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SAKARYA ÜNİVERSİTESİ FEN BİLİMLERİ ENSTİTÜSÜ DERGİSİ

The comparison of the methods used for determining of Schottky diode parameters in a wide temperature range

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ABSTRACT

The current-voltage (*I-V*) data of Ni/*n*-GaAs Schottky diodes with 50 nm Schottky metal thickness has been measured in the temperature range of 60 K to 320 K. The important contact parameters of Ni/*n*-GaAs Schottky diodes have been obtained by using conventional *I-V* method, Norde method, generalized Norde method, and Cheung functions for each temperature. Then, the results have been compared each other.

Keywords: Schottky diode, conventional *I-V* method, Cheung method, Norde method, generalized Norde method, temperature dependence

Schottky diyot parametrelerini belirlemede kullanılan metotların geniş bir sıcaklık aralığı için kıyaslanması

ÖZ

50 nm Schottky kontak kalınlığına sahip Ni/*n*-GaAs Schottky diyotlarının akım-gerilim (I-V) verileri 60 K'den 320 K'e kadar olan geniş bir sıcaklık aralığında ölçüldü. Ni/*n*-GaAs Schottky diyotlarının önemli kontak parametreleri geleneksel *I-V* metodu, Norde metodu, genelleştirilmiş Norde metodu ve Cheung fonksiyonları kullanılarak her bir sıcaklık değeri için ayrı ayrı elde edildi. Daha sonra sonuçlar birbirleriyle kıyaslandı.

Anahtar Kelimeler: Schottky diyot, geleneksel *I-V* metot, Cheung metot, Norde metot, genelleştirilmiş Norde metot, sıcaklık bağlılığı

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1. INTRODUCTION

Several methods based on thermionic emission theory have been derived for determination of Schottky diode parameters by using forward bias current-voltage (*I-V*) data [1-8]. The conventional I-V method is the most popular method to obtain the ideality factor and Schottky barrier height (BH) [1,2]. This method loses its reliability when lnI-V plot has a narrow linear region because of the high series resistance [3]. Norde has proposed a method which overcomes this problem. The reliable values of Schottky BH and series resistance can be determined by means of this method. However, this method is not suitable to determine the contact parameters of non-ideal Schottky diode since it assumes that the contact is abrupt (i.e. ideal) between metal and semiconductor [3,9]. For non-ideal Schottky diodes, Norde's method has been generalized by Bohlin. The method enables to calculate Schottky BH, ideality factor, and series resistance from one I-V measurement [4]. Furthermore, Cheung functions have been presented as another way to find series resistance, Schottky BH and *n* from the downward curvature region of the forward bias ln*I-V* plot [8].

In this study, the forward bias *I-V* measurements of Ni/*n*-GaAs Schottky diodes (SDs) which were fabricated by magnetron DC sputtering system were taken in a wide temperature range of 60–320 K. The common analytical tools have been used for data analysis and the contact parameters obtained by using different methods have been compared to each other. In literature there is no comparison of well-known methods used to find the contact parameters in a wide temperature range. This study presents information about the temperature dependence of the contact parameters obtained by different methods and try to explain the inconsistency between the methods.

2. EXPERIMENTAL

N-type GaAs (100) wafer with 1.46×10^{16} cm^{-3} donor concentration atoms has been used to fabricate the Schottky diodes. Before the Schottky and ohmic metallization, the wafer was exposed to wet chemical cleaning which has the following steps [10,11]:

1) Dipping in trichloroethylene, methanol, and acetone for 3.0 minutes (to remove the organic contamination)
2) Etching in a H_2SO_4: H_2O_2: H_2O (5:1:1) solution for 1.0 minute (to remove the surface damage layer and undesirable impurities),
3) Etching in a H_2O: HCl (1:1) solution (to remove the metallic contamination and thin oxide layer).

Generally, removing of organic contamination realizes before cleaning of the inorganic contamination because the presence of organic layer can prevent the acidic solutions to reach to the wafer surface [12]. After each process, the wafer was rinsed in deionized water with 18 MΩ resistivity. The drying process of the wafer was realized with the high purity nitrogen gas and then the wafer was taken to the deposition chamber, instantly. Ohmic contact was realized by evaporation of indium (In) at 10^{-5} Torr and then the wafer was annealed at 380 °C for 3 minutes in flowing N_2 for low resistance ohmic contact. The Schottky metallization of nickel (Ni) was realized by magnetron DC sputtering. Ni contacts with 50 nm thicknesses have a circular shape with a diameter of 1.5 mm. A Keithley 2400 SourceMeter and a Leybold Heraeus closed-cycle helium cryostat were employed to take the temperature dependent *I-V* measurements of the diodes. A Windaus MD850 electronic thermometer and a copper constantan thermocouple have been used to control sample temperature.

3. RESULTS AND DISCUSSION

3.1. Conventional *I-V* method

The relationship between current and voltage for Schottky diodes if the dominant mechanism is thermionic emission can be given as [1]:

$$I = AA^{*}T^{2}\exp\left(-\frac{q\Phi_{b}^{eff}}{kT}\right)\left[\exp\left(\frac{q(V-IR_{s})}{kT}\right)-1\right] \quad (1)$$

Here, A is the contact area, A^{*} is the effective Richardson constant (8.16 A/cm^{2}K^2 for *n*-GaAs [1]), k is the Boltzmann's constant, T is the absolute temperature in K, q is the elementary charge, Φ_b^{eff} is the effective BH, and R_s is the series resistance. A bias dependent Schottky BH and other effects which cause the deviation from thermionic emission are included by addition of an ideality factor (n) to Eq. (1). The relationship between Φ_b^{eff} and n is given by the following expression [1,10],

$$\Phi_b^{eff} = \Phi_{bo} + \left(1 - \frac{1}{n}\right)V \tag{2}$$

Here, Φ_{b0} is BH under zero bias. For $V\text{-}IR_s > 3kT/q$, Eq. (1) can be written as the following equation by taking into Eq. 2.

$$I = I_0 \exp\left(\frac{qV}{nkT}\right) \tag{3}$$

$$I_0 = AA^* T^2 \exp\left(-\frac{q\Phi_{b0}}{kT}\right) \tag{4}$$

At low and intermediate voltage region, the plot of ln*I*-*V* is linear and the extrapolating of this plot to ln*I* axis gives the reverse saturation current (I_0). The ideality factor can be determined from the slope of ln*I*-*V* plot in according to the following equation.

$$n = \frac{q}{kT}\frac{\mathrm{d}V}{\mathrm{d}\ln I} \tag{5}$$

The ln*I*-*V* characteristics of Ni/*n*-GaAs Schottky diodes as a function of temperatures are given in Figure 1. It can be said that the dominant mechanism for current transport across Ni/*n*-GaAs contacts is thermionic emission because the ln*I*-*V* characteristics are linear over a wide range of current values [11]. For each temperature, the existence of the series resistance which limits the current flow in the diodes causes a downward curvature region in the forward ln*I*-*V* curves [12]. This effect can be shown in Figure1. The ideality factor and the zero-bias BH values determined from ln*I*-*V* curves are listed in Table 1.

Table 1. The ideality and the zero-bias barrier height values obtained by using conventional *I*-*V* method

Temperature (K)	n	Φ_{b0} (*I-V*) (*eV*)
320	1.015	0.720
300	1.026	0.723
280	1.033	0.727
260	1.056	0.735
240	1.048	0.747
220	1.101	0.739
200	1.121	0.739
180	1.113	0.748
160	1.147	0.735
140	1.192	0.709
120	1.321	0.656
100	1.415	0.615
80	1.461	0.588
60	1.934	0.457

In our previous work [13], the temperature dependence of ln*I*-*V* curves and the parameters obtained from *I*-*V* data was studied in detail. As can be seen from the table, the ideality factor and zero-bias BH values change between 60 K and 180 K and the values show very little fluctuations after 180 K. Real metal-semiconductor interfaces where include low and high barrier height regions have an inhomogeneties barrier height distribution [16]. At low temperatures, since the electrons can only across the regions where include low barriers, the zero-bias BH value decreases and the ideality factor value increases as the temperature decreases. As the temperature increases, the electrons are able to surmount regions including high barrier heights. Therefore, effect of the barrier height inhomogeneties on *I*-*V* characteristic loses its importance and ideality factor and zero-bias height values show very little fluctuations at high temperatures [15,16].

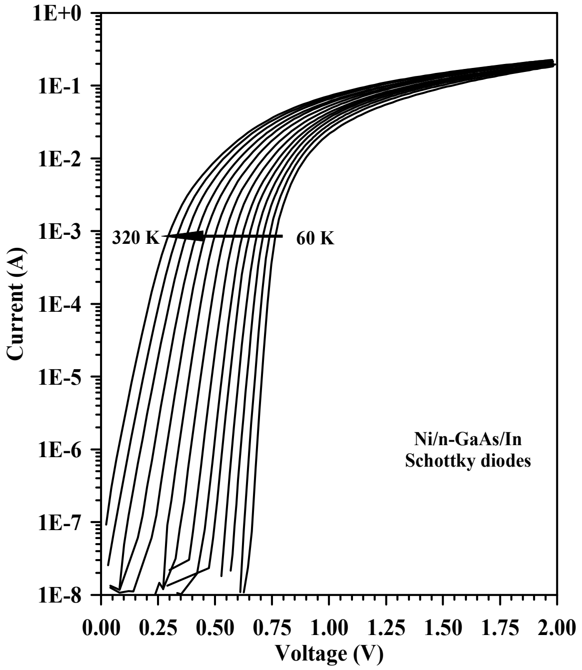

Figure 1. Forward bias *I*-*V* characteristics of Ni/*n*-GaAs/In Schottky diode for different temperatures

3.2. Cheung functions

The series resistance of a diode is the main reason of downward curvature region in an ln*I*-*V* plot [9]. The most common method to calculate R_s is the Cheung method [8]. In addition to R_s, n and barrier height (Φ_b) under a bias can be determined from Cheung's functions. The following equations are known as Cheung's functions:

$$\frac{\mathrm{d}V}{\mathrm{d}\ln I} = IR_s + \frac{nkT}{q} \tag{6}$$

$$H(I) = V - \frac{nkT}{q}\ln\left(\frac{I}{AA^{*}T^{2}}\right) \tag{7}$$

$$H(I) = IR_s + n\Phi_b \tag{8}$$

Taking into above the equations, dV/dln$I$ and $H(I)$ versus I plots are drawn by using data determined from the downward curvature region of ln$I$-V plot should be linear. R_s is determined from slope of these plots. n and Φ_b values is obtained from the y-axis intercept of dV/dln$I$ and $H(I)$ versus I plots, respectively. Table 2 summarizes the evaluation of the Ni/n-GaAs Schottky diode parameters based on Cheung functions is given in Figure 2.

Table 2. Schottky diode parameters obtained by using Cheung functions

Temperature (K)	**d*V*/dln*I*-*I***		***H(I)-I***	
	n	***R*$_s$ (Ω)**	***R*$_s$ (Ω)**	**Φ_b (eV)**
320	2.246	5.724	5.724	0.609
300	2.330	5.788	5.783	0.584
280	2.435	5.571	5.560	0.552
260	2.513	5.726	5.725	0.545
240	2.580	5.491	5.493	0.519
220	2.772	5.498	5.485	0.487
200	3.014	5.271	5.251	0.440
180	3.066	5.546	5.527	0.435
160	3.147	5.503	5.512	0.424
140	3.223	5.525	5.514	0.396
120	3.411	5.668	5.675	0.359
100	4.278	5.734	5.722	0.290
80	4.928	6.116	6.110	0.247
60	5.990	6.816	6.845	0.197

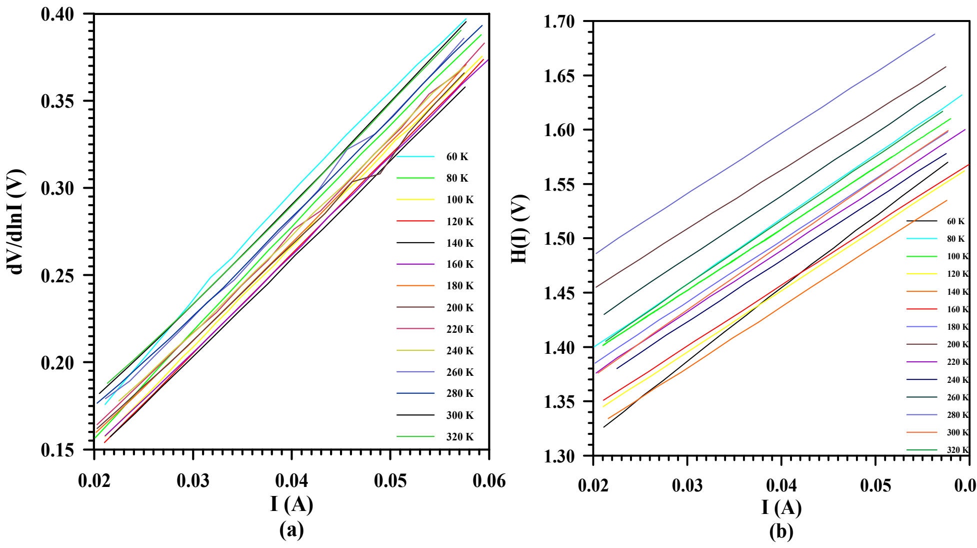

Figure 2. First and second Cheung functions of Ni/n-GaAs Schottky diodes

3.3. Norde and generalized Norde plot

The generalized Norde function has been proposed by Bohlin to calculate Φ_b and R_s values from only one I-V measurement at a fixed temperature. The generalized Norde function is described as [4]:

$$F(V,\alpha) = \frac{V}{\alpha} - \frac{1}{\beta}\ln\left(\frac{I(V)}{AA^{*}T^{2}}\right) \tag{9}$$

α is defined as an arbitrary constant greater than n, β is equal to q/kT, $I(V)$ is extracted from the measured I-V curve. Φ_b and R_s values can be obtained by determining of $F(V,\alpha)$ against V plot minimum in according to following equations [4]:

$$\Phi_b = F_{min}(V\ ,\alpha) + \left(\frac{\alpha - n}{n}\right)\left(\frac{V_{min}}{\alpha} - \frac{1}{\beta}\right) \tag{10}$$

$$R_s = \frac{(\alpha - n)}{\beta I_{min}} \tag{11}$$

where n value is obtained from the ln$I$-V plot. F_{min} (V, α) is the minimum point $F(V, \alpha)$-V plot, V_{min} and I_{min} are the corresponding voltage and current, respectively. For n=1 and α=2, Eqs. (9), (10), and (11) are same for normal Norde method are given in Ref. [3]. Figure 3 shows $F(V, 2)$-V plots for different temperatures. Table 3 contains Φ_b and R_s values obtained from Norde and generalized Norde plots.

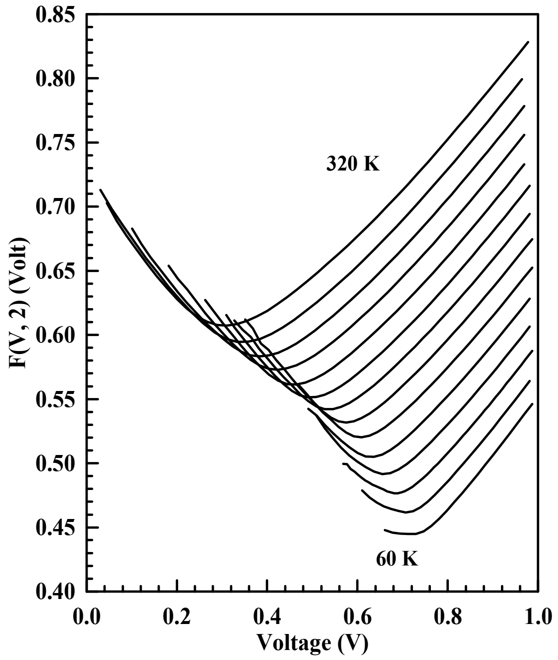

Figure 3. Norde plots of Ni/n-GaAs/In Schottky diodes at different temperatures

Table 3. Schottky diode parameters determined from Norde and generalized Norde method

Temperature (K)	***n***	α	**(Gen. Norde) R_s (Ω)**	**(Norde) R_s (Ω)**	**(Norde) Φ_b (eV)**	**(Gen. Norde) Φ_b (eV)**
320	1.015	2	4.248	4.313	0.757	0.753
300	1.026	2	5.794	5.948	0.756	0.748
280	1.033	2	5.004	5.175	0.770	0.758
260	1.056	2	4.885	5.175	0.780	0.758
240	1.048	2	4.878	5.123	0.789	0.768
220	1.101	2	6.553	7.289	0.791	0.747
200	1.121	2	7.897	8.984	0.800	0.745
180	1.113	2	6.653	7.500	0.814	0.757
160	1.147	2	7.154	8.388	0.819	0.743
140	1.192	2	7.494	9.274	0.818	0.717
120	1.321	2	12.871	18.956	0.813	0.656
100	1.415	2	14.280	24.410	0.811	0.615
80	1.461	2	18.472	34.272	0.809	0.590
60	1.934	2	18.265	276.738	0.796	0.457

3.4. The comparison of the methods

Figure 4 shows the temperature dependence of the barrier heights obtained by different methods. As can be seen from the figure, the barrier heights obtained by using the conventional I-V method are in good agreement with those calculated by using the generalized Norde method. There is an inconsistency between conventional I-V method and Norde method because Norde method assumes that the contact between metal semiconductor is ideal (i.e, n=1). Schottky BH values calculated by Cheung functions exhibit same temperature dependence of Schottky BH values determined by using conventional I-V method.

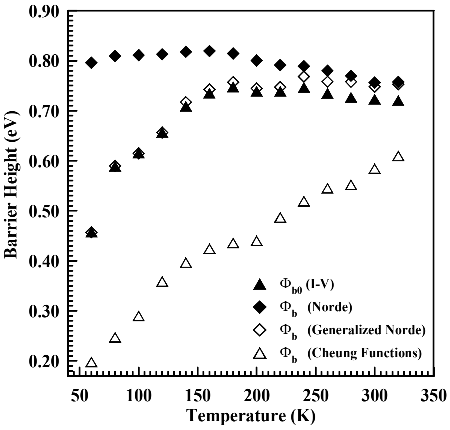

Figure 4.The temperature dependence of barrier height values obtained by different methods

However, BH values calculated from Cheung functions are smaller than those obtained by using conventional *I-V* and generalized Norde methods. The traditional *I-V* and generalized Norde methods use the data on the linear region of the curve. In this part of the *I-V* characteristics the essential effects are interfacial layer and interface states. In the Cheung method the BH values is obtained by using data taken on the nonlinear region of the *I-V* characteristics where also R_s is effective as well as the interfacial layer and interface states. [9,17]. Since the each method use the different regions of ln*I-V* characteristic, the inconsistency between BH values occurs. Same things can be said for ideality factor values obtained by both methods (Figure 5).

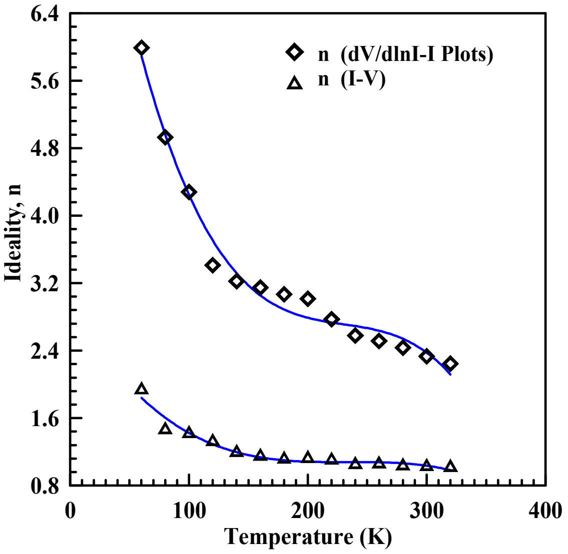

Figure 5. The temperature dependence of ideality factor values obtained by different methods

The temperature dependence of R_s values obtained by different methods is given in Figure 6. R_s values calculated by Cheung functions are different from those determined from Norde and generalized Norde plots. Cheung functions are only applied to downward curvature region of ln*I-V* characteristic. But, Norde and generalized Norde functions are applied to the full forward bias region of the ln*I-V* characteristic. Therefore, R_s values obtained by Norde plots are larger than those determined from Cheung functions [14].

Furthermore, the difficulty in the determination of minimum points of *F*(*V*,2)-*V* plots is still a problem can cause this inconsistency [8,9]. The Norde method and generalized Norde method determines series resistance value by using *I-V* data in the linear region of ln*I-V* characteristic in where the current changes as exponential. Therefore, a little mistake in determining the graphical turning points can affect series resistance value, dramatically. As referring to Figure 4 and Figure 6, all parameters obtained by different methods approach each other at high temperature region. This result is expected since the ideality factor value approaches to the unity as the temperature increases.

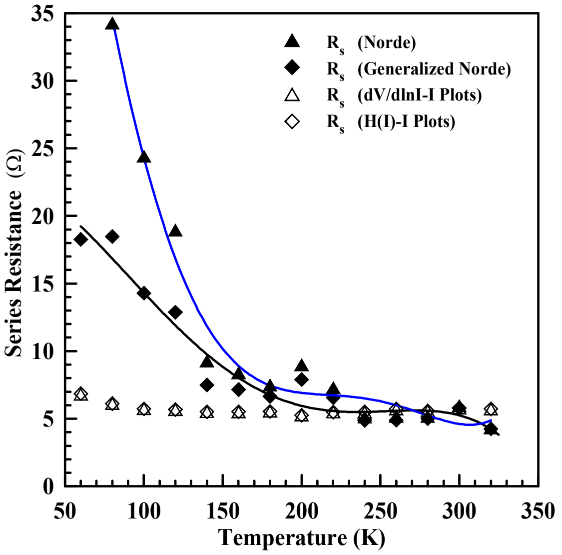

Figure 6. The temperature dependence of series resistance values obtained by different methods (The series resistance value at 60 K determined from Norde plot was excluded for a better visuality)

3.5. Conclusion

The Schottky BH values obtained from conventional *I-V* and generalized Norde methods show good agreement with each other. If we assume the conventional *I-V* method as the reference method, Norde methods lose their reliability at low temperatures. The Schottky BH values calculated by Cheung functions have same temperature dependence of Schottky BH values obtained by the reference method. R_s values determined from Cheung and generalized Norde (also, Norde) functions exhibit inconsistency because that the different nature of the methods. For the reliable results, the *I-V* data must be taken by little voltage steps when the series resistance is calculated by means of Norde and generalized Norde methods.

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