Schottky Diode Applications of the Fast Green FCF Organic Material and the Analyze of Solar Cell Characteristics

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Abstract. In this study, a device applications of organic material Fast Green FCF \((C_{37}H_{34}N_2O_{10}S_3Na_2)\) has been investigated. After chemical cleaning process of boron doped n-Si crystals, Al metal was coated on the one surface of crystals by thermal evaporation and fast green organic materials were coated on other surface of crystals with spin coating method (coating parameters; 800 rpm for 60 s). Finally, Ni metal was coated on Fast Green by sputtering and we obtained the Ni/Fast Green FCF/n-Si/Al Schottky type diode. And then we calculated the basic diode parameters of device with current-voltage \((I-V)\) and capacitance-voltage \((C-V)\) measurements at the room temperature. We calculated the ideality factory \((n)\), barrier height \((\Phi_b)\) of rectifying contact from \(I-V\) measurements using thermionic emission methods. Furthermore, we calculated ideality factory \((n)\), barrier height \((\Phi_b)\) and series resistance \((R_s)\) of device using Cheung and Norde functions too. The diffusion potential, barrier height, Fermi energy level and donor concentration have been determined from the linear \(1/C^2-V\) curves at reverse bias, at room temperature and various frequencies. Besides we measured the current-voltage \((I-V)\) at under light and analyzed the characteristics of the solar cell device.

1. Introduction

It is rapidly developing electronics industry and organic electronics has been started to make significant contribution to the commercial World of industry [1]. Organic materials are inexpensive and easy to prepare. Therefore, there is an increasing application of organic materials such as organic photovoltaic devices (OPV) and organic light emitting Diode (OLED) in electronics technology [1]. Nowadays, the developments in organic electronics have raised and therefore there is an increasing interest to the organic materials and their research.

Fast Green FCF is a progressive dye and it is soluble in either alcohol or water and it is used counterstain to safranin O. It can be used for tinned green peas, sauces, fish, vegetables, jellies, desserts. It may be used instead of light green SF yellowish in Masson's trichrome since it is less likely to fade and it has more brilliant color. Fast Green FCF is used for the preparation of a staining solution that can be used for modified connective tissue. Furthermore, at alkaline pH, it is used as a quantitative stain for histones after acid extraction of DNA. It is also used as a protein...
stain in electrophoresis. In addition, the absorbance of organic Fast Green FCF by the intestines is poor [2].

2. Experimental procedures

In this work, n-Si wafer with phosphorus doped, (100) orientation, 400 µm thickness and 1–10 Ω-cm resistivity was used and the n-Si wafer was chemically cleaned using the RCA cleaning procedure before fabrication device. The RCA cleaning procedure is: 10 min. boil in NH₃ + H₂O₂ + 6H₂O followed by a 10 min HCl + H₂O₂ + 6H₂O at 60 °C. We completed the three stages of the device fabrication. Firstly, the ohmic contact was made by thermal evaporating Al metal on the one surface (back) of the substrate and then was annealed at 450 °C for 10 min in N₂ atmosphere. Then, the native oxide on the front surface of the n-Si substrate was removed in HF + 10H₂O solution at before forming a Fast Green FCF layer on the Si substrate. Secondly, Fast Green FCF was dissolved in deionized water to make 0.5 mg/1 ml solution and an organic Fast Green FCF layer formed on other surface of n-Si by spin coating method with 800 rpm, 60 s in clean rooms (class 1000). Furthermore, Fast Green FCF was coated on cleaned glass for the optical absorption and transmittance measurements. Finally, Ni contact was coated by DC sputtering method on Fast Green FCF film at 10⁻³ torr pressure and hence, we obtained device shown in Fig. 1a and the chemical structure of Fast Green FCF is depicted in Fig. 1b. The I–V and C–V measurements of the device have been performed with KEITHLEY 487 Picoammeter/Voltage Source and HP 4192A (50 Hz to 13 MHz) LF IMPEDANCE ANALYZER, respectively. All electrical measurements have been performed at room temperature in dark and under illumination.

![Diagram](image)

**Fig. 1.** (a) Schematic diagram of Ni/Fast Green FCF/n-Si/Al Schottky diode and (b) the chemical structure of Fast Green FCF

3. Results and discussion

Fast Green FCF organic film was coated on n-Si and the electrical measurements were performed of Ni/Fast Green FCF/n-Si/Al Schottky diode. Furthermore, Fast Green FCF film coated on glass substrate for optical measurements. The optical transmittance and spectra absorption of Fast Green FCF organic film is shown in Fig. 2. Also, plotting (α)² versus hν is shown in this figure. The optical band gap of the Fast Green FCF film can be determined by linear region of plotting (α)² versus hν. The band gap of the Fast Green FCF film has been calculated as 1.79 eV using the optical measurements. The typical absorption peak is at λ_max = 693 nm obtained absorption spectra of the Fast Green FCF organic film.
Fig. 2. Absorption spectra and optical transmittance of Fast Green FCF organic film

3.1. The ideality factor \( n \) and barrier height \( \Phi_b \) parameters by the conventional (TE) method:

The current-voltage relation of Schottky barrier diodes (SBDs) can be expressed as:

\[
I = \left[ A A^* T^2 \exp\left(-\frac{e\Phi_b}{kT}\right) \right] \left[ \exp\left(\frac{eV}{n kT}\right) \right]
\]

\( I_0 \) is the saturation current and it is given by:

\[
I_0 = AA^* T^2 \exp\left(-\frac{e\Phi_b}{kT}\right)
\]

\[
I = I_0 \left[ \exp\left(\frac{eV}{n kT}\right) \right]
\]

\[
n = \frac{e}{kT} \frac{dV}{d(\ln I)}
\]
Where $A$ is effective diode area, $A^*$ is Richardson constant of semiconductor. Eq.(4) equals to “unity” for an ideal Schottky diode. However, $n$ has usually a value greater than unity for non-ideal diode. High values of $n$ can be attributed to the presence of the interfacial thin native oxide layer between junction materials and to a wide distribution of low-Schottky barrier height, to higher series resistance values at higher forward biases, to barrier inhomogeneities, and to the bias dependence of the Schottky barrier height (SBH) [3]. The barrier height of a Schottky diode $\Phi_b$ can be given as:

$$e\Phi_b = kT \ln\left( AA^* T^2 / I_0 \right)$$

(5)

The dark current–voltage ($I–V$) characteristics of Ni/Fast Green FCF/n-Si/Al Schottky barrier diode is shown in Fig.3. This plot gives significant information about the rectifying device such as the leakage current and the series resistance. It is clear from Fig. 3, that a linear relationship exists between $I$ and $V$ for small applied voltages. This linearity deviated at higher biases due to the higher series resistance value.

![Graph showing the dark current-voltage characteristics of Ni/Fast Green FCF/n-Si/Al Schottky barrier diode.](image)

**Fig. 3.** The log ($I–V$) characteristics of the Ni/Fast Green FCF/n-Si/Al Schottky barrier diode.

The dark current–voltage ($I–V$) characteristics of Ni/n-Si/Al and Ni/Fast Green FCF/n-Si/Al devices are shown in Fig.4. The ideality factor $n$ and barrier height $\Phi_b$ values of the Ni/Fast Green FCF/n-Si/Al Schottky barrier diode were determined as 1.11 and 0.69 eV, respectively using the $I–V$ characteristics from Eqs .4 and 5. The higher values than unity of the ideality factor can be attributed to the inhomogeneities of the Fast Green FCF film thickness, to non-uniformity of the
interface states and to the effect of the series resistance $R_s$ [4]. The ideality factor and the barrier height of Ni/Fast Green FCF/n-Si/Al device has been compared with the Ni/n-Si/Al reference diode. The ideality factor and barrier height of Ni/n-Si/Al were calculated as 1.18 and 0.58 eV. As seen that Fast Green FCF increased the barrier height and decreased the ideality factor. Namely, the organic film has improved the quality of device with respect to the Ni/n-Si/Al reference diode.

![Graph](image_url)

**Fig. 4.** The log ($I$–$V$) characteristics of reference the Ni/n-Si/Al the Ni/Fast Green FCF/n-Si/Al Schottky barrier diode.

Figure 5 shows the dark and under illumination the both linear and logarithmic current–voltage ($I$–$V$) characteristics of Ni/Fast Green FCF/n-Si/Al Schottky barrier diode, at room temperature. It is clearly seen that the device has a photosensitive behavior. At higher forward voltages of device, the dark and illuminated currents do not differ by appreciable amounts. But there are changes in the reverse bias voltages [5]. This result suggests that the photodiodes are a photosensitive and show a photodiode behavior [6].
Figure 6 shows the logarithmic plots of the $I-V$ characteristics obtained under forward bias of Ni/Fast Green FCF/n-Si/Al Schottky barrier diode. As seen in the forward bias characteristics three different regions can be identified. This indicates that three distinct current conduction mechanisms: Region I, these plot suggests ohmic conduction at low voltages. Namely, ohmic currents increase linearly with the voltage. The occurrence of space charge limited current (SCLC) requires that at least one contact has good injecting properties to provide an inexhaustible carrier source. In the region II, the slope was found to be 3.14. In the region III, the slope was found to be 1.14 indicating the trap filled SCLC process. The interface states between n-Si and Fast Green FCF are effective in electrophysical behavior of device.

**Fig. 5.** $I-V$ characteristics of the Ni/Fast Green FCF/n-Si/Al device in dark and under illumination
For Ni/Fast Green FCF/n-Si/Al Schottky barrier diode, at the lower forward bias, both current is increasing as linear with voltage. However, series resistance effect is observed at higher voltages. The series resistance values are calculated with Cheung functions as follows:

\[
I = A.J = \left[ A A' T^2 \exp\left( -\frac{e\Phi_b}{kT} \right) \right] \left[ \exp\left( \frac{eV}{nkT} \right) - 1 \right] \text{ if } V = (V) - IR_s \tag{6}
\]

\[
I = A.J = \left[ A A' T^2 \exp\left( -\frac{e\Phi_b}{kT} \right) \right] \left[ \exp\left( \frac{e(V - IR_s)}{nkT} \right) - 1 \right] \tag{7}
\]

\[
V = \left( \frac{nkT}{e} \right) \ln\left( \frac{I}{AA'T^2} \right) + n\Phi_b + IR_s \tag{8}
\]
\[ \frac{dV}{d(\ln I)} = \frac{n k T}{e} + I R_s \quad (9) \]
\[ H(I) = V - \left( \frac{n k T}{e} \right) \ln \left( \frac{I}{AA^* T^2} \right) \quad (10) \]
\[ H(I) = n \Phi_b + I R_s \quad (11) \]

Figure 7 shows the \( dV/d(\ln I) \) versus \( I \) and \( H(I) \) versus \( I \) obtained from forward bias. The values of \( n \) and \( R_s \) have been calculated as \( n = 2.47 \) and \( R_s = 0.76 \, \text{k}\Omega \) using Eq. 9, respectively. Similarly, the values of \( \Phi_b \) and \( R_s \) have been found as \( \Phi_b = 0.51 \, \text{eV} \) and \( R_s = 0.75 \, \text{k}\Omega \), respectively with help of \( H(I) = n \Phi_b + I R_s \). As seen, there is a significant difference for the ideality factor values obtained from the forward-bias \( \ln I - V \) and from the \( dV/d(\ln I) - I \) plots. This can be explained by the existence of a high series resistance \( R_s \) and the interface states and to the voltage drop across the interfacial layer of the device \[3\].

**3.3. The barrier height (\( \Phi_b \)) and series resistance (\( R_s \)) parameters by the Norde methods:**

Norde’s method is an alternative method for calculation the barrier height (\( \Phi_b \)) and series resistance (\( R_s \)) parameters of Schottky barrier diodes. Eq. (12) is defined in the modified Norde’s method.

\[ F(V) = \frac{V}{\gamma} - \left( \frac{kT}{2} \right) \ln \left( \frac{I(V)}{AA^* T^2} \right) \quad (12) \]
\[ \phi_b = F(V_0) + \frac{V_0}{\gamma} - \frac{kT}{q} \]  
\[ R_s = \frac{kT(\gamma - n)}{qI_o} \]

(13)
(14)

where \( \gamma \) is an arbitrary integer (dimensionless) greater than ideality factor. \( I(V) \) is current which obtained from the \( I-V \) curve. In determining the junction parameters, firstly, the \( F \) against \( V \) curve should be plotted, and then the value of barrier height can be obtained from it. where \( F(V_0) \) is the minimum point of \( F(V) \), and \( V_0 \) is the corresponding voltage [7].

Figure 8 shows a plot of \( F(V) \) versus \( V \) for the device. From the plot, the some parameters of the structure have been obtained as \( \Phi_b = 0.79 \) eV, \( R_s = 0.41 \) k\( \Omega \) using \( F(V_0)=0.75 \) V, \( V_0 = 0.16 \) V values.

![Fig. 8. The F(V) versus V plot of the Ni/ Fast Green FCF/n-Si/Al Schottky barrier diode](image)

Idenity factor and barrier height value can be controlled by the interfacial energy states. In an n-type semiconductor, 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 with Eq. 15 [3]. For our device, the energy of the interface states \( E_{ss} \) with respect to the bottom of the conduction band \( E_c \) at the surface of the Si is shown in Fig.9. It is seen that the interface state density \( N_{ss} \) has an exponential decreasing toward higher \( E_{ss} - E_c \) values for Ni/ Fast Green FCF/n-Si/Al Schottky barrier diode. The interface state density \( N_{ss} \) obtained from the forward bias \( I-V \) ranges from \( 1 \times 10^{15} \) cm\(^{-2} \) eV\(^{-1} \) to \( 6 \times 10^{15} \) cm\(^{-2} \) eV\(^{-1} \). 

\[ E_{ss} - E_c = q\Phi_c - qV \]  

(15)
Fig. 9. $N_s$ versus $E_{ss}-E_c$ plots of the Ni/ Fast Green FCF/n-Si/Schottky barrier diode

3.4. Calculated of the device parameters with the capacitance-voltage (C-V) measurements:

Capacitance–voltage (C–V) measurement is another common electrical measurement technique for calculate the parameters of the Schottky barrier diode. We can use the following equations for calculate the basic diode parameters as the diffusion potential $V_d$, barrier height, Fermi energy level $E_f$ and donor concentration $N_d$:

$$C = A \left( \frac{\varepsilon \varepsilon_0 e N_d}{2} \right)^{1/2} \left( V_d - \frac{kT}{e} \right)^{1/2}$$  \hspace{1cm} (16)

$$C^{-2} = \frac{2(V_d + V)}{\varepsilon \varepsilon_0 e A^2 N_d}$$  \hspace{1cm} (17)

$$\frac{d(C^{-2})}{dV} = \frac{2}{\varepsilon \varepsilon_0 e A^2 N_d}$$  \hspace{1cm} (18)

$$n_0 = N_c \exp \left( \frac{E_f - E_c}{kT} \right) \quad n_o \approx N_d \text{ for } N_d \gg n_c \text{ and } N_c \approx 2.8 \times 10^{19} \text{ cm}^{-3}$$  \hspace{1cm} (19)

$$N_d = N_c \exp \left( \frac{E_f - E_c}{kT} \right)$$  \hspace{1cm} (20)
\[ E_f = kT \ln \left( \frac{N_d}{N_c} \right) \]  
(21)

\[ \Phi_b = \frac{V_d}{n} + E_f \]  
(22)

Fig. 10 show the forward and the reverse bias $C-V$ characteristics of the Ni/ Fast Green FCF/n-Si/Al device at 100, 200 and 500 kHz frequencies. It is clearly seen in Fig.10 the capacitance increased with voltage. Basic diode parameters can calculate from the reverse bias $1/C^2-V$ characteristics. Fig. 11 show the reverse bias $1/C^2-V$ characteristics of the Ni/ Fast Green FCF/n-Si/Al structure at various frequencies. In the $1/C^2-V$ plots the dashed lines shows the linear fits.

**Fig. 10.** (a)The forward and reverse bias $C-V$ characteristics, (b) the reverse bias $C-V$ characteristics of the Ni/Fast Green FCF/n-Si/Al device at various frequencies.
The reverse bias $1/C^2-V$ characteristics of the Ni/ Fast Green FCF/n-Si/Al structure at various frequencies.

The junction parameters of Ni/ Fast Green FCF/n-Si/Al Schottky barrier diode obtained from the reverse bias $1/C^2-V$ characteristics are given in Table 1. As seen, there is no significant variations with frequency.

**Table 1:** The junction parameters of Ni/ Fast Green FCF/n-Si/Al Schottky barrier diode obtained from the reverse bias $1/C^2-V$ characteristics

| Frequencies (kHz) | $V_d$ (V) | $N_d$ (cm$^{-3}$)$\times 10^{15}$ | $E_t$ (eV) | $\Phi$ (eV) |
|-------------------|-----------|----------------------------------|-----------|------------|
| 100               | 0.46      | 5.5                              | 0.22      | 0.63       |
| 200               | 0.46      | 5.3                              | 0.22      | 0.63       |
| 500               | 0.47      | 5.1                              | 0.22      | 0.65       |

**4- Conclusions**

In summary, a Ni/Fast Green FCF/n-Si/Al device was successfully fabricated and it was investigated the electronic properties of the device using the current–voltage ($I-V$) and capacitance–voltage ($C-V$) characteristics at room temperature. It has been shown that thin films of the Fast Green FCF between Ni and n-Si may be employed to increase the barrier heights of the Ni/n-Si Schottky contacts. At The forward bias $\log (I-V)$ characteristics, three separate regions; as ohmic (region-I), space charge limited currents (SCLC) (region-II) and trap filled SCLC(region-III) has been observed for Ni/Fast Green FCF n-Si/Al Schottky barrier diode . These characteristics show ohmic conductivity at low voltages, space charge limited currents and trap filled SCLC at higher voltages. The difference in apparent barrier height as obtained from the capacitance–voltage and current–voltage measurements on Ni/ Fast Green FCF Schottky barrier has been attributed to
I–V and C–V techniques to have a different nature. Similarly, the difference in apparent barrier height from the thermionic emission method and Cheung, Norde methods has been attributed to the difference of the methods and non-ideal behavior of the Ni/Fast Green FCF/n-Si/Al device. The response of the device with a Fast Green FCF interlayer investigated and it has been thought that Fast Green FCF may be a novel material for solar cell applications in the future.

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