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The current–voltage–temperature characteristics of Al/NPB/p-Si contact

Wen-Chang Huang [a,*], Chia-Tsung Horng [b], Jin Chang Cheng [c], Chien-Chou Chen [a]

[a] Department of Electronic Engineering, Kun Shan University, No. 949, Da Wan Road, Yung-Kang City, Tainan Hsien 710, Taiwan, ROC
[b] Department of Electro-Optical Engineering, Kun Shan University, No. 949, Da Wan Road, Yung-Kang City, Tainan Hsien 710, Taiwan, ROC
[c] Department of Accounting and Information System, Chang Jung Christian University, Taiwan, ROC

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ABSTRACT

The current–voltage (*I–V*) characteristics of the Al/NPB/p-Si contact shows rectifying behavior with a potential barrier formed at the contact interface. The barrier height and ideality factor values of 0.65 eV and 1.33 are measured at the forward bias of the diode. The barrier height of the Al/NPB/p-Si diode at room temperature is larger that (~0.58 eV) of conventional Al/p-Si diode. It reveals the NPB organic film control the carrier transport of the diode at the contact interface. The temperature effect on the *I–V* measurement is also performed to reveal the junction characteristics. The ideality factor of the Al/NPB/p-Si contact increases with decreasing temperature. And the barrier height decreases with decreasing temperature. The effects are due to the existence of the interface states and the inhomogeneous of the barrier at the junction.

1. Introduction

Organic semiconductors have attracted increasing interest owing to their potential application in various electronic and opto-electronic devices. Such as optical switches [1], batteries [2], field effect-transistors [3], solar cells [4], organic light-emitting diodes (OLEDs) [5] are studied. The organic semiconductor also shows the advantageous of low synthesis costs and relative easiness of handling make this new class of materials attractive for the above-mentioned applications. The Schottky barrier diodes are one of the simplest metal–semiconductor contact devices in the semiconductor device technology. The reliability and stability of the Schottky barrier diodes is dominated by the properties of the contact interface. Due to the existence of interface dipoles, defects of a real Schottky diode. The effective Schottky barrier height ϕ_b, in general, is restricted to within 0.4–0.7 eV range for a p-Si independent of contact metal. To improve the Schottky barrier height, the formation of high-quality Schottky diode with a low ideality factor by using thin interfacial films is one of essential process for devices [6]. A systematic study of the energy level alignment at the interfaces between metals and organic semiconductors had been discussed in the reports [7,8]. The current–voltage–temperature (*I–V–T*) characteristics of a Schottky diode had also been reported [9–11].

In this paper, we studied the possibility of the barrier improvement of the metal/p-Si Schottky diodes. Fabricated by using the *N*,*N*′-diphenyl-*N*,*N*′-bis (1-naphthyl)-(1,1′-biphenyl)-4,4′-diamine (NPB) as a interfacial film between metal and silicon.

2. Experiment

The samples were prepared using mirror cleaned and polished p-type Si wafers with (1 0 0) orientation and with the resistivity of 5–10 Ω cm. The evaporating of Al on the back surface of the substrate and then was annealed in a furnace at 550 °C for 5 min to form ohmic contact. The native oxide on the front surface of the substrate was removed in BOE solution and finally the wafer was rinsed in de-ionized water for 30 s before forming organic layer on the p-type Si substrate the wafer with the ohmic contact and then was cut into pieces to form the thin film layer of NPB on their front surfaces. Thermal evaporator was used to deposit NPB on the front surface of p-Si substrate in a vacuum of 4×10^{-5} Torr chamber. The metal contact was defined by using a shadow mask in the deposition the metal electrode. Al was chosen to be the Schottky contacts. The thickness of the Al is 1000 Å, and the Schottky contacts electrodes are circle with diameters of 200, 300 and 400 μm, respectively.

3. Results and discussion

3.1. Schottky diode characteristics

The effective barrier height ϕ_b and ideality factor n, were determined by using the thermionic emission current voltage expression [12]:

* Corresponding author. Tel.: +886 6 2727175x530.
E-mail addresses: wchuang@mail.ksu.edu.tw, huangwc.huang@gmail.com (W.-C. Huang).

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

where

$$I_s = AA^*T^2\exp[-q\phi_b/kT] \quad (2)$$

where R_s is the series resistance of the diode, V is the applied voltage, q is the electronic charge, k is the Boltzmann constant, T is the absolute temperature, A is the area of diode, A^* is the effective Richardson constant, ϕ_b is the effective Schottky barrier height at zero-bias, and n is the ideality factor. Theoretical A^* value of 32 A cm^{-2} K^{-2} is used for Si. The saturation current density, J_s, is obtained by extrapolating the linear region of the semilog forward I–V curves to the zero applied voltage and the ϕ_b values are calculated from Eq. (2). The values of ideality factor n are determined from the slope of the linear region of the forward bias semilog I–V characteristics through the relation: $n = q/kT[\partial V/\partial(\ln J)]$. The ideality factor, n depends on the current flow at the interface, is equal to 1 for an ideal diode.

Fig. 1 shows the current–voltage (I–V) characteristics of the Al/NPB/p-Si. As can be seen from the figure, the I–V characteristic of the Al/NPB/p-Si SBD exhibits a good rectifying behavior and when reverse bias is applied a leakage current appears. The saturation current density, J_s, of the diode is 3.28×10^{-5} A/cm^2. The effective Schottky barrier height which derived from the thermionic emission model is 0.65 eV. Its ideality factor is 1.33 and shows a straight line over four decade of the plot. For the reverse leakage current, the current density of the diode is 8.79×10^{-4} A/cm^2 at the reverse bias voltage of -4 V.

The C–V characteristics of the diode with measured at different frequency is shown in Fig. 2. The capacitance decreases with the applied bias, which reveals that a depletion region exists at the NPB and Si substrate, and the depletion region width increases with the reverse bias. For the forward biased capacitance, the capacitance of the diode is 38.5, 5.84 and 2.15 nF for the 100, 300 and 500 KHz, respectively. The value of the forward biased capacitance is increased as the operating frequency is decreased. The dependence of the capacitance of a Schottky contact upon frequency can also arise due to the presence of deep lying impurities in the depletion region of semiconductor. Presence of deep traps in the depletion region of the Schottky barrier makes the junction capacitance a complicated function of the bias voltage and the measuring frequency. Also, it is observed that the low-frequency capacitance increase with the applied bias while the high-frequency capacitance remains almost constant [13]. As the electrode

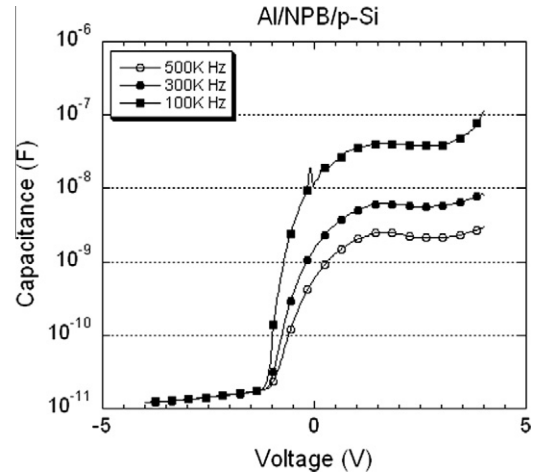

Fig. 2. The C–V characteristics of the Al/NPB/p-Si diode.

voltage is decreased, the p-Si substrate becomes depleted. And as the depletion width increased, the depletion capacitance of the diode is decreased. The capacitance is nearly constant at the reverse biases region. The depletion capacitance is in serial with the capacitance of the organic film. The total capacitance will reach its minimum values as the depletion width reaches its maximum width. The minimum capacitance in the reverse bias region is given as [14]: $C_{\min} = \frac{\varepsilon_i}{d + (\varepsilon_i/\varepsilon_s)W_m}$ where ε_i is the permittivity of the organic film, ε_s the permittivity of the semiconductor, d the thickness of the NPB film, and W_m the maximum width of the depletion region. The maximum width of the depletion layer is 1.409 μm which was calculated by the relationship of the capacitance.

The plots of A^2/C^2 vs. reverse bias voltage are linear which indicates the formation of Schottky junction [15]. Therefore, it follows a standard Mott–Schottky relationship: $\frac{1}{C^2} = \frac{2[V_{bi} - V - kT/q]}{q\varepsilon_o\varepsilon_s A^2 N_A}$ where C is the diode capacitance, V_{bi} is the built in voltage, ε_s is the semiconductor dielectric constant, ε_o is the permitivity in vacuum, V is the applied voltage, q is the charge, A is the diode active area, kT/q is the thermal voltage at 300 K and N_A is the charge carrier concentration. The value of V_p was obtained from the following relation: $V_p = kT\ln\left(\frac{N_v}{N_A}\right)$. The value of the ϕ_b can be obtained by the relation: $q\phi_b = V_{bi} + V_p$. The charge carrier concentration can be determined from the slope of A^2/C^2 vs. V plots. From the extrapolated intercept on voltage axis V_{bi} can be estimated. Fig. 3 shows the A^2/C^2–V plot

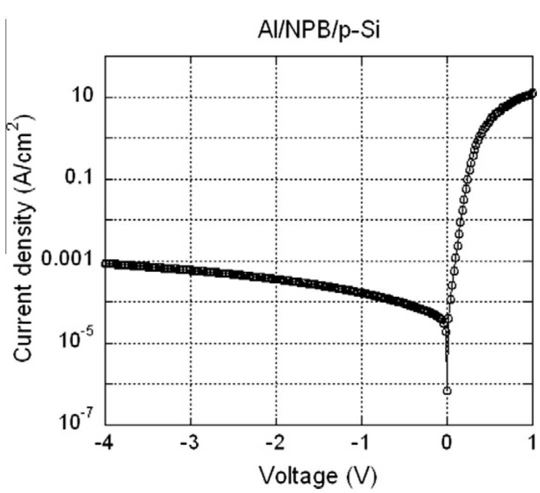

Fig. 1. The I–V characteristics of the Al/NPB/p-Si diode.

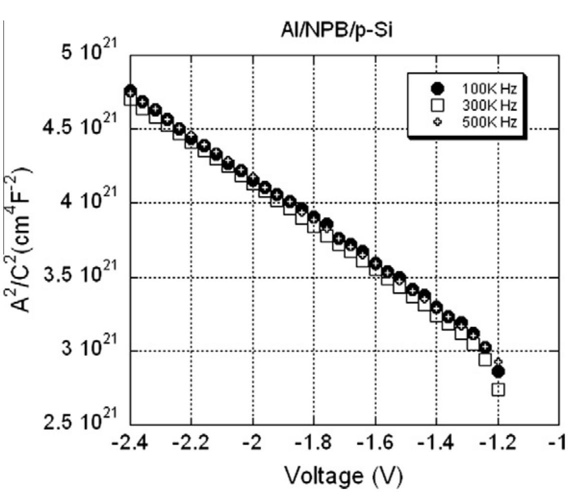

Fig. 3. The A^2/C^2–V plot of the Al/NPB/p-Si diodes.

of the diode that was measured at the frequency of 100–500 KHz. It shows the built in voltage is 0.99 V, the effective barrier height is 1.27 eV and the effective carrier concentration is 6.92×10^{14} cm^{-3} at 100 KHz. Built in voltage is 1.02 V, the effective barrier height is 1.29 eV and the effective carrier concentration is 6.98×10^{14} cm^{-3} at 300 KHz. Built in voltage is 1.05 V, the effective barrier height is 1.33 eV and the effective carrier concentration is 6.97×10^{14} cm^{-3} at 500 KHz measurement.

3.2. The I–V–T characteristics of the diode

The current–voltage–temperature (*I–V–T*) characteristics of the Al/NPB/p-Si diode is discussed and shown in Fig. 4. The temperature of measurement is performed from 213 to 353 K. The figure shows a decreasing of saturation current density, J_s, as the temperature is decreased. The value of the saturation density decreases from 5.41×10^{-5} to 5.45×10^{-7} A/cm^2 as the measured temperature decreases from 353 to 213 K. The reverse bias leakage current density is also decreased as the temperature is decreased.

The barrier height is 0.68 eV with ideality factor of 1.19 at the 353 K-measured diode. As the measured temperature decreases, the effective barrier decreases while the ideality factor increases. The effective barrier height decreases to 0.49 eV at the 213 K measurement environment, while the ideality factor increases to 1.71. These data are summarized and plotted in Fig. 5. For the current transports across the metal/organic/semiconductor interface is a temperature-activated process [16]. At low temperature, electrons can only surmount a lower barriers and therefore the transportation of current will be dominated by current flowing through the patches of lower Schottky barrier height and resulting a larger ideality factor. As the temperature is increased, more and more electrons gains sufficient energy to surmount a higher barrier. As a result, the dominant barrier height will increase with the temperature and applied voltage. For the temperature dependent ideality, according Sheats et al. [16], the ideality factor of an inhomogeneous Schottky barrier diode with a distribution of low Schottky barrier heights may increase with a decrease in temperature. The Schottky barrier consists of laterally inhomogeneous patches of different barrier heights. The high value of ideality factor as showed in the Al/NPB/p-Si diode indicated a deviation from the thermionic emission model of the carrier transport at the metal/semiconductor junction.

For a further discussion of the ideality, the increase of the ideality factor at decrease of the measured temperature is also known as T_0 effect [17]. Such a phenomenon may be due to the interface state density at the metal/semiconductor interface, image force lowering and tunnelling of the carrier through the barrier [9]. Fig. 6 shows the plot of n vs. $1000/T$ of the Al/NPB/p-Si diode obtained from I to V. The ideality factor n is found to be inversely proportional with temperature and it can be express as $n(T) = n_o + \frac{T_0}{T}$. The n_o and T_0 are constants which were found to be 0.399 and 280 K, respectively.

Schmitsdorf et al. [18,19] used Tung's theoretical approach and they found a linear correlation between the experimental zero-bias Schottky barrier heights and ideality factors. The plot of the effective barrier height vs. the ideality factor is shown in Fig. 7. The straight line in Fig. 7 is the least squares fitting to the experimental data. As can be seen from Fig. 7, there is a linear relationship between the experimental effective barrier heights and the ideality factors of the Schottky contact that was explained by lateral inhomogeneities of the barrier heights in the Schottky diodes. The extrapolation of the effective barrier heights vs. ideality factor plot to $n = 1$ has given a homogeneous barrier height of approximately 0.756 eV. Thus, it can be said that the significant decrease of the zero-bias barrier height and increase of the ideality factor especially at low temperature are possibly caused by the barrier inhomogeneities.

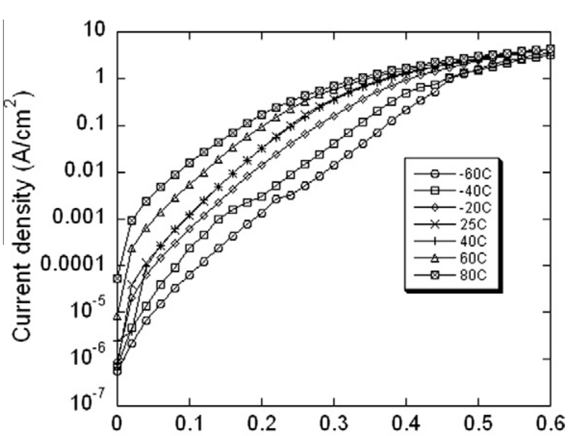

Fig. 4. The *I–V–T* characteristics of the Al/NPB/p-Si diodes.

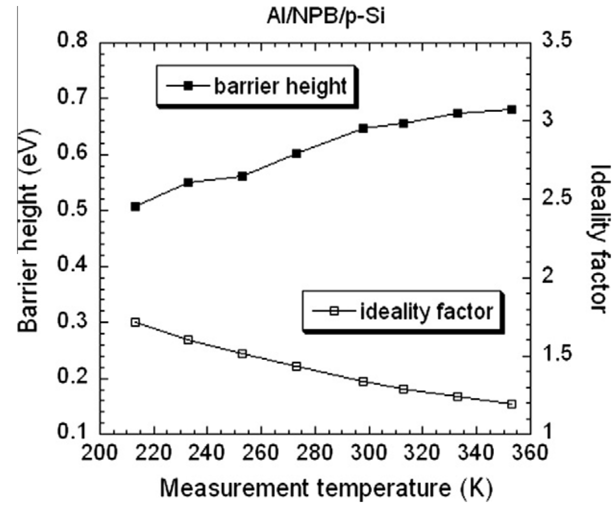

Fig. 5. Temperature dependent of the effective barrier height and ideality factor of the Al/NPB/p-Si diodes.

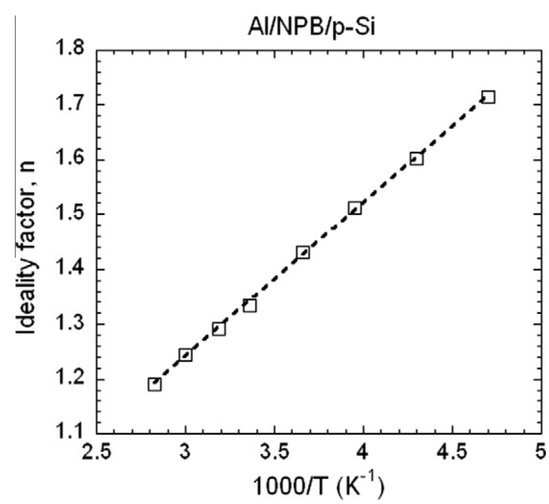

Fig. 6. Plot of n vs. $1000/T$ of the Al/NPB/p-Si diode obtained from I to V.

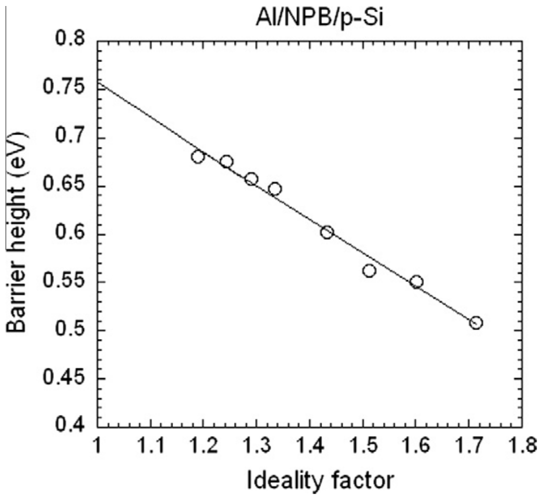

Fig. 7. The relationship between effective barrier height and ideality factor of the Al/NPB/p-Si diodes, at different measured temperature.

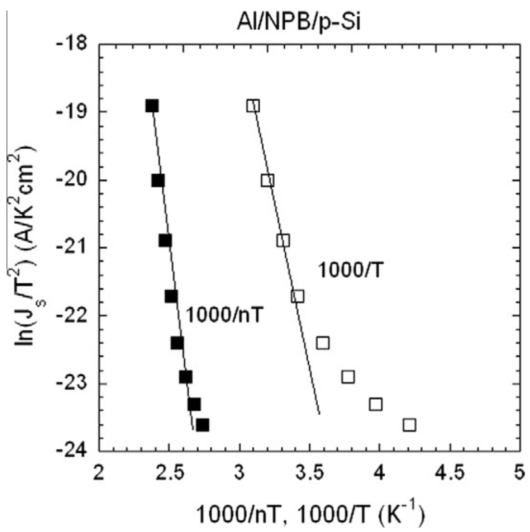

Fig. 8. The Richardson plots of $\ln(I_s/T^2)$ vs. $1000/nT$ or $1000/T$ of the Al/NPB/p-Si diodes.

Fig. 8 shows the Richardson plot of $\ln(I_s/T^2)$ against $1000/T$ or $1000/nT$. The dependence of $\ln(I_s/T^2)$ vs. $1000/T$ is found to be non-linear in the temperature measured; however, the dependence of $\ln(I_s/T^2)$ vs. $1000/nT$ gives a straight line. The non-linearity of the conventional $\ln(I_s/T^2)$ vs. $1000/T$ is due to the temperature dependence of the barrier height and ideality factor. Some author [17,20–22] had reported similar results. The data are shown to fit as a straight line at higher measured temperatures only. The Richardson constant of 1.47×10^{-2} A cm^{-2} K^{-2}, which is much lower than the known value of 32 A cm^{-2} K^{-2} for p-Si was obtained. The deviation in the Richardson plots mainly due to the spatially inhomogeneous barrier heights and potential fluctuations at the contact interface [17,20–22]. That is, for the passing through of the carrier to the metal/semiconductor junction, it preferentially through the lower barriers in the potential distribution. As was explained by Horvath [23], the Richardson constant value which obtained from the temperature dependence of the *I–V* characteristics is affected by the lateral inhomogeneity of the barrier, and it resulted in the difference from the theoretical value.

4. Conclusion

The diode characteristic of the temperature effects of the Al/NPB/p-Si Schottky diodes are discussed in the paper. The barrier height and ideality factor values of 0.65 eV and 1.33 are measured at the forward bias of the diode. The barrier height also obtains from the *C–V* measurement is 1.33 eV which is higher than that from *I–V* measurement. The effective Schottky barrier height and ideality factor determined from the *I–V* plots are found to be a strong function of temperature. Due to the present of the inhomogeneous barrier at the junction, the ideality increases from 1.19 to 1.71 and the barrier height increases from 0.68 to 0.49 eV as the measured temperature decreases from 353 to 213 K.

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