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Research Article

# Electrical Characterization of 6H-SiC/MEH-PPV/Al Schottky Diode by Current-Voltage Measurements in A Wide Temperature Range

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**Abstract**

In this paper, the 6H-SiC/MEH-PPV/Al Schottky diode with polymer interface was fabricated and characterized using current-voltage data in the temperature range 80-400 K. Important parameters of the fabricated diode such as ideality factor, barrier height was calculated from current-voltage measurements. The saturation current also was determined from the plots obtained from experimental results. In addition, the series resistance of the diode was calculated by using Cheung and Norde methods. On the other hand, the calculated diode characteristics were discussed by comparing with the each other and literature. Strong dependence of the calculated characteristics on temperature has been determined.

**Keywords:** 6H-SiC/MEH-PPV diode, 6H-SiC, MEH-PPV, Schottky barrier, barrier height, ideality factor, resistance

## 6H-SiC/MEH-PPV/Al Schottky Diyotunun Geniş Bir Sıcaklık Aralığında Akım-Gerilim Ölçümleri İle Elektriksel Karakterizasyonu

**Öz**

Bu çalışmada, 6H-SiC/MEH-PPV/Al polimer ara yüzlü Schottky diyotu üretilmiş ve 80-400 K sıcaklık aralığında akım-voltaj verileri kullanılarak karakterize edilmiştir. Üretimi yapılan diyotun İdealite faktörü, engel yüksekliği gibi önemli parametreleri akım-voltaj ölçümlerinden hesaplanmıştır. Doyma akımı ise deneysel sonuçlardan elde edilen grafiklerden belirlenmiştir. Ayrıca diyotun seri direnci Cheung ve Norde yöntemleri kullanılarak hesaplanmıştır. Diğer yandan hesaplanan diyot özellikleri birbirleri ve literatür ile karşılaştırılarak tartışılmıştır. Hesaplanan özelliklerin sıcaklığa güçlü bir şekilde bağlı olduğu belirlenmiştir.

**Anahtar Kelimeler:** 6H-SiC/MEH-PPV diyot, 6H-SiC, MEH-PPV, Schottky engeli, engel yüksekliği, idealite faktörü, direnç

## 1. Introduction

Silicon carbide (SiC) semiconductor occupies a special position in semiconductors for reasons of wide band gap, high thermal conductivity, high electron drift rate and high durability (Kosyachenko, Sklyarchuk, & Sklyarchuk, 1998; Zhao, Sheng, & Lebron-Velilla, 2006). In addition, it is distinguished from others with its ability to be used in high temperature, high power and high radiation environments where conventional semiconductors cannot perform enough (Neudeck, 2006). Therefore, it is widely used in the construction of devices that can operate in high frequency, high power, high and low temperature environments (Belous, 2021; Vali et al., 2020; Wang, Qi, Yang, & Zhang, 2020). Due to its indirect band structure, its optical properties are also prominent, so there are photovoltaic studies on this material (Sciuto et al., 2017). Apart from these, SiC, which has a wide range of uses from various sensors to detectors, continues to be the focus of many researches (Bernat et al., 2021; Bodie, Lioliou, & Barnett, 2021; Zaťko et al., 2021). Determining the electronic parameters of SiC, which has such a wide application area, is very valuable. Because these parameters play an important role in determining the usage area technologically. Schottky barrier diodes have a very important place in determining these parameters. The current-voltage characteristics of these diodes are the most important elements in determining some vital parameters (Cheung & Cheung, 1986; Rhoderick & Williams, 1988). On the other hand, the manufacturing steps of the Schottky diode determine its electrical properties. Therefore, controlling the electrical parameters of the Schottky diode have remained one of the biggest obstacles for researchers. Among the many factors that affect the electrical parameters of the diode are the organic/inorganic materials used in their manufacture (Gülen, Ejderha, Nuhoğlu, & Turut, 2011). One of these materials is the conductive polymer known as Poly [2-methoxy-5- (2-ethyl) hexoxy-1,4-phenylenvinylene] (MEH-PPV). These polymers are used in the production of sensors and organic diodes, especially organic light emitting LEDs (OLED) due to their high environmental stability and easy conductivity control (Aydin, Yakuphanoglu, Eom, & Hwang, 2007; Sevim & Mutlu, 2009). Therefore, studies on determining the electrical parameters of diodes are still up-to-date.

According to the literature, although there are no studies on the 6H-SiC based Schottky diode with MEH-PPV polymer interface, there are very few reports on diodes similar to this diode structure. Altan et al. compared the experimental results obtained from the current-voltage data of the P3HT:PCMB/6H-SiC Schottky diode with polymer interface in the temperature range 300-375 K with the results they calculated with different current conduction model. They reported harmony between experimental results and theoretically calculated results (Altan, Özer, & Ezgin, 2020). Felix et al. investigated the current-voltage properties of a SPAN/6H-4H SiC polymer interface hybrid diode in the temperature range of 20-440 K. They explained that these diodes have good rectifying properties (J. Felix et al., 2012). Felix et al. made the electrical characterization of the diode using the current-voltage data obtained in the temperature range of 20-430 K of the PANI/4H-6H SiC Schottky diode fabricated using a conductive polymer. They showed that the electrical parameters of these fabricated diodes are affected by a certain amount of radiation (J. F. Felix et al., 2014). Kavasoğlu et al. investigated the current conduction mechanism with the current-voltage measurement of Si/MEH-PPV diode in the temperature range of 230-330 K. They reported that different conduction mechanisms are dominant depending on the temperature (Kavasoglu et al., 2010). Zhu et al. stated that the MEH-PPV/Al Schottky diode's electrical parameters were calculated using the current voltage measurement between 303 and 405 K temperature range. They showed that increasing the thickness of the MEH-PPV layer negatively affects the diode performance (Zhu, Cui, & Varahramyan, 2004).

In this study, for the first time, the electrical characterization of 6H-SiC/MEH-PPV/Al

Schottky diode in a wide temperature range has been made. The basic parameters of the fabricated diode such as ideality factor, barrier height, saturation current and resistances have been calculated using different methods. Calculated electrical parameters have been discussed in comparison with the literature and with each other.

## 2. Experimental

6H-SiC/MEH-PPV Schottky diode is fabricated by Cree Inc. A 280 µm thick n-type 6H-SiC semiconductor wafer, with a diameter of 2 inches (001), with a donor density of 2.610$^{17}$ cm$^{-3}$, was used. The surface of the SiC wafer was cleaned using the clean method known as RCA (i.e. a 10 min boil in $NH_4$ + $H_2O_2$ + $6H_2O$ followed by a 10 min boil in HCl + $H_2O_2$ + $6H_2O$).

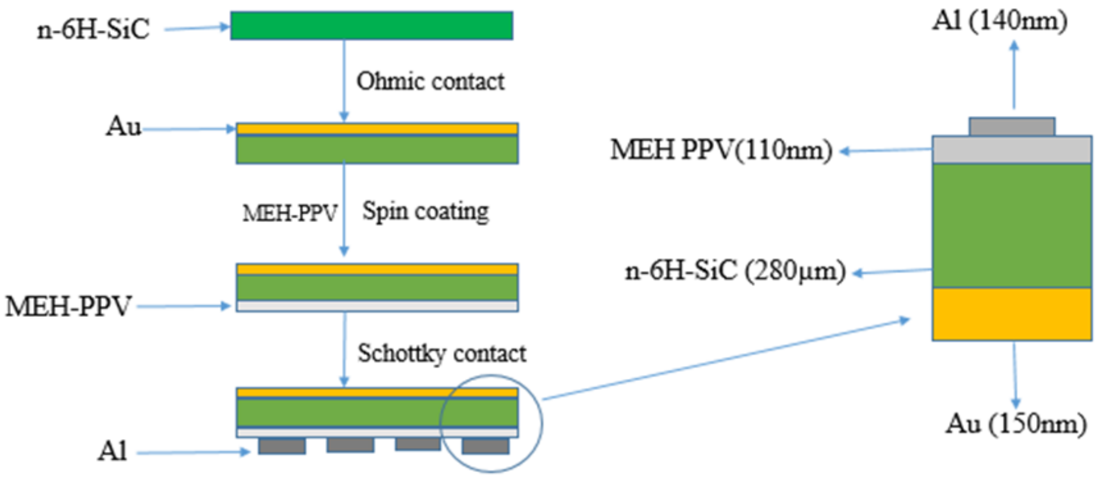

**Figure1**. Schematic diagram of 6H-SiC/MEH-PPV Schottky diode

Then, it was kept in HF/$H_2$0 (1:10) solution for 20 seconds to remove the oxide layer formed on the surface. After this process, pure gold (Au, 99.995%) of 150 nm thickness was evaporated to the matte surface of the SiC wafer under 10$^{-6}$ Torr pressure. To create ohmic contact, the sample was annealed at 500 °C for 5 minutes in the metal evaporation system. Then dissolved in toluene, MEH-PPV was coated with a spin coater on the polished surface of the SiC wafer at 2000 rpm for 60 seconds. The coated SiC was annealed at 60 °C for 5 minutes to remove toluene from the wafer surface. After this process, pure aluminum (Al, 99.999%) of 140 nm thickness was evaporated to form rectifier(Schottky) contact. For this, a 1 mm diameter stainless steel mask is used. Experimentally fabricated 6H-SiC/MEH PPV Schottky diode is shown in Figure 1. The current-voltage (I-V) measurements of diode were performed by the use a Keithley 2400 Sourcemeter. Measurements were carried out with the help of an IEEE-488 AC / DC converter card installed in the computer. The current-voltage was done with 0.05 V increments in the voltage range of -3 V to + 3 V. The thickness of the polymer layer at the interface of the fabricated diode was measured using an optical profilometer.

## 3. Result and Discussion

Thermionic emission model can be used to determine the I-V dependent characteristics of Schottky diodes (Rhoderick & Williams, 1988). According to this model; The expression giving the relationship between current and voltage,

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

$$I_0 = A\,A^{**} \exp\left(\frac{-q\Phi_b}{kT}\right) \quad (2)$$

Here Io is saturation current, V applied voltage, q electron charge, T, absolute temperature, a contact area, k Boltzmann constant, $\Phi_b$ Schottky barrier height, n is the ideality factor and A** is the Richardson coefficient of the semiconductor. For n-6H-SIC used here, this coefficient is equal to 194 $Acm^{-2}K^{-2}$ (Pham, Tran, Holland, & Partridge, 2019). If n ideality factor and barrier height $\Phi_b$ expressions are written from Equations 1 and 2, respectively;

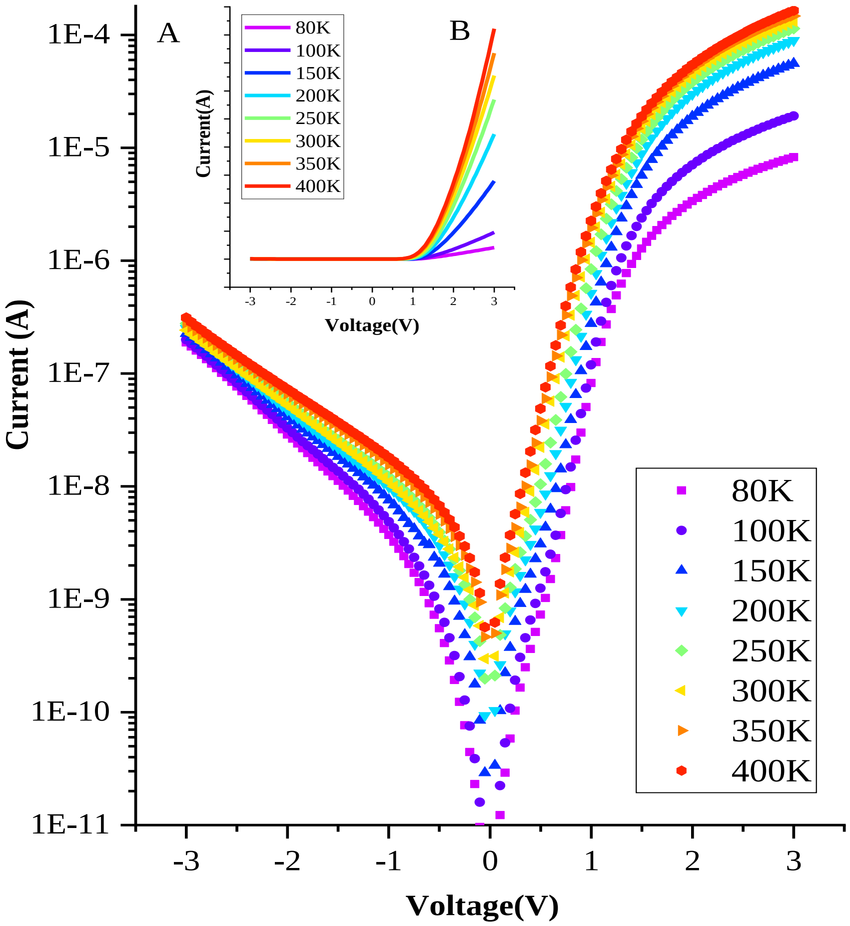

**Figure 2.** Semi-logarithmic I-V characteristics of the A-6H-SiC/MEH-PPV Schottky diode in a wide temperature range. B- I-V characteristics of Diode

$$n = \frac{q}{kT}\left(\frac{dV}{dlnI}\right) \tag{3}$$

$$\Phi_b = \frac{kT}{q} \, \mathrm{Ln} \left(\frac{AA^*T^2}{I_0}\right) \tag{4}$$

expressions can be written. Using equations 3 and 4 of the LnI-V plot obtained from experimental I-V measurements, $\Phi_b$, n and $I_o$ can be calculated from the most important electrical parameters for diodes. Accordingly, n is calculated using equation 3 from the slope of the linear region of the LnI-V plot, and $I_o$ is calculated from the cut-off point.

**Table 1**. Parameters calculated from the I-V measurement results of the 6H-SiC/MEH-PPV diode.

| ***T(K)*** | ***LnI-V*** | | | ***H(I)-I*** | | ***dV-d(LnI)*** | | ***F(V)-V*** | |
|---|---|---|---|---|---|---|---|---|---|
| | *n* | *Φb(eV)* | *$I_o$ (A)* | *Φb(eV)* | *R(kΩ)* | *n* | *R(kΩ)* | *Φb(eV)* | *R(kΩ)* |
| **80K** | 16,832 | 0,188 | 1,80E-11 | 0,225 | 176,830 | 18,841 | 202,29 | 0,227 | 260,29 |
| **100K** | 14,999 | 0,290 | 2,74E-11 | 0,267 | 70,73 | 17,855 | 81,22 | 0,269 | 57,61 |
| **150K** | 10,283 | 0,432 | 8,41E-11 | 0,389 | 21,97 | 13,604 | 25,53 | 0,400 | 19,53 |
| **200K** | 7,668 | 0,574 | 1,58E-10 | 0,513 | 13,22 | 10,841 | 15,41 | 0,535 | 18,45 |
| **250K** | 5,826 | 0,720 | 2,28E-10 | 0,690 | 12,65 | 6,446 | 14,23 | 0,690 | 14,88 |
| **300K** | **4,357** | **0,868** | **2,79E-10** | **0,787** | **10,08** | **6,325** | **12,4** | **0,828** | **12,07** |
| **350K** | 3,787 | 1,005 | 4,86E-10 | 0,904 | 8,96 | 6,228 | 10,75 | 0,967 | 10,55 |
| **400K** | 3,303 | 1,150 | 6,21E-10 | 1,017 | 7,7 | 6,029 | 9,2 | 1,075 | 9,11 |

In addition, using these values, the value of $\Phi_b$ is calculated according to equation 4. Experimental I-V characteristics of the 6H-SiC/MEH-PPV diode can be seen in Figure 2A. It can also be seen in Figure 2B that the fabricated diode shows a rectifying character at every temperature. Accordingly, the parameters calculated according to Figure 2 can be seen in Table 1. When Table 1 is examined, it can be seen that the ideality factor decreases from 16.32 to 3.3 as the temperature increases, while the barrier height increases from 0.225 to 1.15 eV. This clearly demonstrates the strong temperature dependence of both the barrier height and the ideality factor. This situation can be seen better in Figure 3A. Since the current conduction at the metal and semiconductor interface depends on the temperature, the current at low temperatures consists of currents that exceed low barrier height. Therefore, as the barrier height decreases, the ideality factor increases. With the increase of temperature, more electrons with sufficient energy overcome the barrier, which increases the barrier height and decreases the ideality factor (Padma & Reddy, 2014). Another reason for the decrease of the barrier and the increase of the ideality factor at low temperatures may be shown as the interface state density, the inhomogeneity in the interface and irregular charge distribution (Quan & Hbib, 1993). Another reason may be that another current conduction mechanism is dominant at low temperatures, which is different from the current conduction mechanism predicted by the thermionic emission model (Aydoğan, Sağlam, & Türüt, 2005)

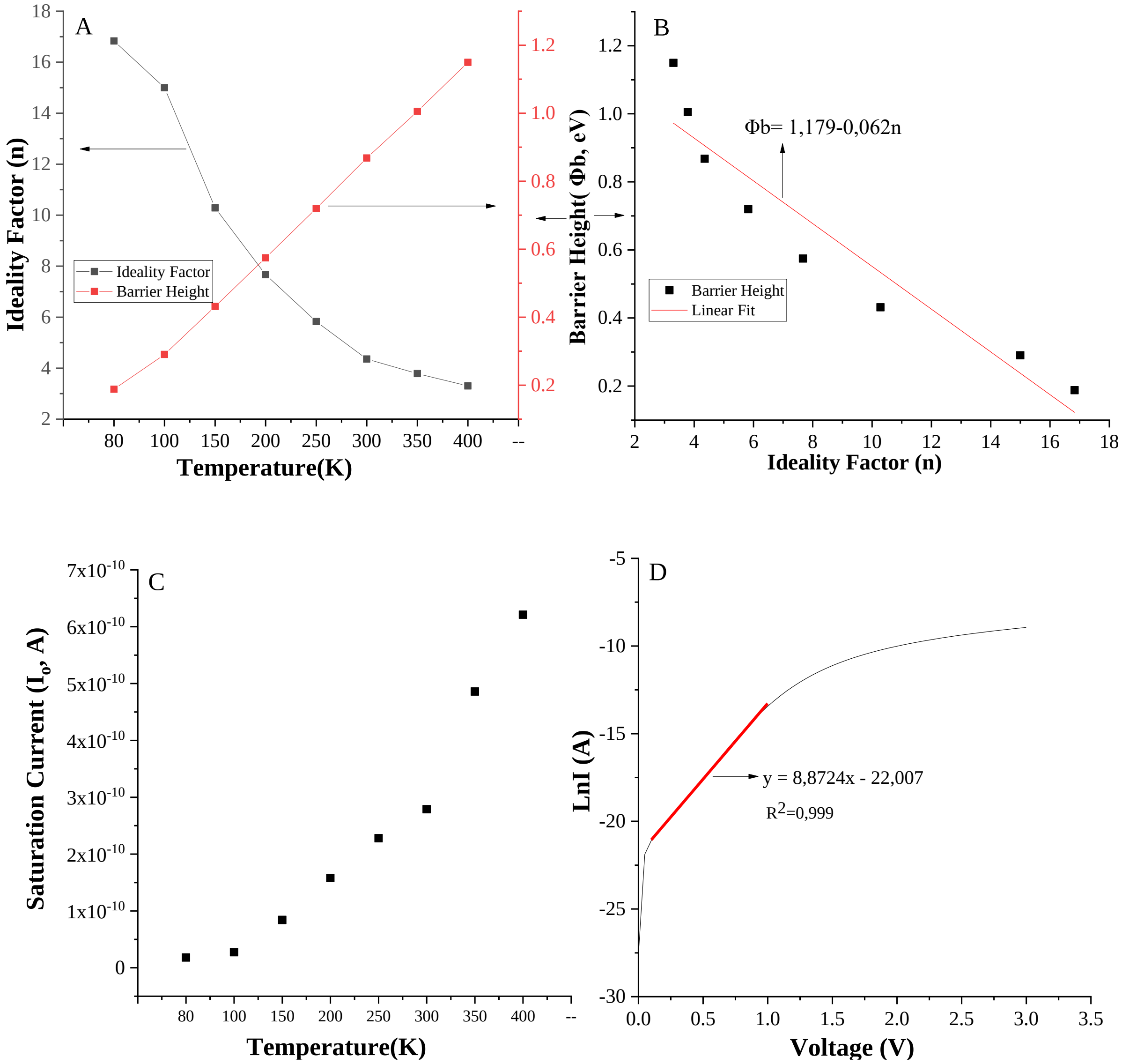

**Figure 3.** A-Temperature dependent change of barrier height ($\Phi_b$) and ideality factor (n) values of 6H-SiC/MEH-PPV diode. B-Plot of barrier height versus ideality factor. C-Saturation current change plot with temperature. D- LnI-V plot obtained from experimental measurements of diode at room temperature (300K).

As in 6H-SiC, current transmission mechanisms such as thermionic field emission or carrier recombination may be dominant in semiconductors with wide band structure at low temperatures (Mamor, 2009). The reason for this can be explained by the weak dependence of the band gap of the semiconductor on temperature. On the other hand, as in this study, the MEH-PPV polymer at the interface may also have affected the current conduction dynamics. Since the polymer affects the interface, it may have contributed to the formation of inhomogeneity in the barrier (Aydoğan, Sağlam, & Türüt, 2008). However, the variation of barrier height and ideality factor with temperature may be due to lateral fluctuations in barrier height. Tung et al. explained that this situation is caused by the homogeneous barrier height between the semiconductor and the metal being high or low in locally irregular or patchy regions (Tung, 2001). This situation can be seen better in Figure 3B. According to Figure 3B, there is a close linear relationship between the ideality factor of the effective barrier height calculated from experimental parameters depending on the temperature. This is related to the lateral inhomogeneity of the barrier height (Güzel, Bilgili, & Özer, 2018; Leroy, Opsomer, Forment, & Van Meirhaeghe, 2005). From the plot, lateral homogeneous barrier height for n = 1 value was calculated as 1.11 eV for 6H-SiC/MEH-PPV polymer interface diode. In addition, the change of saturation current with temperature can be seen in Figure 3C. The increase of saturation current with temperature may due to the increasing number of free carriers. According to the literature, Altan et al. reported $\Phi_b$, n values of P3HT: PCBM/6H-SiC polymer interface diode as 3.93 and 0.77 eV at 300 K temperature, 3.50 and 0.94 eV at 375 K, respectively (Altan et al., 2020). On the other hand, Felix et al. studied the electrical parameters of PANI/6H-SiC diodes in the temperature range of 110-430 K. They calculated the values of $\Phi_b$, n at 110 K as 0.28, 3.16, and 0.76 eV, 1.2 at 430 K, respectively (J. F. Felix et al., 2014). Felix et al. explained the electrical characteristics of the SPAN/6H-SiC polymer interface diode in the 20-400 K temperature range Φb, n as 0.08 eV and 13.5 with 0.98 eV and 1.1, respectively (J. Felix et al., 2012). Aydın et al. calculated the electrical parameters of the Al/MEH-PPV/Si diode at room temperature. They reported the values of $\Phi_b$, n as 0.80, 1.88, respectively (Aydin et al., 2007). In addition to these, Kavasoğlu et al. made the electrical characterization of n-Si/MEH-PPV polymer's diode in the temperature range of 110-330 K. They explained the values of $\Phi_b$, n as 0.90 eV, 3.20 at 110 K, and 1.36 eV, 2.25 at 330 K, respectively (Kavasoglu et al., 2010). In addition, although the known $\Phi_b$ value of 6H-SiC/Al diode, which is one of the traditional metal/semiconductor contacts, is 0.98 eV at room temperature, 0.86 eV was found in this study (Davydov, 2004; Zetterling et al., 1998). This may be attributed to the MEH-PPV polymer layer, which affects the barrier height (Vearey-Roberts & Evans, 2005). This may be caused by the interface dipole induced by the passivation organic polymer layer (Bolognesi, Di Carlo, Lugli, Kampen, & Zahn, 2003; Zahn, Kampen, & Méndez, 2003). Similarly, Zahn et al. stated that the change in barrier height due to the organic interlayer is related to the alignment of the energy level of the lowest unoccupied molecular orbital (LUMO) with respect to the conduction band minimum (CBM) of the inorganic semiconductor (Zahn et al., 2003).

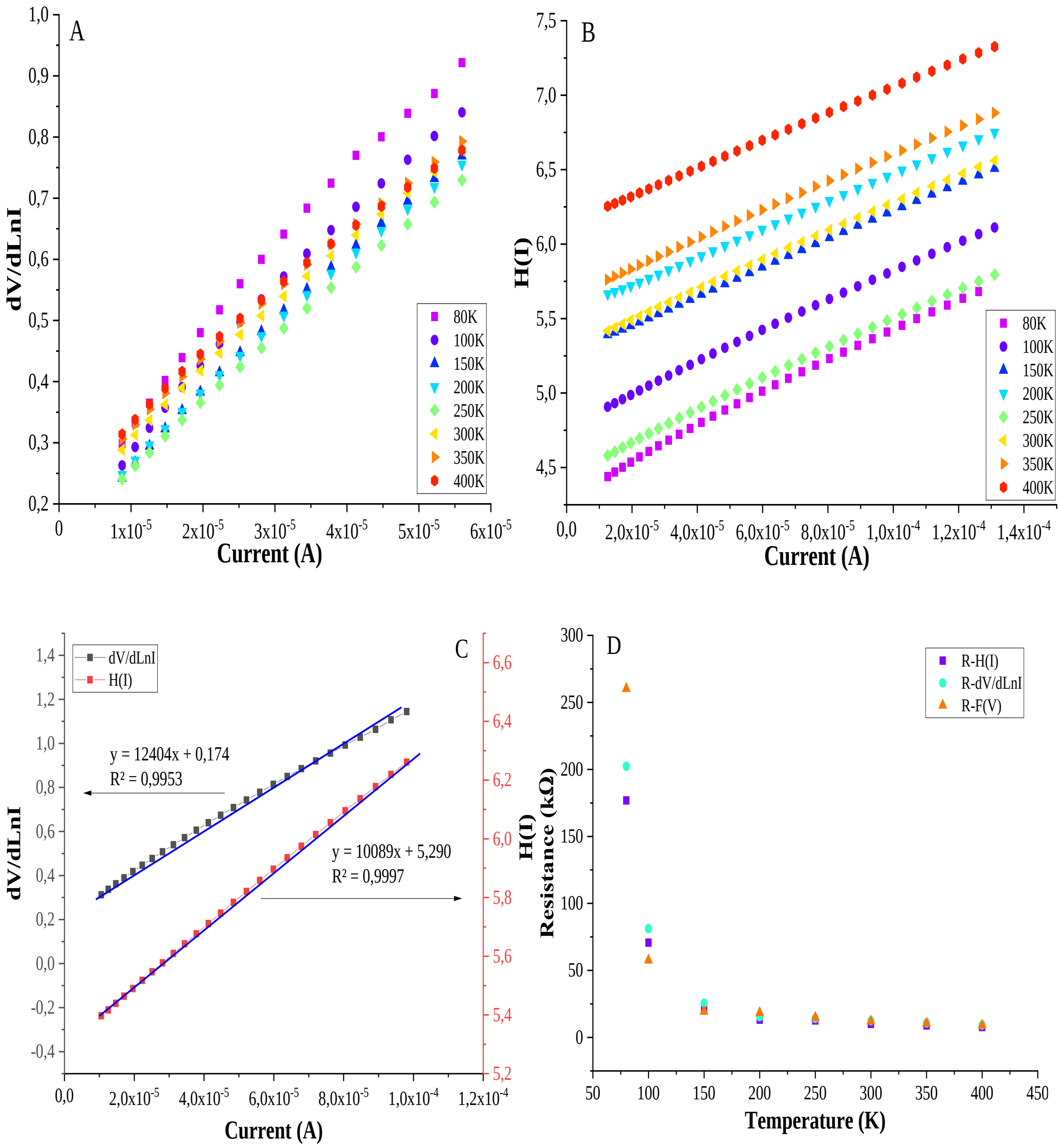

**Figure 4.** A-Plots of dV/dLnI versus current(I) obtained from experimental measurements of 6H-SiC/MEH-PPV diode. B-Plot of H (I) versus current (I). C- The plots of H (I) and dV / dLnI versus current(I) obtained at room temperature (300K). D- Temperature dependent changes of resistances calculated by Cheung and Norde methods

On the other hand, it can be seen that the semi-logarithmic I-V characteristic in Figure 2 deviates from linearity in the forward voltage region. This may be attributed to the effect of increasing series resistance. Resistance (Rs) is among the important electrical parameters for semiconductors that can affect current conduction. A number of theories have been presented in the literature to calculate the resistance of semiconductors. One of them is the Cheung-Cheung method (Cheung &

Cheung, 1986). In this method, resistance can be calculated in two different ways.

$$\frac{dV}{dLnI} = IR_s + \frac{nkT}{q} \qquad (5)$$

$$H(I) = IR_s + n\Phi_b \qquad (6)$$

According to Equation 5, the plot of dV/dLnI versus current (I) is expected to give a linear line where the resistance region is dominant. While the slope of this line gives resistance (Rs), the ideality factor can be calculated from the point where it intersects the vertical axis. On the other hand, according to equation 6, the resistance can be found from the slope of the linear line of the plot drawn against the current of the function H(I) and the barrier height can be calculated from the vertical axis cut-off point. Plots of dV/dLnI and H(I) versus current obtained from experimental measurements of 6H-SiC/MEH-PPV diode can be seen in Figure 4A, B. As expected, linearity can be seen in the resistance region at Figure. Calculations made from the slope and cut points of these linear lines are shown in Table 1. According to the dV/dLnI-I plot, the resistance was calculated as 202.29 kΩ at 80 K, while this value decreased to 9.2 kΩ at 400 K. According to the H(I)-I plot, 176.83 kΩ at 80 K temperature was calculated and 7.7 kΩ at 400 K. It can be seen that the values calculated with both techniques are quite consistent with each other. On the other hand, the barrier height calculated by the H(I)-I plot is in good agreement with the values calculated from the LnI-V plot. However, there is not much agreement between the ideality factor value calculated in the dV/dLnI plot and the values obtained from the LnI-V plot before. This may be due to the difference in calculation technique. Another resistance calculation method was proposed by Norde.

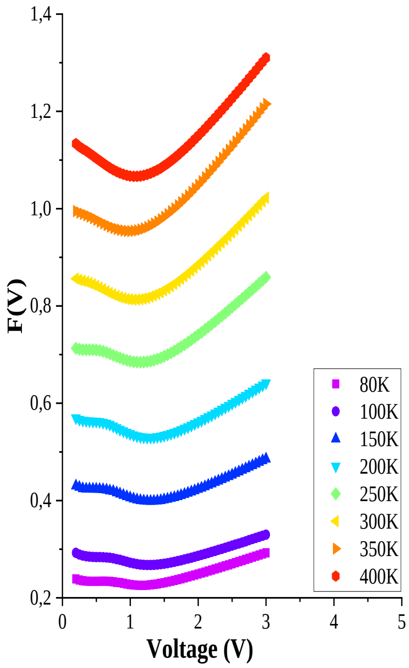

**Figure 5.** Voltage versus plot of the F (V) function obtained from the experimental measurements of the 6H-SiC/MEH-PPV diode.

According to this,

$$F(V) = \frac{V}{\gamma} - \frac{1}{\beta}\ln\left(\frac{I(V)}{AA^{**}T^2}\right) \qquad (7)$$

Here, the plot F(V)-V passes through a minimum, where β= q / kT and γ is a larger integer than the ideality factor (n). $V_{min}$ value corresponding to $F_{min}$ value,

$$\varphi_b = F_{min} + \frac{V_{min}}{\gamma} - \frac{kT}{q} \qquad (8)$$

It is given with the expression. The barrier height is calculated from the equation 8. In addition, the current ($I_{min}$) corresponding to the value of $V_{min}$,

$$R = \frac{kT(\gamma - n)}{qI_{min}} \qquad (9)$$

with the expression, the resistance can be calculated. Accordingly, the plot of the function F(V) versus voltage (V) is given in Figure 5. Again, resistance values calculated according to the Norde method are shown in Table 1. According to Table 1, while the resistance of the 6H-SiC/MEH-PPV diode at 80 K temperature was calculated as 260.29 kΩ, it was found to be 9.11 kΩ at 400 K. In the literature, Felix et al. calculated the room temperature resistance of the Schottky diode with PANI/6H-SiC polymer interface as 0.67 kΩ (J. F. Felix et al., 2014). Aydın et al. reported the series resistance of the Al/MEH-PPV/Si diode at room temperature as 7.13 kΩ (Aydin et al., 2007). On the other hand, Kavasoğlu et al. declared that the series resistance of the n-Si/MEH-PPV diode at room temperature is 6.20 kΩ (Kavasoglu et al., 2010). Altan et al. reported the resistance of the P3HT:PCBM/6H-SiC/Ag diode at room temperature as 0.5 kΩ (Altan et al., 2020). In addition to these, it was reported that the series resistance of the P3HT:PCBM/6H-SiC/Al organic-inorganic Schottky diode at room temperature is 9.38 kΩ (Güzel, 2015). The barrier height values calculated from the Norde method are in good agreement with the values calculated with other techniques. In addition, for this diode, the resistance values calculated by Cheung and Norde methods are in good agreement, contrary to the literature (Duman, Ejderha, Yiğit, & Türüt, 2012). This situation can be seen much better in Figure 4D. According to the figure, an exponential decrease in the resistance value can be seen with the temperature increase. It may be suggested that this is because the contribution of thermally increased free carriers will dominate that of the doping atoms, so the resistance will decrease exponentially with the increase in temperature. This behavior may be attributed to the absence of free carriers at low temperatures (Chand & Kumar, 1996). It were reported that the resistances of metal/ semiconductor Schottky diodes fabricated with 6H-SiC semiconductor in the traditional sense are in the range of 60-100 Ω at room temperature (Asubay, Genisel, & Ocak, 2014; Çınar, Coşkun, Aydoğan, Asıl, & Gür, 2010; Güzel et al., 2018; Zhang, Madangarli, Tarplee, & Sudarshan, 2001). However, in this study, the resistance of the polymer interface diode at room temperature was calculated as 10.08 kΩ. The reason for the significant change in resistance may be the MEH-PPV polymer layer on the interface. Because the high value series resistance may be caused by the reduced free carrier concentration due to the organic layer at the interface (Aydoğan, İncekara, Deniz, & Türüt, 2010).

## 4. Conclusion

Au/6H-SiC/MEH-PPV/Al diode was fabricated and characterized by using I-V measurements in a wide temperature range of 80-400 K. From the measured I-V measurements of the diode, it showed rectify behavior at all temperatures. Also, parameters such as ideality factor (n), barrier height ($\Phi_b$) were calculated from the I-V outputs. The saturation current($I_o$) also was determined from the plots obtained from experimental results In addition to these, another important parameter, the series resistance(Rs), was calculated by Cheung and Norde methods. Calculated results were discussed in comparison with the literature and with each other. Strong dependence of the ideality factor and barrier height on temperature was also found in this study. It was determined that as barrier height increases with temperature, while the ideality factor decreases. This behavior was attributed to the presence of the spatially inhomogeneous barrier height that occurs at the organic/inorganic semiconductor interface. In addition, it was found that the resistance decreases with the increase in temperature. This was attributed to the free carrier density increasing with the increase in temperature. Barrier Height was calculated as 0.188 and 1.15 eV at 80 K and 400 K, respectively. In addition, the series resistance was found as 202.29 and 12.4 kΩ in the 80 K and 400 K temperature range, respectively. On the other hand, in this study, it was found that there is a good agreement in Cheung and Norde method calculations.

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