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Improve the efficacy of Al/CuPc/n-Si/Al Schottky diode based on strong light absorption and high photocarriers response

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Abstract

Copper phthalocyanine has been prepared by simple chemical approach and its structural and optical properties were investigated. X-ray diffraction pattern exhibits a notable peak at $2\theta = 6.75^\circ$ assigned to the $\alpha -$ phase of CuPc. SEM images show the particles distributed in nanospheres with average size at about 50 nm. The linear optical constants like optical band gap ($E_g$) and dielectric constants ($\varepsilon'$, $\varepsilon''$) were estimated from transmittance and reflectance spectra in the wavelength range from 250 to 900 nm. The energy gap was founded to be 1.62 and 2.90 eV dependent on the incident photon energy. Al/CuPc/n-Si/Al Schottky diode has been fabricated using thermal evaporation technique. The electronic parameters such as the ideality factor ($n$), series resistance ($R_s$), and barrier height ($\phi_b$) were evaluated in dark by applying the $(I-V)$, Cheung-Chung, and Norde models. At various illumination intensities, the photocurrent sensitivity was studied based on the response of trapped charge carriers. At 1 Mhz, the built-in voltage ($V_{bi}$) and donor concentration ($N_d$) were calculated from $(C-V)$ measurements. The findings revealed that CuPc/n-type Si can be used as photodiode in optoelectronic applications.

1. Introduction

Recently, the researchers work to improve the performance of organic based electronic devices by producing new organic materials and analyze the change of electronic configuration at the interface by charge transfer mechanism [1]. Phthalocyanines (Pcs) are synthetic analogs of natural porphyrin, aromatic planar and highly conjugated molecules that have been classified as one of the most stabilized organic materials [2]. The photophysical properties of phthalocyanine can be easily adjusted according to the requirements of the desired applications by incorporating adequate substituent either at axial or peripheral positions of Pc ring or changing the metal atom in the center of cavity [3]. Indeed, phthalocyanines can be incorporated by more than 70 metal and each metal imparts different chemical and physical characteristics to aromatic compounds [3, 4]. Further, metal phthalocyanines (MPcs) have attracted great importance in nanotechnology field based on its unique properties like simple preparation, high flexibility, less weight, higher current density, and a broad light absorption with very high molecular coefficient [5, 6]. For example, copper phthalocyanine (CuPc) was used as a buffer-zone layer in production of OLEDs and photovoltaic devices [6, 7]. Besides, platinum phthalocyanine (PtPc) has been utilized to manufacture different types of optical switching devices [7–9]. In the previous study, Kerp and Van Faassen (2000) thoroughly discussed the influence of oxygen on organic solar power systems composed of zinc phthalocyanine (ZnPc) [9]. Recently, Lessard et al (2019) have worked on P and N type copper phthalocyanines as an effective semiconductor layer in organic thin film transistor–based DNA biosensors [10]. Generally, the practical applications of Pc derivatives are limited by fair solubility in common organic solvents and unfavorable dye aggregation because of the strong $\pi-\pi$ interaction between the macrocycle core which arises from the planar structures of Pc ring [10, 11]. Because of Schottky barrier diodes are the basis of most semiconductor electronics such as field-effect transistors and photodetectors. Thus, it is important to improve
their efficiency using novel organic nanomaterials with superior optical and electrical properties [12, 13]. In the present work, the structural, morphological, and optical properties of CuPc thin films have been characterized and the Schottky diode parameters of Al/CuPc/n-Si/Al were determined by applying different models.

2. Experimental details

2.1. Synthesis of copper phthalocyanine
Copper phthalocyanine has been prepared according to a literature procedure based on cyclotetramerization of corresponding phthalonitrile C6H4(CN)2 in the presence of copper (II) acetate Cu(OAc)2 in dimethylaminoethanol (CH3)2NCH2CH2OH. Tetrasubstituted Pcs obtained using the statistical method starting from corresponding phthalonitriles substituted in position 4 are constituted by a maximum of eight regioisomers in a ratio that strongly depends on the stoichiometry of the reactants. CuPc compound is indeed mixture of eight regioisomers that could not be separated by chromatography led to desired Pcs in 41% and 32% yield, respectively [14]. The preparation route of CuPc was described from the schematic diagram illustrated in figure 1 [15].

2.2. Fabrication of Al/CuPc/n-Si/Al Schottky barrier diode
The CuPc solution was deposited on the surface of n-type silicon using a spin coater. Before coating procedure, the silicon wafers have been etched by HF then rinsed in deionized water using an ultrasonic bath for 15 min and finally cleaned with methanol and acetone baths, respectively. Al metal top contact was evaporated giving a diode contact area equal 3.14 × 10⁻² cm² by using thermal evaporation technique [16]. The schematic diagram of fabrication Al/CuPc/n-Si/Al Schottky diode was provided in figure 2 [16, 17].

2.3. CuPc thin film and Schottky diode characterization
The microstructure of copper phthalocyanine was examined using (XRD Model; Rigaku Smart Lab.) and the surface morphological properties were investigated by (SEM; Helios Nanolab. 400). Spectrophotometer JASCO (V-570) has been utilized for optical analysis. Al/CuPc/n-Si/Al Schottky diode was analyzed using a programmable (Keithley 6517b) electronic device. Besides, the photocurrent response has been studied using
solar simulator IV characterization and the light intensity was measured by solar power meter (TM-206) \([17]\). In the frequency range of 100 hz – 1 Mhz, a computerized HIOKI 3531-Hi-tester LCR meter has been employed for capacitance-voltage \(C-V\) and series resistance-voltage \(R_s-V\) measurements.

3. Results and discussion

3.1. Microstructure and morphological analysis of CuPc thin film

X-ray diffraction (XRD) pattern of CuPc thin film deposited on n-type Si and annealed at 150 °C is shown in figure 3(a). The thin film exhibits a pronounced peak at \(2\theta = 6.75^\circ\) correspond to 200 reflection of \(\alpha\)–phase \([18]\). The narrow full width at half maximum (FWHM) of the diffraction peak supports the big crystal size of copper phthalocyanine owing to the annealing temperature \([19]\). The crystalline diameter \((D)\) of the prepared sample has been determined from the sharp intensity peak using Scherrer equation \([19]\):

\[
D = \frac{K\lambda}{\beta \cos \theta}
\]

Figure 3. (a) XRD and (b), (c) SEM images of CuPc thin films deposited on n-type silicon.
\[ \delta = \frac{1}{D^2} \]  
\[ \varepsilon = \frac{\beta \cos \theta}{4} \]  

The \( \delta \) and \( \varepsilon \) of CuPc were calculated as \( 8 \times 10^{-4} \text{ nm}^{-2} \) and \( 1.04 \times 10^{-3} \) respectively, indicating the high quality of the prepared thin film [20]. The surface morphology of CuPc nanomaterial was investigated from SEM described in figures 3(b), (c). The different magnification images show the particles are grown in spherical granules uniformly distributed on the surface of n-type silicon with average size ranging from 45–55 nm [21]. As observed, the CuPc surface composed of little nanopores which are very useful for absorption of light energy [22].

3.2. Optical properties of CuPc thin films

Figures 4(a), (b) displays the transmittance and reflectance spectra of the deposited CuPc thin film through the wavelength range from 250–900 nm. It was observed from figure 4(a) that, the transmittance spectrum has two fundamental absorption edges at 450 and 750 nm correspond to the electron transition [23, 24]. Furthermore, figure 4(b) shows the reflectance spectrum with a wide peak at spectral value 520 nm. The reflectance peaks detected beyond ultraviolet and inside the visible region are associated with the interference of light whereas the valleys attributed to the structure disturbance occurred inside the CuPc material during the photon-electron

![Figure 4](image-url)
interaction that enables more electrons jump to the higher energy levels [25, 26]. The absorption coefficient ($\alpha$) was defined from the relation [23, 25]:

$$\alpha = \frac{1}{d} \ln \left[ \frac{(1 - R^2)}{2T} + \sqrt{\frac{(1 - R)}{4T^2} + R^2} \right]$$

(4)

Figure 5(a) presents two absorption bands, Q band lies in the visible region assigned to $\pi-\pi^*$ electron transition from the valence band to conduction band of phthalocyanine and Soret band (B band) appears near the UV spectrum related to free electron oscillation inside the copper atoms [27, 28]. The optical band gap ($E_g$) of the thin film was described from Tauc’s formula as [23–25]:

$$\alpha = \frac{A}{h\nu}(h\nu - E_g)^n$$

(5)

where, $A$ is independent constant, $h\nu$ the photon energy, $n$ the number describes the transition process; $n = 1/2$ for direct allowed transition, and $E_g$ the energy gap given by extrapolating the linear part of $(\alpha h\nu)^2$ on $h\nu$ axis as illustrated in figure 5(b). The direct energy gap of CuPc was estimated to be 1.62 and 2.90 eV. For further information about the optical behavior of copper phthalocyanine, the refractive index ($n$) and extinction coefficient ($k$) were introduced using the equations [23, 24]:

$$n = \left( \frac{1 + R}{1 - R} \right) + \sqrt{\frac{4R}{(1 - R)^2 - k^2}}$$

(6)

$$k = \frac{\alpha \lambda}{4\pi}$$

(7)

Figure 5. (a) $\alpha$ versus $h\nu$ and (b) $(\alpha h\nu)^2$ versus $h\nu$ plots of CuPc films.
Figure 6 (a) Refractive index (n) and (b) Extinction coefficient (k) of CuPc films as a function of hν.

Figure 6 (a) describes the refractive index with multi oscillation peaks (anomalous dispersion) arise from the scattering of light. Figure 6 (b) depicts sharp extinction coefficient peak at the UV spectrum related to the absorption of light [26–28]. The optical dielectric properties demonstrate the capability of material atoms to interact with applied electric field have been investigated by the following relations [23, 24]:

$$\varepsilon' = n^2 - k^2 \text{ and } \varepsilon'' = 2nk$$  \hspace{1cm} (8)

Figures 7 (a), (b) shows real $\varepsilon'$ and imaginary $\varepsilon''$ parts of dielectric constant depend on the applied photon energy. The real part exhibits weak and strong peaks in the UV-visible wavelength range attributed to a broad absorption of CuPc and strong electron-photon interaction [29, 30]. Besides, the imaginary part revealed two sharp peaks near the interband transition associated with the dissipative energy of dielectric medium [31].

3.3. Electrical characterization of CuPc/n-Si Schottky diode in dark
The electronic properties of Al/CuPc/n-Si/Al Schottky barrier diode have been discussed from the current − voltage (I−V) in dark and at room temperature illustrated in figure 8. The diode has a good rectification ratio (RR) ~ $1.77 \times 10^3$ at ±3 V. According to I−V characteristics, the charge carrier transfer through Schottky diode could be explained by thermionic emission model that relates the current to applied voltage by the following equation [32, 33]:

$$I = I_s e^{\left(\frac{q(V - IR)}{nkT}\right)}$$  \hspace{1cm} (9)
where, $V$ the applied voltage, $q = 1.6 \times 10^{-19}$ C the electronic charge, $n$ the ideality factor, $k = 1.38 \times 10^{-23}$ J K$^{-1}$ the Boltzmann constant, $T$ the absolute temperature, $R_s$ the series resistance and $I_s$ the reverse saturation current was defined by the formula [32, 34]:

$$I_s = A A^* T^* e^{\frac{-q \phi_b}{kT}}$$

(10)

where, $A$ the effective diode area, $\phi_b$ the barrier height at zero bias, and $A^*$ the effective Richardson’s constant equal 112 A cm$^{-2}$ K$^{-2}$ for n-type silicon which significantly effects on the flowing electrons from semiconductor to metal. The saturation current of Al/CuPc/n-Si/Al diode was calculated equal $3 \times 10^{-9}$ A, suggesting the small leakage current. In the forward bias region, the ideality factor was determined from the slope of In $I$–$V$ using the relation [35]:

$$n = \frac{q}{kT} \frac{dV}{d \ln(I)}$$

(11)

The ideality factor of the synthesized diode was calculated greater than unity. There are many factors affect the ideality factor make it greater than unity includes inhomogeneities at the interface, diode defect and series resistance [36, 37]. The Schottky diode efficiency strongly depends on the series resistance was estimated using the junction resistance equation [37]:

*Figure 7. (a) Real ($\epsilon'$) and (b) Imaginary ($\epsilon''$) part of dielectric constant as a function of $h\nu$.\*
As illustrated in figure 9, the $R_s$ was determined from the forward bias and the shunt resistance $R_{sh}$ was obtained from the reverse bias [38, 39]. The $R_s$ and $R_{sh}$ were evaluated as 2460 $\Omega$ and 3 M$\Omega$ respectively, exhibiting the high Schottky diode performance. To confirm the electronic parameters of the fabricated device, Cheung-Cheung method was applied in the forward bias region using the equations [37, 39]:

\[
\frac{dV}{d\ln I} = \frac{nkT}{q} + IR_s
\]

\[
H(I) = V - \left(\frac{nkT}{q}\right) \ln\left(\frac{I}{AA^*T^2}\right) = n\phi_b + IR_s
\]  

Figure 10(a) shows $\frac{dV}{d\ln I}$ versus I, the slope gives $R_s$ and the intercept on the current axis presents $n$. The second Cheung method was described in figure 10(b), the slope of $H(I)-I$ provides the second $R_s$ and the $y$-axis intercept equal $n\phi_b$ offers $\phi_b$ using the value of $n$ obtained from $\frac{dV}{d\ln I} - I$ plot. It is worthy to note that the low
The values of barrier height 0.52 and 0.59 eV enable much more free charges to overcome the Schottky barrier [40]. Moreover, Norde function is an alternate method used for the definition of $R_s$ and $\phi_b$ as [37–40]:

$$F(V) = \frac{V}{\gamma} - \frac{kT}{q} \ln \left( \frac{I(V)}{AA^*T^2} \right)$$  \hspace{1cm} (15)$$

$$\phi_b = E_b(V) + \frac{V}{\gamma} - \frac{kT}{q}$$  \hspace{1cm} (16)$$

$$R_s = \frac{kT(\gamma - n)}{qI_{min}(V_b)}$$  \hspace{1cm} (17)$$

where, $\gamma$ the first integer greater than the ideality factor, $I_{min}$ the current defined from $I$–$V$ curve, $V_c$ the corresponding voltage, and $E_b(V)$ the minimum point determined from $F(V)$–$V$ plot illustrated in figure 11. The calculated electrical parameters are summarized in table 1. The presented data revealed that Cheung method is closely matched with $I$–$V$ characteristic. On the other side, the deviation of the electronic parameters values obtained from Norde method related to the difference in voltage bias. In addition to, the non-ideal behavior that makes Norde function not suitable for Schottky diode analysis [37, 41].

3.4. The photocurrent sensitivity of synthesized diode

The study of photoconductivity is a key element for most of optoelectronic devices. When the diode subjects to light, the trapped charge carriers absorb the photon energy and become free to conduct the current [41]. As
Shown in figure 12, the reverse current of Al/CuPc/n-Si/Al photodiode was increased from 1.14 \( \mu \)A in dark to approximately 0.1 mA under 100 mW cm\(^{-2}\). Furthermore, the transient current was examined by illuminating the diode to 100 mW cm\(^{-2}\). From \((I-t)\) plot described in figure 13, after switching light on, the current rapidly increased then takes a flat shape. After turning light off, the charges trapped in the deep levels and the current suddenly decreased to its initial state \[42\]. It was observed that, the time it takes for free charges to reach the surface is very short which means there is no charge generation-recombination equilibrium \[43\]. Also, the upper part of the current takes a flat shape without reaching a stable level which supports the generation of free charge carriers that has great importance in manufacturing solar power systems and light emitting diodes \[44, 45\]. The sensitivity of the photodiode to light intensity was determined by the following equation \[43, 46\]:

\[
I_{ph} = AP^m
\]

where \(I_{ph}\) the photocurrent, \(A\) constant, \(P\) the light power and \(m\) an exponent was calculated from the slope of \ln \(I_{ph}\) against \ln \(P\) presented in figure 14. The exponent \(m\) was found to be 1.12 indicating that the interface states are responsible for enhancement the electrical properties of the diode \[46, 47\]. The findings revealed that Al/CuPc/
Table 1. The Schottky diode parameters estimated in dark from the \((I-V)\), Cheung-Cheung, and Norde models.

| Schottky diode         | \(n\) | \(I_o\) (nA) | \(\phi_s\) (eV) | \(R_s\) (\(\Omega\)) | \(R_{sh}\) (M\(\Omega\)) |
|------------------------|------|-----------|--------------|-------------|------------------|
| Al/CuPc/n – Si/Al      | 3.91 | 2.80      | 0.59         | 2460        | 3.00             |

Cheung-Cheung model

| \(dV/d[ln I] - 1\) | \(R_s\) (\(\Omega\)) | \(n\) | \(H(I) - 1\) | \(R_s\) (\(\Omega\)) | \(\phi_h\) (eV) | Nord’s model |
|---------------------|---------------------|------|-------------|---------------------|----------------|--------------|
| 2400                | 3.80                | 2365 | 0.52        | 4463                | 0.98           |              |
n-Si/Al of high efficiency compared with Tamara et al [32] who reported $R_s = 0.5 \ \text{M} \Omega$ and $n = 10$ of CuPc/Au Schottky diode.

3.5. Capacitance/conductance-voltage (C/G–V) and series resistance-voltage (Rs–V) analysis

The capacitance-voltage (C–V) characteristics as a function of various frequencies have been investigated. Figure 15(a), shows a high flat capacitance peak slightly decreases with increasing frequency [48]. The flatness may be due to the presence of copper ions inside the central cavity of phthalocyanine, the thickness of interfacial layer or series resistance [49]. Besides, the capacitance dependent on the series resistance was corrected using the equation [49, 50]:

$$C_{adj} = \frac{G_m^2 + (\omega C_m)^2}{a^2 + (\omega C_m)^2} C_m$$  \hspace{1cm} (19)
\( \omega = 2\pi f \) the angular frequency, \( C_m \) the measured capacitance and \( G_m \) the measured conductance. Figure 15(b) depicts the corrected capacitance peak sharply decreases with frequency based on the presence of the interface states that follows the alternating current (ac) signals at lower frequencies whereas do not contribute to the capacitance at higher frequencies \[50, 51\]. Moreover, the influence of applied voltage and frequency on the photodiode conductance has been measured and the impact of series resistance was corrected using the following relation \[50, 51\]:

\[
G_{\text{adj}} = \frac{G_m^2 + (\omega C_m)^2}{a^2 + (\omega C_m)^2}
\]  

(20)

As demonstrated in figures 16(a), (b), the conductance \( G \) and the corrected conductance \( G_{\text{adj}} \) have been increased with applied frequencies based on the increase of free charges transfer to the metal electrode \[51, 52\]. On the other hand, the series resistance behavior as a function of frequency has been described using the relation \[52, 53\]:

\[
R_s = \frac{G_m}{G_m^2 (\omega C_m)^2}
\]  

(21)

From \( R_s - V \) plot illustrated in figure 17, the series resistance decreased with increasing frequency based on the response of interface states to the variation of ac signals \[50, 51\]. The built-in voltage \( V_b \) and donor concentration \( N_d \) were estimated using the capacitance equation \[52, 53\]:

Figure 15. (a) \( C-V \) and (b) \( C_{\text{adj}}-V \) characteristics of Al/CaPc/n-Si/Al diode at various frequencies.
Figure 16. (a) $G$–$V$ and (b) $G_{adj}$–$V$ characteristics of Al/CuPc/n-Si/Al diode at various frequencies.

Figure 17. $R_s$–$V$ characteristics of synthesized diode as a function of different frequencies.
where, \( \varepsilon_s \) the static dielectric constant, \( C \) the space charge capacitance, and \( \varepsilon_0 = 8.85 \times 10^{-14} \text{ F.cm}^{-1} \) the vacuum permittivity. At 1 MHz, \( V_{bi} \) was evaluated by extrapolation the linear part of \( \frac{1}{C^2} \) versus \( V \) to \( V \)-axis and the \( N_d \) was given from the slope illustrated in figure 18. Furthermore, the barrier height \( \phi_b \) of the photodiode was calculated using the relation \[ \phi_b = V_{bi} + \frac{kT}{q} \left( 1 + \ln \frac{N_c}{N_d} \right) \] where, \( N_c = 2.8 \times 10^{19} \text{ cm}^{-3} \) the density of states in the conduction band. The Schottky diode parameters \( V_{bi}, N_d \) and \( \phi_b \) obtained from the \((C-V)\) measurements are presented in table 2. The barrier height of Al/CuPc/ n-Si/Al diode recorded 1.02 eV which is low compared with Chel-Jong Choi et al who obtained the barrier height equal 1.13 eV of Al/n-type Si Schottky diode composed of CuPc (80%) to Au (20%) interlayer \[55\]. In addition, the \( \phi_b \) obtained from \((C-V)\) characteristics higher than the \( \phi_b \) calculated from \((I-V)\) plot. The increase in the barrier height arise from the insensitive of capacitance to the potential fluctuations while depends on the mean value of the barrier height distribution that affect the current flow \[56, 57\].

4. Conclusions

The structural and morphological properties of the prepared CuPc nanomaterial have been studied from XRD pattern and SEM images showing that CuPc of \( \alpha \)-phase in nanoscale, uniformly distributed on the n-type Si surface. The optical constants such as the energy gap, refractive index, and dielectric constants were estimated from transmittance and reflectance spectra in the ultraviolet-visible region dependent on the strong absorption of the thin film to photon energy. In dark, Al/CuPc/ n-Si/Al Schottky diode has been characterized from \((I-V)\) plot indicating the high rectification ratio. Under various illumination intensities, the photocurrent sensitivity was examined based on the presence of trapped charge carriers in the deep levels. In the frequency range from

![Figure 18.1/C^2-V plot of Al/CuPc/n-Si/Al photodiode.](image-url)
100 kHz — 1 MHz, the capacitance, conductance, and series resistance of the fabricated Schottky diode were investigated affected by the response of the interface states to ac signals.

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References

[1] Petraki F, Peisert H, Uhllein J, Aygul U and Chassé T 2014 CoPc and CoPcF16 on gold: site-specific charge-transfer processes Beilstein J. Nanotechnol. 5 524–31
[2] Aboo M A, Abdulameer A F, Ai-essa I M and Mustafa F I 2016 Optical investigations of bulk heterojunction blend (NiPcTs/PEDOT: PSS) thin film AASCIT Journal of Materials 6–11
[3] Claessens C G, Hahn U and Torres T 2008 Phthalocyanines: from outstanding electronic properties to emerging applications Chem. Rev. B 75–97
[4] Sahih S, Altun S, Altindal A and Odabas Z 2013 Synthesis of novel azo-bridged phthalocyanines and their toluene vapour sensing properties Sensors Actuators, B Chem. 206 601–8
[5] Martinez-Diaz M V, de la Torre G and Torres T 2010 Lighting porphyrins and phthalocyanines for molecular photovoltaics Chem. Commun. 46 7090–108
[6] Bottari G, de la Torre G, Guld D M and Torres T 2011 Materials for chemical sensing Chem. Rev. 110 6768–816
[7] Aziz-Argahi M E and Rizaiy S 2013 Synthesis, morphology and optical properties of nanocomposite thin films based on polypropylene-bromo-aluminium phthalocyanine J. Mater. Sci., Mater. Electron. 24 4488–93
[8] Urbani M, Gratzel M, Nazareuddin M K and Torres T 2014 Chromic phenomena: technological applications of colour chemistry Chem. Rev. 114 12330–96
[9] Kerp H R and Van Faassen E E 2000 Effects of oxygen on exciton transport in zinc phthalocyanine layers Chem. Phys. Lett. 332
[10] Boileau N T, Melville O A, Minka B, Cranstion R and Lessard B H 2015 P and N type copper phthalocyanines as effective semiconductors in organic thin-film transistor-based DNA biosensors at elevated temperatures RSC Adv. 5 21335
[11] Keskin B, Okuyucu O, Altindal A and Erdogmuş A 2016 Novel indium(iii) phthalocyanines; synthesis, photophysical and humidity sensing properties New J. Chem. 40 5537–45
[12] Yadav A B, Pandey A, Somvanshi D and Jit S 2015 Sol-gel based highly sensitive Pd/n-ZnO thin film/n-Si schottky ultraviolet photodiodes IEEE Trans. Electron Dev. 62 1879–84
[13] Li X, Zhu H, Wang K, Cao A, Wei J, Li C, Jia Y, Li Z, Li X and Wu D 2010 Graphene on silicon schottky junction solar cells Adv. Mater. 22 2743–8
[14] Ragoussi M E, Ince M and Torres T 2013 Recent advances in phthalocyanine-based sensitizers for dye-sensitized solar cells Eur. J. Org. Chem. 29 6475–89
[15] Bottari G, de la Torre G, Guld D M and Torres T 2010 Covalent and noncovalent phthalocyanine-carbon nanostructure systems: synthesis, photoinduced electron transfer, and application to molecular photovoltaics Chem. Rev. 110 6768–816
[16] Huang C-Y, Lin S-Y, Cheng S-S, Chou S-T, Yang C-Y, Ou T-M, Wu M-C, Chan I-M and Chan Y-Y 2007 Transport mechanisms and the effects of organic layer thickness on the performance of organic Schottky diodes J. Vac. Sci. Technol. B 25 43–51
[17] Sari F A, Kazici M, Harputlu E, Bozar S, Koyun O, Sahin Y, Ugur N, Ince M and Gunes S 2018 Zn Phthalocyanine Derivatives for Solution-Processed Small Molecular Organic Solar Cells Chemistry Select 5 13692–9
[18] Sumona Sinha C-H, Wang M, Mukherjee and Yang Y-W 2014 The effect of gate dielectric modification and film deposition temperature on the field-effect mobility of copper (II) phthalocyanine thin-film transistors J. Phys. D: Appl. Phys. 47 245103
[19] Aia X, Lina J, Changy B, Zhou L, Zhangya R and Qin G 2018 Phase modification of copper phthalocyanine semiconductor by converting powder to thin film Appl. Surf. Sci. 428 788–92
[20] Keeratithiwakorn P, Songkaw P, Onlaor K and Tunhoo B 2017 Structural properties of copper phthalocyanine films grown by electrophoretic deposition process Materials Today: Proceedings 4 6194–9
[21] Zhai Z and Xu M 2020 All-solution-processed small-molecule solar cells by stripping-transfer method J. Mater. Sci., Mater. Electron. 31 5789–93
[22] Mekprasart W, Jarernboon W and Pecharapa W 2010 TiO2 thin films for optoelectronic applications Mater. Res. Express 7 095102
[23] Ganesh V, Zahrhan H Y, Yahia I S, Shikir M and AlFeify S 2016 Enhancement of nonlinear optical susceptibility of CuPc films by ITO layer Opt. Mater. 62 184–91
[24] Yahia I S, Ganesh V, Shikir M, AlFeify S, Zahrhan H Y, Algharni A, Abutalib M M, Al-Ghamdi A A, El-Nagar A M and Al Bassam A M 2016 An investigation on linear and non-linear optical constants of nano-spherical CuPc thin films for optoelectronic applications Physica B 496 9–14
[25] Farag A M 2007 Optical absorption studies of copper phthalocyanine thin films Opt. Laser Technol. 39 728–32
[26] Wang X Y, Zheng J B, Qiu K, Qu J R and Cao D Y 2014 Studies on structure and Raman spectroscopy of Ni-doped copper phthalocyanine thin films Appl. Surf. Sci. 297 888–94
[27] Wu W, Harrison N M and Fisher A J 2013 Electronic structure, and exchange interactions in cobalt-phthalocyanine chains Phys. Rev. B 88 024426
[28] Basova I V, Kiselev V G, Dubkov I S, Latteyer F, Gromilov S A, Peisert H and Chasse T 2013 Optical spectroscopy and XRD study of molecular orientation, polymorphism, and phase transitions in fluorinated vanadyl phthalocyanine thin films J. Phys. Chem. C 117 7097–106
[29] Yahia I S, Ganesi V, Shkib M, Al Faify S, Zahran H Y, Algarhi H, Abutalib M M, Al Ghantih A A, El-Naggar A M and Al Bassam A M 2016 An investigation on linear and non-linear optical constants of nano-spherical CuPc thin films for optoelectronic applications Physica B 496 9–14

[30] Metfaha B S E, Benhalila B M, Kaledic M, Benouissa B C E, Yasvur C A and Bayram A B 2020 Optical and electrical characterization of thin film MSB heterojunction based on organic material Al/p-Si/P3HT/Ag Physica B 593 412238

[31] Alsaada A M, Al-Bataineh Q M, Ahmad A A, AlBatainehb Z and Tellah A 2020 Optical band gap and refractive index dispersion parameters of boron-doped ZnO thin films; a novel derived mathematical model from the experimental transmission spectra Optik— International Journal for Light and Electron Optics 211 164641

[32] Basova T V, Parkhomenko R G, Polyakov M, Gurek A, Atilla D, Yuksel F, Ryabchikova E I, Kadem B Y and Hassan A K 2016 Effect of dispersion of gold nanoparticles on the properties and alignment of liquid crystalline copper phthalocyanine films Dyes Pigm. 125 266–73

[33] Yang J, Ren F, Tadjer M, Pearton S J and Kuramata A 2018 Gallium oxide: materials properties, crystal growth, and devices ECS J. Solid State Sci. Technol. 7 Q92

[34] Jyothi I, Janardhanam V, Rajagopal Reddy V and Choi C J 2014 Modified electrical characteristics of Pt/n-type Ge Schottky diode with a pyrrole–B interlayer Superlatt. Microstruc. 75 806–17

[35] Rhoderick E H and Williams R H 1998 Metal Semiconductor Contacts 2nd edn (Oxford: Clarendon)

[36] Uma N, Balaram N, Sekhar Reddy P R, Janardhanam V, Rajagopal Reddy V, Yun H J, Lee S N and Choi C J 2019 Structural, chemical and electrical properties of Au/La2O3/nGaN MIS junction with a high-k lanthanum oxide insulating layer J. Electron. Mater. 48 4217

[37] Demircioglu O, Karatas S, Yildirim N and Bakkaloglu O F 2011 Effects of temperature on series resistance determination of electrodeposited Ge/n-Si/Au–Sb Schottky structures Microelectron. Eng. 88 2997

[38] Cheung S K and Cheung N W 1986 Extraction of Schottky diode parameters from forward current-voltage characteristics Appl. Phys. Lett. 49 85

[39] Ranaa V S, Raiputa J K, Pathaka B T K and Purohit I P 2019 Cu sputtered Cu/ZnO Schottky diodes on fluorine doped tin oxide substrate for optoelectronic applications Thin Solid Films 769 79–83

[40] Karimov K S, Ahmed M M, Moiz S A and Fedorov M I 2005 Temperature-dependent properties of organic-on-inorganic Ag/p-CuPC/ n-GaAs/Ag photoelectric cell Sol. Energ. Mater. Sol. Cells 87 61–75

[41] Benhalila M 2020 A growth of A–Z phthalocyanine layers onto Si by thermal evaporation process to achieve organic heterojunction diodes Optik - International Journal for Light and Electron Optics 217 164832

[42] Gokcen M, Tatkaroglu A, Altindal S and Bulbul M M 2008 The effect of 60Co (γ-ray) irradiation on the electrical characteristics of Au/SnO2/n-Si (MIS) structures Radiation. Phys. Chem. 77 74–8

[43] Gupta R K and Singh R A 2004 Electrical properties of junction between aluminum and poly(aniline)-poly(vinyl chloride) composite Mater. Chem. Phys. 86 279–83

[44] Bell N J, Ng Y H, Du A, Coster H, Smith S C and Amal R 2011 Understanding the enhancement in photoelectrochemical properties of Al–p–Si Schottky diodes with the polyaniline–SiO2 nanocomposite interfacial layer Thin Solid Films 519 6004–9

[45] Zhou M, Bao J, Xu Y, Zhang J, Xie J, Guan M, Wang C, Wen L, Lei Y and Xie Y 2014 Photoelectrodes based upon Mo: BiVO4 inverse opals for photoelectrochemical water splitting J. Appl. Phys. 115 519401

[46] Jyothi I, Janardhanam V, Rajagopal Reddy V and Choi C J 2014 Modified electrical characteristics of Pt/n-type Ge Schottky diode with a pyrrole–B interlayer Superlattices Microstruct. 75 806

[47] Williams R H 1983 Physics and Chemistry of III–V Compound Semiconductor Interfaces (New York: Plenum)

[48] Aldemir D A, Essen M, Kökce A, Karataş S and Özdemir A F 2011 Analysis of current–voltage and capacitance–voltage–frequency characteristics in Al/p–Si Schottky diode with the polysilphophene–SiO2 nanocomposite interfacial layer Thin Solid Films 519 6004–9

[49] Güllü Ö, Aydınoglu S and Türüt A 2008 Fabrication and electrical characteristics of Schottky diode based on organic material Microelectron. Eng. 85 1647–51

[50] Karatas S, Türüt A and Altindal S 2009 Irradiation effects on the C–V and G/w–V characteristics of Sn/p–Si (MS) structures Radiation. Phys. Chem. 78 130–4

[51] Hill W A and Coleman C C 1980 A single-frequency approximation for interface-state density determination Solid-State Electron. 23 987–93

[52] Nicollian E H and Gootzberger A 1967 The Si–SiO2 interface–electrical properties as determined by the metal–insulator–silicon conductance technique Bell Syst. Tech. J. 46 1035–133

[53] Tung R T 2001 Recent advances in Schottky barrier concepts Mater. Sci. Eng. R 35 1–3

[54] Patel A, Pathak V M, Solanki G K, Patel K D and Pataniya P 2020 The influence of antimony doping on I–V, C–V and f(G)–w–f characteristics of indium/Al/n-GaAs/(X = 0, 0.1, 0.3) alloy Schottky diodes Superlattices Microstruct. 137 106348

[55] Sekhar Reddy P R, Janardhanam V, Jyothi I, Chang H S, Lee S N, Lee M S, Reddy V R and Choi C J 2017 Microstructural and electrical properties of Al/n-type Si Schottky diodes with Au/CuPc nanocomposite films as interlayer Superlattices Microstruct. 111 306–17

[56] Jyothi I, Janardhanam V, Lim Y R, Rajagopal Reddy V, Ahn K S and Choi C J 2015 Effect of copper phthalocyanine (CuPc) interlayer on the electrical characteristics of Au/n–GaP Schottky rectifier Mater. Sci. Semicond. Process. 30 420–8

[57] Zhou Y, Wang D, Ahlyi C, Tinh C C, Williams J, Park M, Williams N M, Hanvas A and Preble E A 2007 Temperature–dependent electrical characteristics of bulk GaN Schottky rectifier J. Appl. Phys. 101 024506