International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075, Volume-8 Issue-10, August 2019

Gate Dependent Tunable Photosensitivity of Copper Phthalocyanine Based Organic Field Effect Transistors

Lekshmi Vijayan, Anna Thomas, K. Shreekrishna Kumar, K.B. Jinesh

Abstract**:** ***Organic field effect transistor (OFET) based photodetector with high sensitivity was fabricated using copper phthalocyanine (CuPc) as photoactive channel for weak light detection. The device fabrication was conducted at room temperature using thermal evaporation technique. The opto-electrical properties of the devices under dark and light conditions are studied in this work. The performance of the photodetector depends on the incident wavelength and the intensity of the incident monochromatic light. We also show that the photoresponse could be tuned by the gate bias, which offers an additional benefit for practical applications. The transfer characteristics of the devices appear to enhance under light illumination. A slight enhancement in the carrier mobility was also detected upon illumination. Similarly, the subthreshold swing has been reduced from 1.31 ± 0.18 V/decade under dark condition to 0.76 ± 0.12 V/decade under illumination. Further impact of gate voltage on responsivity, on/off ratio and detectivity was also studied for the proposed device. The maximum photosensitivity and responsivity obtained from these OFET based photodetectors was 237.21 ± 8.02 and 7.77 ± 0.17 A/W respectively at a power density of 1 mW/cm^2 while operating at an input voltage of 4 V and bias voltage of -5 V. Also, a maximum detectivity of 1.38 ± 0.03×10^{12} Jones was obtained under the same operating condition. The high sensitivity, good stability, low noise and fast response towards weak light with different wavelength imply that OFET based photodetectors are particularly suitable for photodetection in the visible region of electromagnetic spectrum.***

Keywords**:** ***Detectivity, Organic Field Effect Transistors Photosensitivity, Responsivity.***

I. INTRODUCTION

Research on photodetectors has extensively been increasing for the last few years as it is a necessary element in the field of optoelectronics and photonics. Nowadays, low power and highly sensitive photodetectors are widely used in many applications such as image sensing, environmental monitoring, radiation detection, surveillance cameras etc. [1]-[4]. The technological developments in these fields demand high sensitivity, fast response, low noise, high reliability and efficiency, low cost and wide bandwidth photodetectors [5]. Response speed is the speed or time at which the device responds. For a good photodetector the response speed should be very less in range of milliseconds.

Recently the demand of low-cost photodetectors with high EQE, sensitivity, detectivity and quick response were increased rapidly. Most of the predominant photodetectors are made of inorganic semiconductors [6]. These photodetectors are expensive and some of them require to be operated in high voltage, which certainly limits their applications. Majority of inorganic semiconductor based detectors are highly sensitive to UV light and are more expensive [7]. Moreover, these detectors exhibit some inherent limitations such as high cost and low quantum efficiency [8],[9]. For weak light sensing, preamplifiers are utilized to identify the light [10]. This will increase the size and also make the system more expensive.

Organic semiconductor (OSC) devices, such as light emitting diodes (LEDs) [11], field effect transistors (FETs) [12] and photodetectors (PDs) [13] have grown quickly in the past few years. These devices have the advantages of light weight, low cost, high speed, ease of fabrication and variety in substrates, making them suitable for large area, flexible electronic applications [14]. Low working voltage of organic photodetectors (OPDs) enable them more competitive and adaptable than inorganic counterparts for portable consumer electronics. Ray *et al*. reported a high efficiency OPD with a low responsivity in the range of mA/W [15]. These types of photosensors have high photoresponsivity, so they didn’t need any external amplifying components. Currently, ongoing researches are mainly focused on OPDs with a conventional device structure.

Utilization of organic field effect transistor (OFET) in different optoelectronic applications like image sensing, radiation detection and optical communications has been widely investigated because of photosensitive nature of OSCs [1]-[3]. Just like the inorganic based devices, organic devices can also react to incident light rapidly, which encourages researchers to combine the photoconductive impact of OSCs with the field effect of OFETs and fabricate OFET-based photodetectors with high photoresponsivity and detectivity [16]. The CMOS compatibility of OFETs has been helpful in interfacing it with current technology. Photodetectors other than OFET based structures have their own limitations such as low speed, high noise and low efficiency [8],[9]. OFET-based photodetectors dissipate less power due to very high input impedance of the device. Thus, OFET based photodetectors are promising for a wide variety of scientific and industrial

Revised Manuscript Received on August 05, 2019.

Lekshmi Vijayan, Department of Electronics, School of Technology and Applied Sciences, Mahatma Gandhi University, Kottayam, Kerala, India. Email: lekshmivijayan@gmail.com

Anna Thomas, Department of Physics, Indian Institute of Space Science and Technology (IIST), Valiamala, Thiruvananthapuram, Kerala, India. Email: annamol2aug@gmail.com

K. Shreekrishna Kumar, Department of Electronics, School of Technology and Applied Sciences, Mahatma Gandhi University, Kottayam, Kerala, India. Email: kshreekk@gmail.com

K.B. Jinesh[*], Department of Physics, Indian Institute of Space Science and Technology (IIST), Valiamala, Thiruvananthapuram, Kerala, India. Email: kbjinesh@iist.ac.in

applications, owing to the advantages of room-temperature operation, low cost manufacture, thin profile, flexibility, large area and low working voltage. Visible light detection has been greatly promoted by practical applications such as color image sensors and scanners [1]. Today majority of the research works are completely focused on highly photoconductive material and dielectric thickness to enhance the photosensitivity [16],[17], but in this paper we introduce an effective control of gate voltage to achieve the targets.

Generally, large bandgap semiconductor photosensors have the advantage of low dark current due to the intrinsic thermal excitation of electrons, which gives large on-off current ratios. When the incident light has equal energy or greater than the bandgap of the material, a large photocurrent is generated. Therefore, though large bandgap semiconductors are advantageous in terms of large on-off ratios, they are mostly operational only in the UV wavelengths. To overcome this, these materials are usually doped to create defects levels in the visible spectrum. In this work, we report the photosensing using copper phthalocyanine (CuPc) as the photosensitive medium. CuPc has two different absorption edges due to π-π* transitions [18]. One absorption edge is in the UV region and the other is in visible region. Therefore, CuPc is photoresponsive to selected wavelengths in UV and visible spectrum without any external doping.

II. MATERIALS AND METHODS

In this work, p-type OFET based photodetector was fabricated on silicon (Si) substrate with CuPc as the photoactive channel. The top contact structures are commonly utilized in OFET based detectors because the photosensitive layer is exposed on the top in this configuration. We used CuPc as the photosensitive channel for device fabrication due to its interesting optical properties. CuPc was purchased from Sigma Aldrich with high purity and no further purification was performed. Before starting the fabrication, Si wafers were properly cleaned in an ultrasonic bath using acetone, iso-propyl alcohol and deionized water for 15 minutes each. Then the wafer was dried in open air in a cleaned room. The OFET device was fabricated by depositing a thin CuPc film on this Si wafer with 50 nm thermally grown oxide on top. CuPc films were deposited at an evaporation rate of 0.1 nm/sec without heating the substrate. The thickness of CuPc was approximately 50 nm. Next, gold contacts with 100 nm thickness were deposited onto the photoactive CuPc layer through a metal shadow mask with area of 175×10^{-5} $cm^2$by vacuum evaporation. Fig. 1 shows a three dimensional view of the fabricated OFET based photodetector. After depositing the CuPc films, its optical bandgap was studied by UV-Visible spectrophotometer. Photoconductivity of the prepared thin film was carried out in an electrical probe station under dark and light conditions. The optical power density of illumination was 1 mW/cm^2.

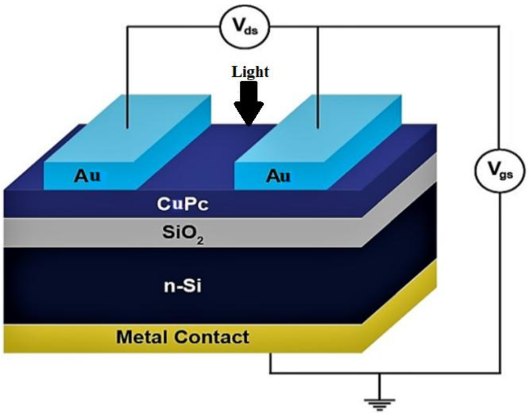
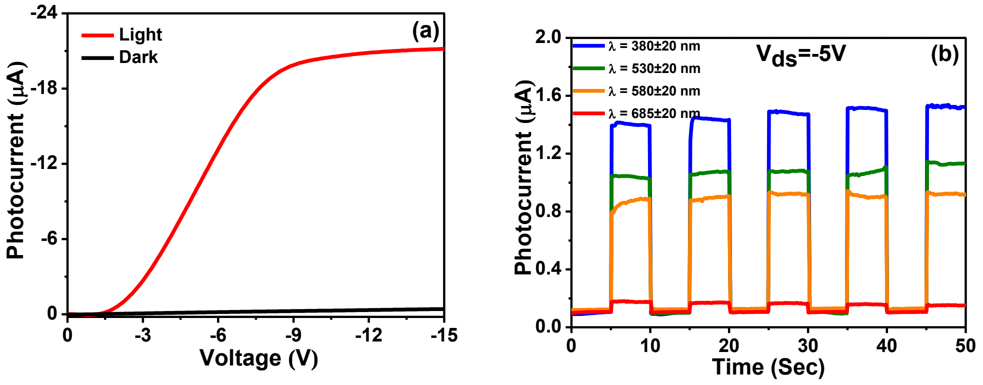


Fig. 1. Device structure of the OFET based CuPc photodetector.

III. RESULT AND DISCUSSIONS

A. Photodetection at Different Wavelength

Fig. 2 (a) shows the normal photoconductivity of the fabricated device under dark and white light illumination. A larger photoresponse was detected at higher bias voltages. Hence, we investigated the wavelength dependence of the photocurrent and estimated the performances of the photodetector in terms of photosensitivity, responsivity, EQE, detectivity etc. Fig. 2 (b) shows the photoresponse of the OFET based photodetector with different wavelengths of 380 ± 20, 530 ± 20, 580 ± 20 and 685 ± 20 nm. On comparing, the light with a wavelength of 380 ± 20 nm shows better photoresponse and the highest photosensitivity. This highest photoresponse and thus the highest responsivity is due to the fact that photon energy corresponding to that wavelength is sufficient to excite the electrons over the bandgap of CuPc.



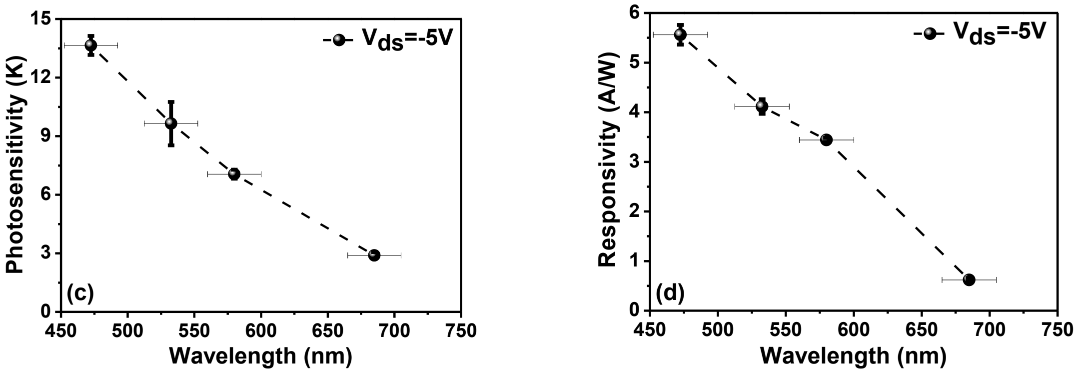


Fig. 2. (a) I–V characteristics of the organic photodetectors in the dark and under illumination of different wavelengths, (b) The photo-induced current characteristics of the OFET based photodetector under different wavelengths, (c) The photosensitivity measured under different wavelength at drain voltage of -5 V, (d) Responsivity as a function of wavelength.

All the performance parameters of the photosensors have been calculated using the observed photocurrents and dark currents. The photosensitivity of the device is simply the ratio of currents when light is on and off, given by $K = I_{on}/ I_{off}$, where I_{on} is the photocurrent and I_{off} is the photocurrent when light is off [19]. The estimated photosensitivities of the devices for different wavelengths are shown in Fig. 2 (c). At higher wavelengths the photosensitivity is small, as the electrons may not have sufficient energy to be excited to the conduction band [20]. Responsivity is another important parameter, which indicates the input-output gain of a photodetector. It always depends on power of the incident light. The responsivity can be calculated from $R = I_{Ph} / P_{in}$, where I_{Ph} is the current under illumination and P_{in} is the incident optical power density in W/cm^2 [19]. For a good photodetector the value of responsivity should be high. The calculated photoresponsivity values for the photodetector are plotted in Fig. 2 (d). A maximum photoresponsivity of 5.56 ± 0.19 A/W was obtained at a V_{ds} of -5 V under wavelength of 380 ± 20 nm.

The performance of a photodetector can be evaluated using external quantum efficiency (EQE). It can be estimated from the measured responsivity by

$$\mathrm{EQE} = \left(\frac{R}{e} \times \frac{hc}{\lambda}\right) \tag{1}$$

where, R is the responsivity, h is Planck’s constant, c is the speed of light, e is the charge of electron and λ is the wavelength of incident monochromatic light [19]. The device shows a maximum efficiency of 14.64 ± 0.52. Fig. 3 (a) shows the plot of EQE for various wavelength of incident light. The term detectivity is used to characterize the performance of the photodetector. Detectivity varies with responsivity and effective area of the device using the following equation,

$$D^{*} = \left(\frac{R \times \sqrt{A}}{\sqrt{2 \times e \times I_{off}}}\right) \tag{2}$$

where, R is the photoresponsivity, A is the effective area of the device, e is the charge of electron and I_{off} is the off light current [21]. By using the effective area of the device, it is possible to estimate the detectivity of the detector. The determined detectivity values of the device are plotted in Fig. 3 (b). In this case a maximum detectivity of $9.73 \pm 0.35 \times 10^{11}$ Jones is obtained for monochromatic light with optical power density of 1 mW/cm^2.

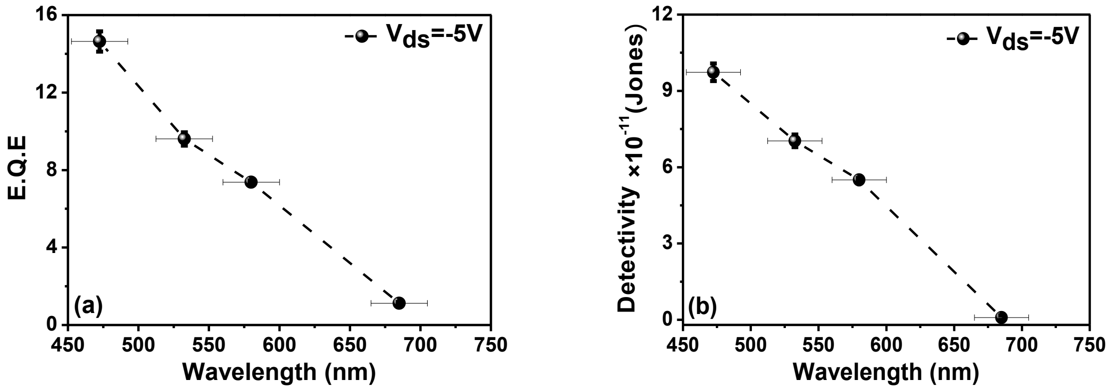


Fig. 3. (a) EQE versus wavelength for a drain voltage of -5 V, (b) Variation of detectivity of OFET based photodetector with different wavelength.

B. Optical Properties of CuPc

In order to understand the photoresponse of CuPc, the optical properties of CuPc thin films are characterized by using absorption spectroscopy. From the absorption spectrum of CuPc thin film it can be seen that maximum absorption of light takes place in 300-400 nm regions. From absorption spectrum, the optical bandgap of the material is around 2.7 eV, and the other two peaks in absorption spectrum originate from the molecule aggregation or molecular distortion [22]. The optical bandgap of the material can be calculated from the Tauc plot by extrapolating the linear portion of the $(\alpha h\nu)^2$ versus hν plot as shown in Fig. 4. CuPc molecules have two main absorption bands, Q-band and B-band in the absorption spectrum. In the absorption spectrum of CuPc thin film, Q-bands are broadened and overlapped so that they can absorb light throughout the entire visible region of the electromagnetic spectrum [18]. Hence from the above results, the proposed device can be effectively used as a highly sensitive photodetector in the visible region.

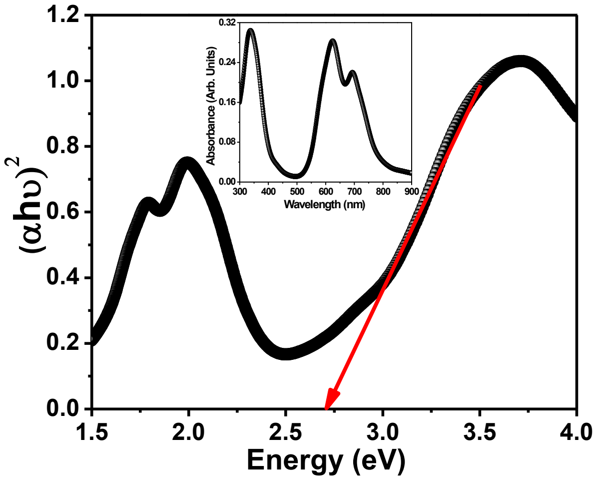
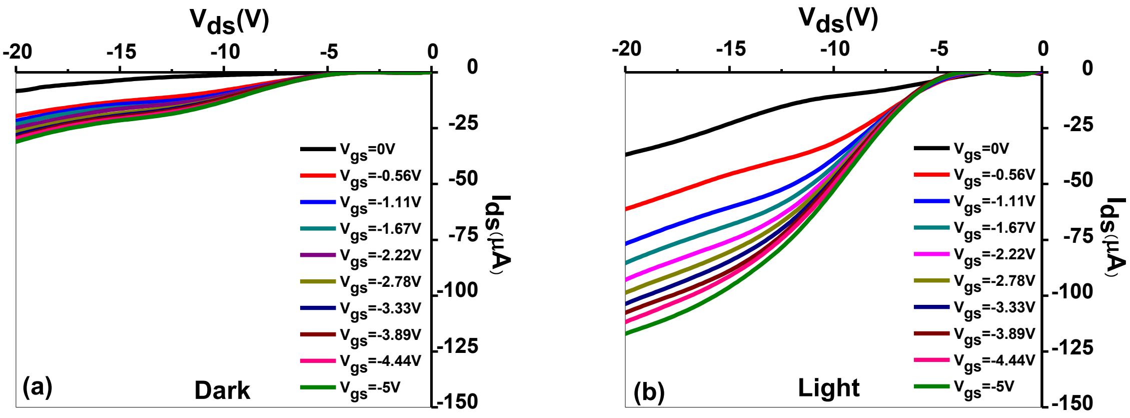


Fig. 4. Tauc plot of CuPc thin film, inset shows the UV absorption spectrum of CuPc thin film.

C. Photodetection of White Light

The wavelength dependence results clearly demonstrate that the OFET based photodetectors are very interesting for image sensing applications in the visible region. The electrical characteristics of CuPc-based OFETs have been reported in our previous study [23], while the transfer parameters are slightly better than those of our previous studies due to the introduction of gold electrode in the present study. The output characteristics of the devices under dark and light conditions are shown in Fig. 5 (a) and (b). From the figure it is clear that with illumination, the drain - source current (I_{ds}) value of the device increases. In dark condition, the maximum I_{ds} of the device was ~ 50 µA, while under the illumination, the I_{ds} value of the device increased to ~ 150 µA at a gate - source voltage (V_{gs}) of -5 V. Fig. 5 (c) and (d) shows the effect of dark and light respectively on the transfer characteristics of the fabricated device on logarithmic and linear scales.



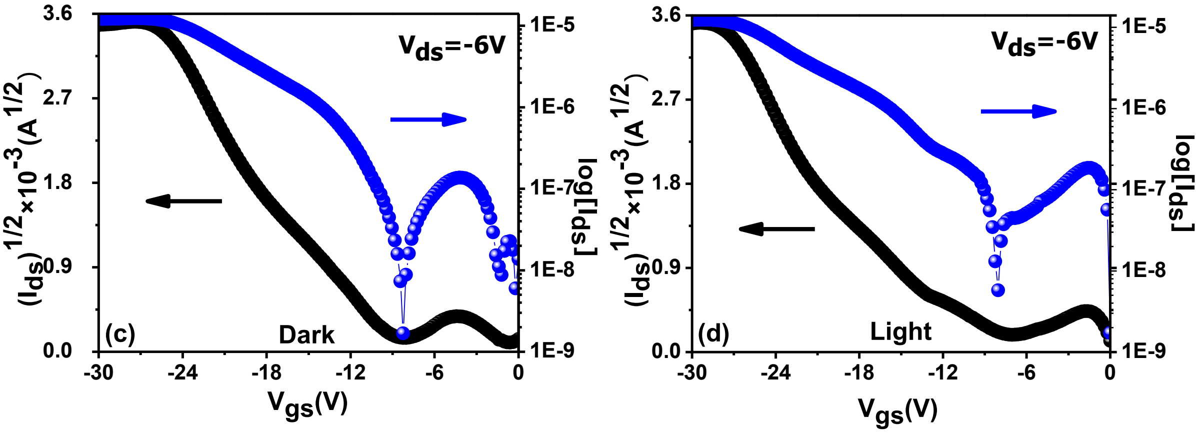


Fig. 5. Output characteristics of the OFET based photosensor under (a) dark, (b) illumination; Transfer characteristics of the OFET based photosensor under (c) dark, (d) illumination.

Table 1 shows the performance comparison of transfer parameters of OFET under dark and light conditions. From the table it is clear that the OFET has comparatively lower V_{th} and higher mobility due to effective control of gate over channel while illuminated. Besides that, illumination causes a substantial reduction in subthreshold swing (SS) and threshold voltage (V_{th}). Hence the fabricated device can be utilized as a low power photodetector in the visible region.

Table 1 Summary of transfer parameters of OFET based photodetector with and without illumination with constant drain-source voltage of -6 V.

Parameters	Dark	Light
μ (cm^2/Vs)	0.92±0.06	0.99±0.06
$I_{On/Off}$	7.34×10^3	2.14×10^3
V_{th} (V)	-8.37±0.09	-7.71±0.26
SS (V/decade)	1.31±0.18	0.76±0.12
N_{it} ($cm^{-2}eV^{-1}$)	$5.67\pm0.53\times10^{11}$	$3.16\pm0.28\times10^{11}$

Fig. 6 (a) shows the photoresponse of the device with different drain - source voltage (V_{ds}). From the figure it is evident that detector presents a photocurrent of ~ 44 μA under illumination and photocurrent quickly go to zero once the light is turned off. The estimated photosensitivity of the device for different V_{ds} is shown in Fig. 6 (b). More than 20 devices are fabricated and all of them show very good photoresponse behavior. For the devices the photosensitivity increases with increasing V_{ds} and at -9 V, it shows the maximum photosensitivity of 217.33 ± 15.93. For small V_{ds} the photosensitivity of the photodetector is small and when the voltage is increased, the value is also increased. Beyond a certain V_{ds} the photosensitivity becomes saturated. The reduction in the interface trap density under illumination with high bias voltage led to the saturation of the photocurrent. The presence of trap states either in CuPc or at the interface between the dielectric layer and the CuPc layer may be responsible for such a reduction in photosensitivity. The OFET based photodetector exhibits a maximum photoresponsivity of 8.44 ± 0.13 A/W at a V_{ds} of -12 V, which is appreciably better than that of the inorganic photodetectors reported [24]. By using the effective area of the device, it is possible to estimate the detectivity of the detector and the maximum value obtained in this case is $1.29 \pm 0.02\times10^{11}$ Jones. But the fabricated device shows better performance with a responsivity of 6.21± 0.09 A/W and detectivity of $1.18 \pm 0.01\times10^{11}$ Jones at -9 V respectively because of the highest photosensitivity at this voltage. The calculated photoresponsivity and detectivity values for the devices are plotted in Fig. 6 (c) and (d) respectively.

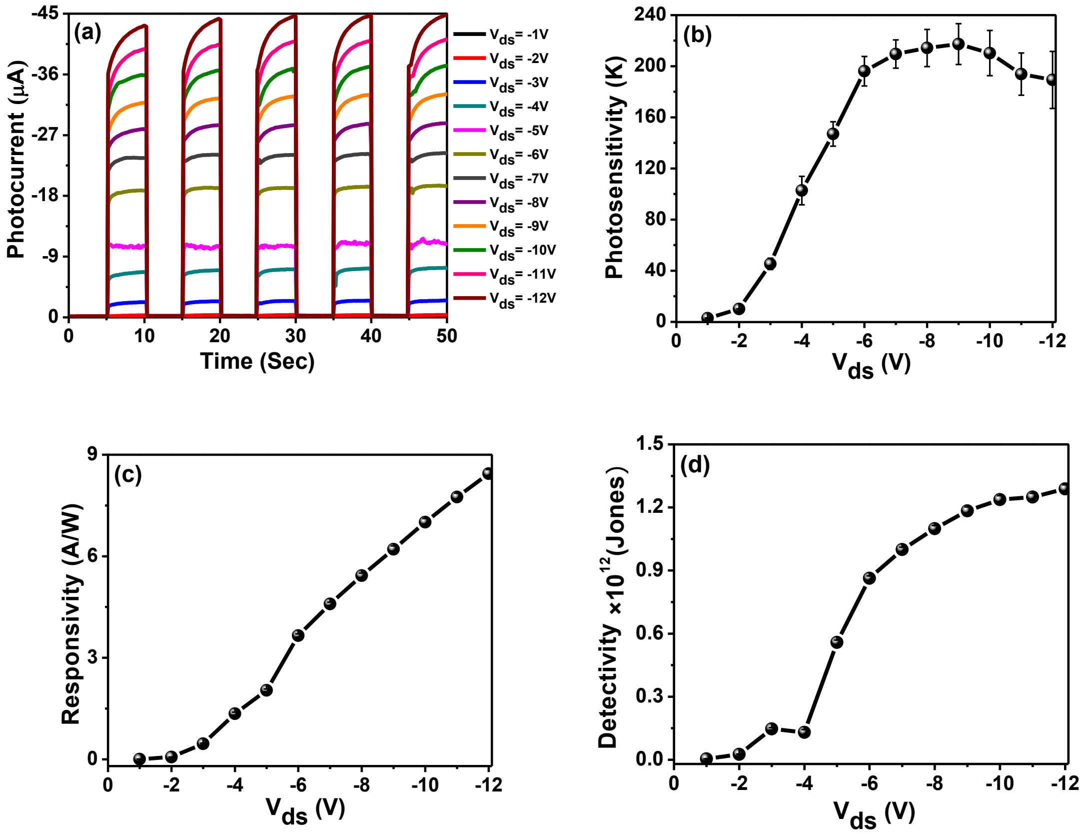


Fig. 6. (a) Photoresponse curves of OFET based photodetector with different V_{ds} under white light illumination, (b) Plot of the photosensitivity as a function of drain voltage, (c) Variation of responsivity of the device with different $V_{ds,}$ (d) Detectivity of the organic photodetectors with different $V_{ds.}$

Another important parameter of photodetector is speed of response. Speed of response or response time is the time required for the detector to respond to an optical input. Photodetectors with sufficiently fast response provide a measurable output for a small amount of light and are economical for applications in high-speed optical communications. In order to understand the time response of the photodetector, the photocurrent in the initial stage of light with both on and off modes was recorded and is shown in Fig. 7(a) and (b) respectively. The rise (τ_{on}) and fall (τ_{off}) time are calculated to be 207 ms and 200ms, respectively, based on curve fits of the transients with an exponential function, which is one of the fastest among the data so far reported for inorganic photosensors [7].

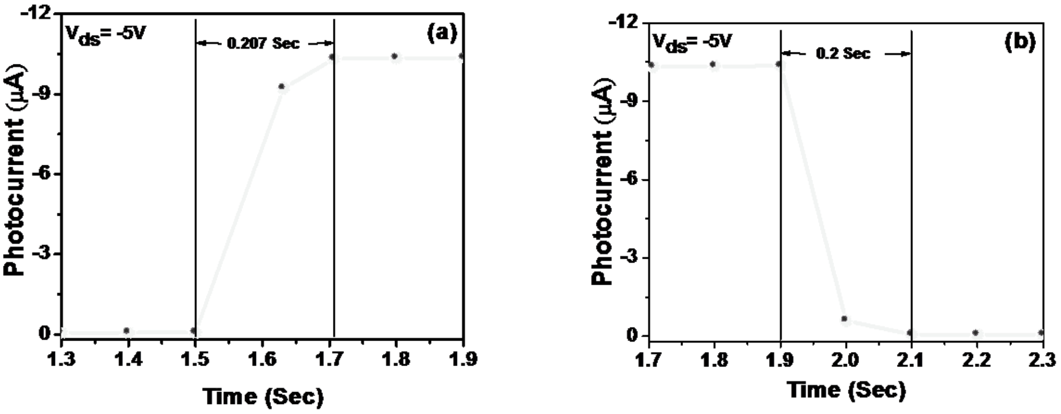


Fig. 7. Estimation of time response of OFET based photodetector with a drain-source voltage of -5V (a) Rise time, (b) Fall time

D. Mechanism of Gate Tunability

In this section, the gate voltage tunability of the photodetector is described. That is, the photocurrent of the device is adjusted by tuning the V_{gs} of the fabricated device. The gate dependence of the photocurrent was measured and shown in Fig. 8 (a). The photocurrent gradually increases when changing the V_{gs} from positive to negative.

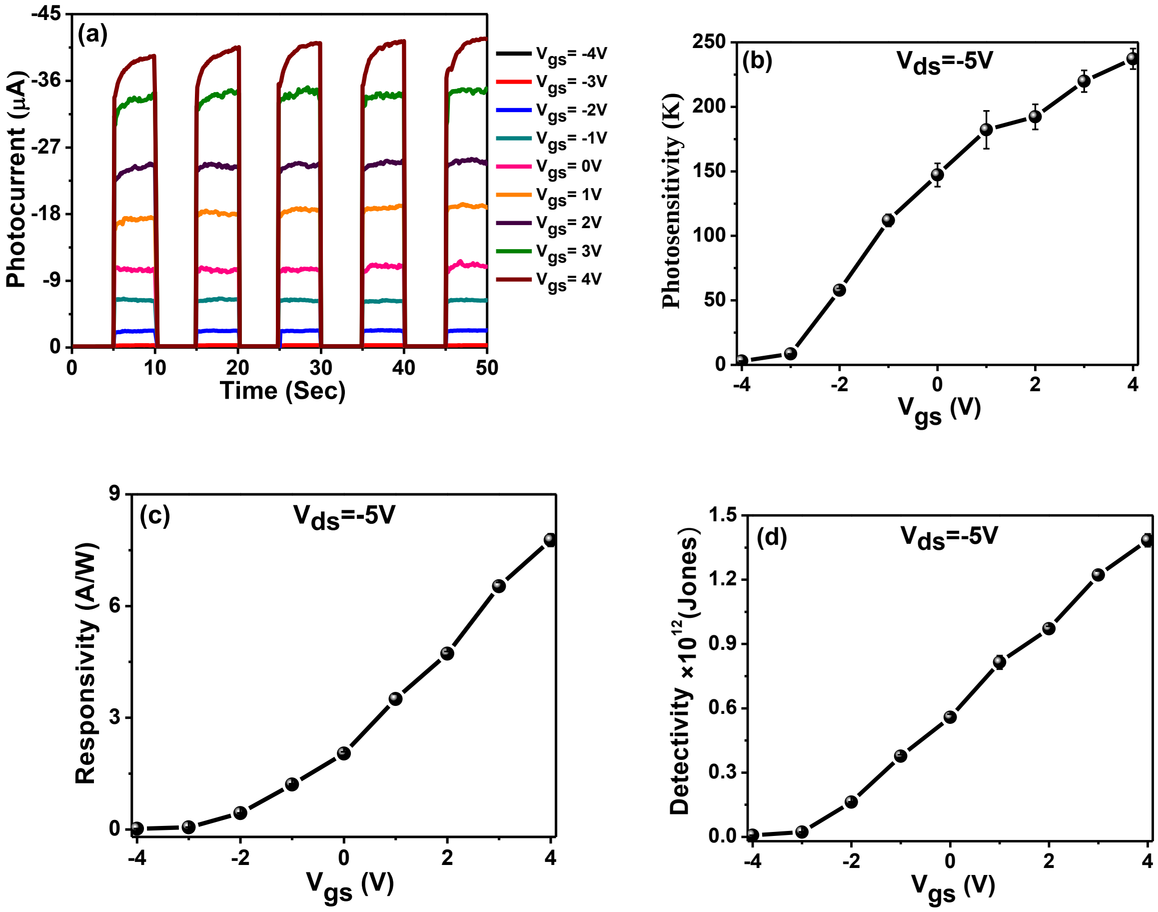


Fig. 8. (a) Plot of photocurrent response of the optimized device as a function of different gate voltages with a constant drain voltage of -5 V, (b) Photosensitivity of OFET based CuPc photodetectors as a function of V_{gs} under white light with constant V_{ds} of -5 V, (c) Plots of photoresponsivity versus gate voltage at an incident power density of 1 mW/cm^2, (d) Specific detectivity as a function of the gate voltage under white light with constant V_{ds} of -5 V.

The photocurrent generation was recorded by monitoring the I_{ds} under illumination by scanning the V_{gs} from -4 V to 4 V in step of 2 V, keeping a fixed V_{ds} of -5 V. Fig. 8 (b) and (c) shows the estimated photosensitivity and responsivity of the device respectively. The device shows a maximum photosensitivity and responsivity of 237.21 ± 8.02 and 7.77 ± 0.17 A/W respectively for a V_{gs} of 4 V. Specific detectivity of the device after applying V_{gs} is also calculated and the maximum value obtained is $1.38 \pm 0.03\times10^{12}$ Jones. After applying the positive V_{gs}, all the detector parameters are increased due to the reduction of noise. Hence the above results imply that the photosensitivity of our device can be effectively tuned, which is an attractive feature for developing tunable photodetectors for image sensing applications.

IV. CONCLUSION

In summary, CuPc-based photosensing OFET with SiO_2 dielectric shows very good photosensitivity at low power density. An enhanced photosensitivity factor of 237.21 ± 8.02 is observed with an input voltage of 4 V and bias voltage of -5 V. The peak responsivity value of approximately 7.77 ± 0.17 A/W and the peak detectivity of $1.38 \pm 0.03\times10^{12}$ Jones were obtained under the same operating condition. The extremely high photosensitivity of the device makes them particularly attractive for weak light detection. These high performance parameters demonstrated that OFET based photodetectors are comparable to or better than inorganic counterparts. The low operational voltage, appropriate photosensitivity and high detectivity directly determine the efficiency of the OFETs, which are crucial for the photodetector.

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AUTHORS PROFILE

Lekshmi Vijayan is currently pursuing the Ph.D. degree in Electronics with Mahatma Gandhi University, Kerala, India. She received the B.Tech. degree in Electronics and Communication Engineering from Kerala University and the M.Tech. (Electronics) with specialization in VLSI and Embedded Systems from Cochin University of Science and Technology.

Anna Thomas is currently doing the Ph.D. degree in Physics with Indian Institute of Space-Science and Technology (IIST), Thiruvananthapuram, Kerala, India. And received M.Sc and B. Sc. in Physics from Mahatma Gandhi University, Kottayam, Kerala, India.

Dr. K. Shreekrishna Kumar is currently working as the Regional Director of School of Technology and Applied Sciences, Mahatma Gandhi University, Kottayam. He received the M.Phil. degree in Solid State Physics from Mangalvore University, Kartnataka. And received M.Tech. degree in Information Technologyfrom Punjabi University,Punjab. He achieved Ph.D. in Solid State Ionics from Mahatma Gandhi University, Kerala. He was the former Director of All India Council for Technical Education (AICTE), Govt. of India, Newdelhi. He is involved in the development of organic thin film transistors for sensor applications.

Dr. K.B. Jinesh is an Associate Professor in the Physics Department of Indian Institute of Space-Science and Technology. He achieved PhD in Physics from Leiden University, the Netherlands, and in Electrical Engineering from Twente University of Technology, The Netherlands. He worked in NXP Semiconductors, The Netherlands as a scientist, working in CMOS integration of passive devices employing ALD. Later he joined as a scientist in Holst Center (IMEC Netherlands) working on developing ultra-low power chemical sensors. In 2010, he joined Nanyang Technological University in Singapore as a senior researcher. He has published over 50 international research papers, 12 patents and more than 45 conference papers. His current research interests are in future memory technologies and flexible electronics applications.