity of semiconductor by equation (5) below

$$\Phi_B = \Phi_m - \chi_s \quad (5)$$

Equation (1) is called Schottky – Mott model. The model assumes that the bands are aligned with respect to the vacuum level of the metal and the semiconductor Gaur and Gupta (2011).

Ideality Factor, n; this is a factor that describes the deviation of practical diodes from ideal diodes (for ideal diodes, n = 1) Guler et al (2009).

Series Resistance, R_s (in Ω); the series resistance is one of the important electrical parameters in diode formation that is also temperature dependent Murugeshan and Sivaprasath (2012). It includes the lump resistance of the semiconductor, metal and the contacts. Some models such as Rhoderick model have no specific equation for the evaluation or the extraction of the series resistance.

Both n-type and p-type semiconductor can develop Schottky barrier but the n-type plays a more significant role because the n-type semiconductor has high concentration of majority charge carriers (electrons) compared to the p-type semiconductor, which makes n-type preferable in Schottky contact (Dhabal, 2012) and (yang, et al 2005). The majority carriers are quickly injected into the conduction band of the metal contact on the other side of the diode to become free moving electrons therefore, no slow random recombination of the n- and p-type carriers is involved (as in p n junction). So that the Schottky diode can cease conduction faster than an ordinary p-n rectifier diode This Schottky barrier results in both very fast switching and low forward voltage drop. In fabrication, the metal side acts as the anode and the n-type semiconductor as the cathode of the diode. Typical metals used in Schottky diode fabrication are molybdenum, platinum, chromium or tungsten or certain silicates such as palladium silicate and platinum silicate. But the choice of metal chosen in this work will depend on the outcome of the saturation current which should be in the range of between μ Amperes to nano Amperes which can give rise to a nearly ideal Schottky diode (Gholami and Khakbaz, 2011).

Basic Thermionic theory

All semiconductor devices and materials are characterized through the use of test structures. Metal – semiconductor contacts are subject of considerable interest, and the capacitance – voltage (C-V) and current – voltage (I – V) as electrical characterization techniques are most commonly used to extract junction parameters pipinys and Lapeika(2010). The Schottky barrier diode is a temperature dependent device. This could be seen in the relationship between the current and voltage of the diode described by thermionic emission. For a Schottky diode the relationship between the applied forward voltage and current is given by eqn [1] or

$$I = I_o \exp\left[\frac{qV}{kT}\right] \qquad (6)$$

where n is the ideality factor, q is the electronic charge, k is the Boltzmann's constant, T is the absolute temperature in Kelvin, and I_o is the saturation current expressed as

$$I_o = AA^{\bullet}T^2 \exp\left(\frac{-q\Phi_B}{kT}\right)$$

(7)

where A is the effective diode area, A^* is the effective Richardson constant that varies from one semiconductor to the other, and Φ_B is the barrier height. Equation (2) was modified and referred to as the Richardson equation for Schottky diode given as

$$I = I_o\left[\exp\left(\frac{q(V - IR_S)}{nkT}\right) - 1\right]$$

(8)

where IR_s is the voltage across the series resistance of the Schottky diode. Equation (8) was further modified and referred to as the Lieu model (for the values of $V > 3KT/q$) given as (9, 10)

$$I = I_o\left[\exp\left(\frac{q(V - IR_S)}{nkT}\right)\right]$$

(9)

From equation (7),

$$\ln I_o = \ln\left(AA^*T^2\right) - \frac{q\Phi_B}{kT}$$

(10)

or

$$\Phi_B = \frac{kT}{q}\ln\left(\frac{AA^*T^2}{I_o}\right)$$

(11)
Equation (11) is the expression for barrier height.

The Cheung – Cheung's Model

The Cheung – Cheung's model also known as Cheung's model is one of the efficient methods that can be used to evaluate the electrical properties of Schottky diode Kudryk et al(2014). Using the I – V characteristics, this model has the advantage of evaluating the ideality factor; series resistance, and the barrier height. The Cheung's model could be built from equation (6) as

$$\ln I - \ln I_o = \frac{q(V - IR_s)}{nkT}$$

(12)
From equation (12)

$$\frac{nkT}{q}\left(\ln I - \ln I_o + \frac{qIR_s}{nkT}\right) = V$$

(13)
From equation (13)

$$\frac{dV}{d(\ln I)} = \frac{nkT}{q} + IR_s$$

(14)
Equation (13) is the first Cheung's model that is used to obtain the values of ideality factor, and series resistance. From equations (4) and (6)

$$I = AA^*T^2\exp\left(\frac{-q\Phi_B}{kT}\right)\exp\left(\frac{q(V - IR_s)}{nkT}\right)$$

(15a)
From equation (15a)

$$\ln I = \ln AA^*T^2 - \frac{q\Phi_B}{kT} + \frac{qV}{nkT} - \frac{qIR_s}{nkT}$$

(15b)
Equation (15b) can further be simplified as equation (15c) below

$$V = \frac{nkT}{q}\ln\left(\frac{I}{AA^*T^2}\right) + n\Phi_B + IR_s$$

(15c)
or

$$V - \frac{nkT}{q}\ln\left(\frac{I}{AA^*T^2}\right) = n\Phi_B + IR_s$$

(15c)
One can define a function $H(I)$ such that equation (15) can be written as thus

$$H(I) = V - \frac{nkT}{q}\ln\left(\frac{I}{AA^*T^2}\right)$$

(16a)
and

$$H(I) = n\Phi_B + IR_s$$

(16b)
Equations (16a) and (16b) are the second set of Cheung's models that could be used to determine the series resistance and the barrier height of a Schottky diode.

The modified Cheung's model

The electrical parameters of the modified Cheung's model were obtained by using same Cheung's model which was modified by considering the effects of the introduction of interfacial layer on the Cheung model. The plots of $\frac{dV}{d(\ln I)}$ against I , and the plot of $F(I)$ against *(I)* using equation 2.58 and 2.59 after least square fitting we got $y = ax + b$,where $R_s (= a)$ and $b\left(= \frac{KT\chi^{1/2}\delta}{q} + \Phi_B\right)$ were carried and the values of barrier height (Φ_b), ideality factor (n), and series resistance (R_S) were extracted using equation (8)and equation (11) respectively.

II. Materials and Methodology

Materials and Values of Constants to be Used

The metals, semiconductors and constants used in the computation process are presented in Table 1. Other constants used are: Boltzmann's Constant, k = 1.38 x 10^{-23} JK^{-1}; electronic charge, q = 1.602 x 10^{-19} J; Richardson's constant (A^* = 112 $Acm^{-2}K^{-2}$ for n – type Si, and 120 $Acm^{-2}K^{-2}$ for n – type Ge) and effective area A = 2 × 10^{-5} cm^2 for each of the semiconductors.

Table 1. Materials and Constants to be Used

Metal	Work Function Φ_m (eV)	Semiconductor	Electron Affinity χ (eV)	Metal/Semiconductor Contact	Barrier Height Φ_B (Measured) (eV)
Chromium (Cr)	4.50	n – type Silicon (n -Si)	4.05	Cr/n – type Si	0.45
Tungsten (W)	4.55	n – type Germanium (n - Ge)	4.13	W/n – type Si	0.50
Molybdenum (Mo)	4.60	-	-	Mo/n – type Si	0.55
-	-	-	-	Cr/n – type Ge	0.37
-	-	-	-	Cr/n – type Si	0.42
-	-	-	-	Cr/n – type Si	0.47

Equations Used

To compute the values of barrier heights, equation (11) was used. Measured values of the work function was obtained from [5]; diode effective area from [7]: Richardson constant for n – type Si from [10], while for n – type Ge from [9]. To determine the variation of the saturation currents with temperature, equation (4) was used. Simulated values of voltage were between the range of 0.09 V – 0.15 V at three different temperature values of 300 K, 310 K and 320 K for each of the metal – semiconductor contacts. Using equation (11), the dependence of $\frac{dV}{d(\ln I)}$ against I was plotted, and the calculated curved points was approximated with a least square fitted straight line, $y = ax + b$, as suggested by ward et al and Sekhar (2000, 2016). Using the least square fitted equations, values of the first series resistance, $R_{s1}(= a)$ as slope, and $b\left(= \frac{nkT}{q}\right)$ as the intercept was extracted, from which the ideality factor, *n* was obtained. Similarly, the same voltage value is used in equation (16a), and, the dependence of $H(I)$ against *(I)* is plotted using equation (16b). The curved points is also approximated into a least square fitted straight, from which the values of the barrier height, Φ_B , was extracted from the intercept as barrier height calculated, and the values of the second series resistance, R_{s2} is also extracted from the slope.

III. Results and Discussion

Results

The values of the saturation current for the six MIS contacts are presented in Table 1, while the values of the extracted electrical parameters are presented in tables 2 and 3. These values are then compared with the results obtained by Timtere (2019) when there was no effect of interfacial layer.

Table 1: Calculated values of Saturation current at 300K from equations (2) (Timtere, 2019) and (9) (This work)

S/N	Metal-Semiconductor Contact	Saturation Current I_o(A)
1	Cr/I/n-type Si	5.52×10^{-6}
2	W/I/n-type Si	7.98×10^{-7}
3	Mo/I/n-type Si	11.50×10^{-8}
4	Cr/I/n-type Ge	13.10×10^{-5}
5	W/I/n-type Ge	1.89×10^{-5}
6	Mo/I/n-type Ge	2.73×10^{-6}

Table 2: Extracted Values of Ideality Factor, Series Resistance and Barrier Height using Si

S/N	**Metal-Semiconductor Contact**	**Ideality Factor (n)**		**Series Resistance Rs (Ohms)**		**Barrier Height Φ_h(eV)**	
		This work	Timtere (2019)	This work	Timtere (2019)	This work	Timtere (2019)
1	Cr/I/n-type Si	0.066	0.065	1.31	0.94	1.788	1.570
2	W/I/n-type Si	0.051	0.051	3.40	3.50	2.392	1.960
3	Mo/I/n-type Si	0.039	0.041	25.0	15.00	2.872	2.350

Table 3: Extracted Values of Ideality Factor, Series Resistance and Barrier Height Using Ge

S/N	**Metal-Semiconductor Contact**	**Ideality Factor (n)**		**Series Resistance Rs (Ohms)**		**Barrier Height Φ_h(eV)**	
		This work	Timtere (2019)	This work	Timtere (2019)	This work	Timtere (2019)
1	Cr/I/n-type Ge	0.051	0.105	4.40	1.81	2.159	1.050
2	W/I/n-type Ge	0.071	0.078	0.63	0.43	1.657	1.350
3	Mo/I/n-type Ge	0.055	0.059	2.30	1.46	2.118	1.730

IV. DISCUSSION

From Table 1, the introduction of the interfacial layer in a MS contact does not affect the saturation current. This could be as a result of the thickness of the interfacial layer, which still allows current to tunnel through. Similarly, most authors have not identified any effect of the interfacial layer on the saturation current.

However, from Table 2 and 3, the values of the barrier height have been enhanced, from without interface, to when there is interfacial layer. This agrees with the findings of Reddy et al (2016) that introducing an interfacial layer into a MS contact leads to the shift in the barrier height. The values of the series resistance have also increased. The values of the ideality factor decrease in all the M/I/n-type Ge contacts, and does not follow any pattern in the M/I/n-type Si contacts. This could not be farfetched from the fact that there is actually no experimental or theoretical equation that provides a direct relationship between ideality factor and interfacial layer. It could still be subject for further research.

V. CONCLUSION

In this paper we have determined the values of some electrical parameters of some metal-semiconductor contacts using modified Cheungs Model. The result shows that values of all the electrical parameters are altered with the introduction of the interfacial layer, when compared to the work of Timtere (2019). In terms of performance, one can conclude that Cr/I/n-type Si could offer a better performance as regards to its high value of ideality factor, low series resistance and moderate barrier height.

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