Effect of Dielectric Layer Thickness on Rubrene-Based Phototransistors

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Contents

Abstract

Have you ever wondered how sunlight gets converted to electricity? What kind of devices are involved in the amplification of light into electrical signals? It is quite intriguing to know how these kinds of devices are actually fabricated and what are their use cases are in the rapidly developing electronic industry. In this project, we would be studying phototransistors and their working. We would also be studying how they are characterized and what the device architecture is. We will learn how is the fabrication process of rubrene-based photo-transistors for different dielectric thicknesses is done. This project further investigates the effect of dielectric layer thickness on the performance of rubrene-based phototransistors. Rubrene was used as the active layer in the phototransistors, with a bottom-gate, top-contact device structure. A series of devices were fabricated with varying thicknesses of the dielectric layer, and their performance was characterized through electrical and optical measurements for this project.

1 Introduction

A photodetector is an essential optoelectronic device that can detect light and convert it into electrical signals. Depending on the working mechanism, photodetectors are generally categorized into three types: photoconductors, photodiodes, and phototransistors. Phototransistors, integrate light capture capability and signal amplification function in a single device, and exhibit higher optical detectivity and lower noise as compared to that of photoconductors and photodiodes. With the rapid development of organic materials and device fabrication technology, the mobility of organic semiconductors now exceeds that of polysilicon thereby making them able to meet the industrial requirements [1].

1.1 History

The history of phototransistors dates back to the 1940s when scientists first discovered the photoconductivity of semiconductors. In 1948, the first phototransistor was developed by John Northrup Shive at Bell Labs. This phototransistor was made of germanium and consisted of a collector, an emitter, and a base region that was sensitive to light. He discovered that when the light was shone on the base region, it increased the number of electron-hole pairs and resulted in a larger collector current. The first phototransistors were relatively slow and had low sensitivity, but they were an important milestone in the development of optoelectronics. They were used in a variety of applications, including light meters and control systems. In the 1960s and 1970s, the development of phototransistors advanced significantly with the introduction of new materials such as silicon and indium phosphide. These new materials allowed for the development of more sensitive and faster phototransistors [8].

Today, phototransistors are widely used in applications such as optical communication, barcode scanners, and smoke detectors. They are also used in electronic devices such as cameras, sensors, and light meters. The continued development of new materials and technologies is expected to lead to further advancements in phototransistors in the future.

Here, we would be first studying the basic structures, working mechanisms, and fundamental parameters of phototransistors.

2 Understanding organic and inorganic semiconductors for optoelectronics

Both organic and inorganic semiconductors are used in optoelectronics, but they have different properties and characteristics that make them suitable for different applications.

Organic semiconductors are made of carbon-based materials, such as polymers or small molecules, and exhibit unique electronic and optical properties that arise from their molecular structure. They are typically flexible, and lightweight, and can be processed using low-cost techniques such as inkjet printing, roll-to-roll coating, and vacuum evaporation. Organic semiconductors have low carrier mobility and a relatively low dielectric constant, which limits their performance in high-speed devices and high-frequency applications. However, they are suitable for applications such as organic light-emitting diodes (OLEDs), organic photovoltaics (OPVs), and organic phototransistors (OPTs) [1].

Inorganic semiconductors are typically made of elements from groups III-V, II-VI, or IV-VI of the periodic table, such as silicon, gallium arsenide, or indium phosphide. They have higher carrier mobility and a higher dielectric constant compared to organic semiconductors, making them suitable for high-speed and high-frequency devices. Inorganic semiconductors are typically rigid and brittle, and their fabrication requires high-temperature processing techniques such as epitaxy, lithography, or chemical vapor deposition. Inorganic semiconductors are used in various optoelectronic devices, such as photodiodes, light-emitting diodes (LEDs), solar cells, and lasers. Our project is based on the fabrication of organic transistors, so we will focus our understanding in this direction.

3 Organic semiconductor-based phototransistor

Organic phototransistors (OPTs) are photo-activated sensors based on organic field-effect transistors that convert incident light signals into electrical signals. They have several advantages over traditional inorganic semiconductors because of the ease of processing, making them attractive for various optoelectronic applications.

Here are some examples of different organic semiconductor materials and their properties:

- Conjugated polymers: These are a class of polymers with alternating double and single bonds that enable them to conduct electricity. Conjugated polymers have high absorption coefficients, making them suitable for applications such as photovoltaics and OLEDs.
- Small molecules: These are organic molecules that have a defined chemical structure and can be easily synthesized and purified. Small molecules have excellent optical and electronic properties, making them suitable for OLEDs and photovoltaic applications.
- Carbon nanotubes: These are cylindrical tubes made of carbon atoms that exhibit unique electronic properties due to their one-dimensional structure. Carbon nanotubes have high carrier mobility and are suitable for applications such as transistors and sensors.
- Graphene: This is a two-dimensional material made of a single layer of carbon atoms arranged in a hexagonal lattice. Graphene has high carrier mobility, excellent mechanical strength, and high optical transparency, making it suitable for various optoelectronic applications, including transparent conductive electrodes and photodetectors.

3.1 Device Architecture

Now let's study the device architecture of rubrene-based phototransistors and the role of each component: We fabricate bottom-gate top contact devices. What are bottom-gate top contact devices (BGTC)? These devices are a type of organic field-effect transistor (OFET) that consists of a rubrene semiconductor layer deposited on a gate dielectric layer, with source and drain electrodes deposited on top of the semiconductor layer. The gate electrode is located underneath the gate dielectric layer, hence the term bottom gate. The top-contact configuration refers to the source and drain electrodes being located on top of the semiconductor layer, in contrast to the bottom-contact configuration where the electrodes are located beneath the semiconductor layer. The main components of a bottom-gate top-contact (BGTC) rubrene device are the substrate, gate electrode, gate dielectric layer, rubrene semiconductor layer, and source/drain electrodes. Each of these components plays a crucial role in the performance and operation of the device [1].

1. Substrate: The substrate provides support for the device and can also affect its electrical properties. The choice of substrate can depend on factors such as cost, availability, and compatibility with the fabrication process. We use a silicon substrate for fabrication.
2. Gate electrode: The gate electrode is typically made of a conductive material such as metal or doped silicon, and it is used to apply an electric field to the gate dielectric layer. The gate electrode controls the charge carrier concentration in the rubrene semiconductor layer, thereby modulating the conductivity of the channel.
3. Gate dielectric layer: The gate dielectric layer separates the gate electrode from the rubrene semiconductor layer and provides electrical insulation between them. The gate dielectric layer can also affect the capacitance and threshold voltage of the device.
4. Rubrene semiconductor layer: The rubrene semiconductor layer is the active component of the device, where charge carriers (electrons or holes) are transported and modulated by the gate voltage.
5. Source/drain electrodes: The source and drain electrodes are used to apply a voltage to the rubrene semiconductor layer and measure the resulting current flow.

The device architecture:

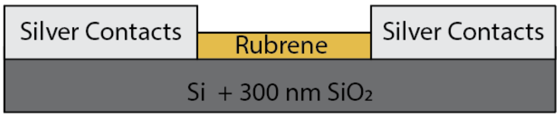


Figure 1: Device Architecture

3.2 Working Principle

In general, the working principle of Organic Phototransistors (OPTs) can be divided into two types according to the different exciton separation modes by the on/off state of the transistors: (i) photovoltaic mode, and (ii) photoconductive mode. We will explain each mode in detail after understanding the basic working mechanism. The main steps involved in the working of an organic phototransistor:

1. Light absorption: When light falls on the organic semiconductor layer, it creates electron-hole pairs (photocarriers) due to the photoexcitation process. The organic semiconductor layer can be made of various organic materials, such as conjugated polymers, small molecules, or carbon nanotubes.

2. Charge transport: The generated photocarriers migrate through the organic semiconductor layer and reach the interface with the gate dielectric layer. The gate dielectric layer acts as an insulator and prevents the photocarriers from reaching the gate electrode.

3. Gate voltage modulation: By applying a voltage to the gate electrode, an electric field is generated that modulates the flow of photocarriers between the source and drain electrodes. The gate voltage controls the conductivity of the organic semiconductor layer and hence, the current flowing through the device.

4. Current amplification: The current flowing through the device can be amplified by the transistor action, which depends on the channel length, channel width, and threshold voltage of the device. Now let us study the two modes.

- **Photovoltaic mode**: In the photovoltaic mode, the OPT acts like a photodiode, where the generated photocurrent is due to the separation of photoexcited electron-hole pairs at the organic semiconductor layer's interface with the source electrode. The photogenerated charges are separated by a built-in potential between the organic semiconductor and the source electrode, resulting in a voltage difference between the two terminals of the device. The photovoltage can be measured directly, and the device acts like a photovoltaic cell. For a p-type semiconductor, the photoexcited holes transport towards the drain electrode while electrons accumulate in the source electrode, which effectively reduces the contact resistance of hole injection in the source electrode. The photocurrent resulting from the photovoltaic effect is given as:

$$I_{ph,pv} = g_m \triangle V_{th} \frac{Akt}{T} ln[1 + \frac{\eta q \lambda P_{op}}{I_{dark} hc}] \tag{1}$$

  where g_m is transconductance, V_{th} is the threshold shift, A is a proportionality parameter, k corresponds to the Boltzmann constant, T signifies the temperature, η is the photo-generation quantum efficiency, q refers to the elementary charge, λ is the wavelength of light, P_{opt} is the incident optical power in the channel area, I_{dark} is the dark current for minority charges and hc/λ is the photon energy.

- **Photoconductive mode**: In the photoconductive mode, the OPT acts like a photoconductive detector, where the generated photocurrent is due to the increase in the conductivity of the organic semiconductor layer upon photoexcitation. The photogenerated carriers increase the charge density in the organic semiconductor, reducing its resistance and resulting in an increase in the current flowing through the device. The photoconductivity can be measured directly, and the device acts like a photoconductive cell [1]

$$I_{ph,pv} = (q\mu_p pE)WD = BP_{opt} \tag{2}$$

where p is the majority charge carrier's mobility, p is the charge carrier concentration, E refers to the electric field in the conducting channel, W is the gate width, and D corresponds to the depth of the absorption region, and B is a proportionality factor.

3.3 Characterization

Characterization of phototransistors involves measuring their electrical and optical properties under different operating conditions. Some of the key parameters that are typically characterized in phototransistors include:

1. Mobility: The mobility of organic field-effect transistors (OFETs) refers to the ability of charge carriers, such as electrons or holes, to move through an organic semiconductor material in the presence of an electric field. The mobility of OFETs can be affected by several factors, including the morphology of the organic material, the degree of crystallinity, the presence of impurities, and the method of device fabrication.

$$\mu = 2\left(\frac{\mathrm{d}\sqrt{\mathrm{Id}}}{\mathrm{dVg}}\right)^2 \cdot \frac{\mathrm{L}}{\mathrm{WC}} \tag{3}$$

2. External Quantum Efficiency: This is the ratio of the number of electrons generated by the photodiode to the number of incident photons and is a measure of the device's efficiency at converting light into electrical current.

$$EQE = \frac{I_{light}/q}{P_{opt}/h\nu} \tag{4}$$

3. Response Time: Response time represents the speed of response to a rapidly modulated signal. modulated light signal.

4. Threshold Voltage: The threshold voltage for organic phototransistors (OPTs) refers to the minimum voltage that needs to be applied to the gate electrode of the device to induce a significant current flow between the source and drain electrodes.

5. Photosensitivity: It is the ratio of light to dark current.

$$P = \frac{I_{D(light)} - I_{D(dark)}}{I_{D(dark)}} \tag{5}$$

6. Responsivity: This is the ratio of the output current to the incident optical power and indicates the sensitivity of the device to light. Responsivity is typically measured as a function of the wavelength of the incident light.

$$R = \frac{I_{D(light)} - I_{D(dark)}}{P_{opt}} \tag{6}$$

7. Detectivity: It is used to describe the ability of weak light detection and is given by.

$$D^* = \frac{R\sqrt{A}}{\sqrt{2qI_{dark}}} \tag{7}$$

   The normalized value is called specific detectivity.

8. Gain: This is the ratio of the output current to the input photocurrent and indicates the amplification provided by the transistor. Gain can be affected by various factors such as the bias voltage, the input light intensity, and the operating temperature.

9. Bandwidth: This is the range of frequencies over which the device can respond to optical signals and is a measure of its speed. Bandwidth can be limited by various factors such as the parasitic capacitance of the device, the transit time of the carriers, and the diffusion length of the photons.

10. Noise figure: This is a measure of the noise added to the signal by the device and is expressed in terms of the signal-to-noise ratio. A low noise figure indicates that the device adds minimal noise to the signal.
    The formulae above are interrelated to each other, for example

$$R = \frac{EQE \cdot \lambda \cdot q}{hc}$$

Now that we have understood the theoretical framework we can move on to the experimental section of our project, that is, fabricating the device.

4 Device Fabrication

There are several steps involved in the fabrication of a phototransistor, and each step plays a crucial role in producing high-quality devices.

4.1 Choosing the right material

Choosing the right material for phototransistors is critical to achieving the desired performance and functionality of the device. So we have to consider several factors in making this vital decision:

1. Optical properties: The material's optical properties, such as absorption coefficient and bandgap energy, determine its ability to absorb light and generate electron-hole pairs. A material with a high absorption coefficient and a suitable bandgap energy for the target wavelength range can improve the device's sensitivity and response time.

2. Carrier mobility: The mobility of charge carriers in the material is a crucial parameter that determines the device's response time and sensitivity. A material with high carrier mobility enables faster and more efficient transport of charge carriers, resulting in faster response times and higher sensitivity.

3. Stability: The material's stability and durability under operating conditions, such as temperature, humidity, and light exposure, are important considerations for long-term device performance and reliability.

4. Processing compatibility: The material's compatibility with the fabrication process is also essential. It should be possible to deposit the material with high quality and uniformity using standard processing techniques such as evaporation, sputtering, or spin coating.

5. Cost: The cost of the material is another important consideration, especially for large-scale production. Ideally, the material should be affordable and readily available.

The project is to fabricate Rubrene based Phototransistors. So let us first understand what is Rubrene and why Rubrene.

4.1.1 What's special about Rubrene?

Rubrene is a highly efficient organic semiconductor that exhibits excellent photoconductive properties. Its chemical formula is $C_{42}H_{28}$, and the structure is as below.

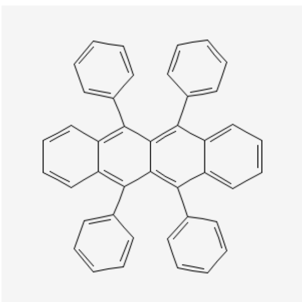


Figure 2: Rubrene [6]

The key reasons for it being so special are :

1. High charge carrier mobility Rubrene has a high charge carrier mobility, which allows for efficient transport of charge carriers in the device. This results in fast response times and high sensitivity.
2. Large absorption coefficient Rubrene has a high absorption coefficient, which means that it can absorb a significant amount of light, even at low intensities. This makes it ideal for low-light detection applications.
3. Suitable bandgap energy The bandgap energy of rubrene is suitable for visible light absorption, which makes it well-suited for phototransistor applications.

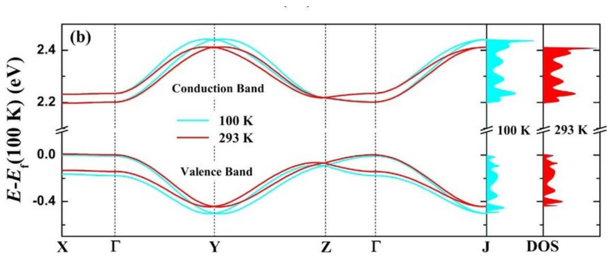


Figure 3: Band Structure of Rubrene [7]

4. Low noise Rubrene has a high absorption coefficient, which means that it can absorb a significant amount of light, even at low intensities. This makes it ideal for low-light detection applications.

4.2 Crystal Growth

Crystal growth using a thermal evaporator is a method of growing crystals by evaporating a material from a heated source and allowing the vapor to condense onto a cooler surface, where it can grow into a crystal. This process is also known as physical vapor deposition (PVD) or thin-film deposition. In this process, the material to be deposited is placed in a crucible, which is then heated to a high temperature, causing the material to evaporate and form a vapor. The vapor then condenses onto a cooler substrate, where it forms a thin film or crystal. The crystal growth process can be controlled by adjusting various parameters such as the temperature of the source material, the pressure in the chamber, and the deposition rate. By carefully controlling these parameters, it is possible to achieve a high degree of precision and accuracy in the crystal growth process. In a thermal evaporator, there are typically three distinct zones, each with a specific function in the crystal growth process:

1. The source zone: This is where the material to be deposited is placed.
2. The transport or intermediate zone: This is where the vapor travels and can interact with gases or other substances present in the chamber.
3. Growth Zone: Zone where the crystal growth occurs.

4.3 Preparing Substrates

The process involves several steps :

1. Firstly, the substrates are cut into smaller substrates of around 1x1 cm or less.
2. These substrates are then washed in acetone and isopropanol in that order. Then, using a blower, we dry off the extra isopropanol, if any.
3. A heat gun is used to heat the substrates for around 5 min.
4. Then we went for oxygen plasma treatment of the prepared substrates for 30 seconds.
5. Subsequent step involves using a spin coater to coat the dielectric layers on the substrates. For PMMA (1 percent solution in toluene), the acceleration time is set constant to 5 seconds and the spinning time to 60 seconds. Acceleration rates are varied for varying the thicknesses of dielectric layers on the substrates, like 1000 rpm, 2000 rpm, etc. For Polystyrene (PS) also everything is also followed in a similar way.

6. Then comes an important process called Annealing, which is basically heating at a finite temperature for an optimized time frame so that the solvent will evaporate and the dielectric settles down. For both PS and PMMA, we anneal for 8 hours at 60 degrees centigrade. Finally, we keep the substrates at room temperature for 2-3 hours before we continue with the experiment.

4.4 Lamination

The lamination of crystals on a substrate is a process of bonding or attaching crystals onto a substrate material to create a thin film or coating. This process is often used in the semiconductor and electronics industries to create thin films of materials. We pick the crystals and place them on the substrate, thus laminating without air gaps and cracks.

4.5 Silver Paste Electrode Deposition

Silver paste electrode deposition is a technique used to deposit a silver paste onto a substrate to create an electrode. Dispensing of the silver paste near the edges of rubrene crystals using a dispenser or printing tool is carried out. The amount of paste and the pattern of deposition are carefully controlled to ensure uniformity and accuracy. The silver paste is dried to remove any solvents or other liquids used in the dispensing process.

4.6 Data collection

The micromanipulators are used to make electrical connections between the phototransistor and the parametric analyzer. The analyzer is connected to a computer, which is used to control the measurement parameters and collect the data. The measurement is then performed, with the parametric analyzer applying a series of voltages and currents to the phototransistor and recording the resulting electrical properties, such as current-voltage (I-V) curves. The data is typically displayed in real-time on the computer, allowing the user to monitor the progress of the measurement and adjust the parameters as needed. Once the data collection is complete, the data is analyzed to extract useful information about the phototransistor, such as its electrical characteristics and performance under different conditions. This may involve fitting the data to mathematical models or comparing the results to reference data to identify any anomalies or deviations. We would be studying three different characteristic curves:

1. **I-V Characteristics**: The I-V (current-voltage) characteristics of a rubrene-based phototransistor describe the relationship between the current flowing through the device and the voltage applied across it. When light is incident on the device, it can induce a photocurrent that can be collected by the electrodes and measured as a change in the I-V characteristics. In general, the I-V characteristics of a rubrene-based phototransistor can be divided into two regions: the linear region and the saturation region. **In the linear region**, the current through the device increases linearly with the applied voltage, and the device behaves as a resistor. The slope of the I-V curve in the linear region is determined by the resistance of the device, which is affected by the mobility of the charge carriers in the rubrene layer and the contact resistance between the rubrene layer and the electrodes. In the absence of light, the linear region of the I-V curve is typically observed, representing the behavior of the device under dark conditions. **In the saturation region**, the current through the device reaches a maximum value, and further increase in the applied voltage does not result in a significant increase in current. The saturation current is related to the carrier concentration in the rubrene layer and can be affected by the intensity of the incident light. When light is incident on the device, the photocurrent generated by the photoexcited charge carriers can increase the current in the saturation region, leading to an increase in the photocurrent-to-dark current ratio (also known as the photoresponsivity) of the device.

   The I-V characteristics of a rubrene-based phototransistor can also exhibit hysteresis, which is a shift in the I-V curve when the voltage is swept in opposite directions. The hysteresis can be caused by the trapping and detrapping of charge carriers at the interface between the rubrene layer and the gate dielectric layer. The hysteresis can affect the stability and reliability of the device and can be minimized by optimizing the device geometry and materials.

2. **The transfer characteristics**: It describes the relationship between the current flowing through the device and the voltage applied to the gate electrode, while the source-drain voltage is held constant.

   When a voltage is applied to the gate electrode, it induces an electric field in the gate dielectric layer, which in turn modulates the carrier concentration and mobility in the rubrene layer. As a result, the current flowing through the device is also modulated, and this modulation can be measured by plotting the transfer characteristics. The transfer characteristics of a rubrene-based phototransistor can exhibit two important features: the threshold voltage and the field-effect mobility. The threshold voltage is the gate voltage at which the current flowing through the device starts to increase significantly. It is a measure of the energy barrier between the Fermi level of the electrodes and the highest occupied molecular orbital (HOMO) level of the rubrene layer. The threshold voltage can be affected by the work function of the electrodes, the dielectric constant and thickness of the gate dielectric layer, and the doping level of the rubrene layer.

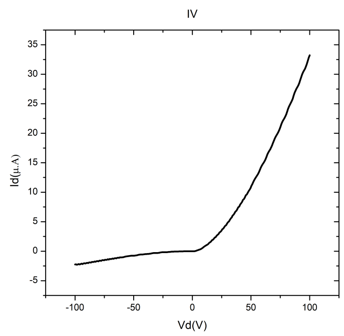
The field-effect mobility is a measure of the charge carrier mobility in the rubrene layer and can be determined from the slope of the linear region of the transfer characteristics. The mobility can be affected by the morphology and purity of the rubrene layer, as well as the presence of defects, impurities, or traps that can scatter the charge carriers and reduce their mobility. The transfer curve can be measured for different wavelengths of incident light to determine the spectral response of the phototransistor, which describes the efficiency of the device in converting light into current as a function of the wavelength. The spectral response can be affected by the absorption and quantum efficiency of the rubrene layer, as well as the device geometry and materials. The spectral response can be used to optimize the device for specific applications, such as photodetection or photovoltaics. The dark transfer curve, obtained in the absence of incident light, can provide valuable information about the intrinsic properties of the device, such as the mobility, threshold voltage, and subthreshold slope.

3. **Output Characteristics** The output characteristics of a rubrene-based phototransistor describe the relationship between the current flowing through the device and the voltage applied between the source and drain electrodes, while the gate voltage is held constant. The output curve of a rubrene-based phototransistor typically exhibits two important features: the saturation current and the responsivity. The saturation current is the maximum current that can flow through the device at a given source-drain voltage, and it depends on the carrier concentration, mobility, and injection efficiency in the rubrene layer. The saturation current can be affected by the purity, morphology, and doping level of the rubrene layer, as well as the quality of the electrodes and contacts.

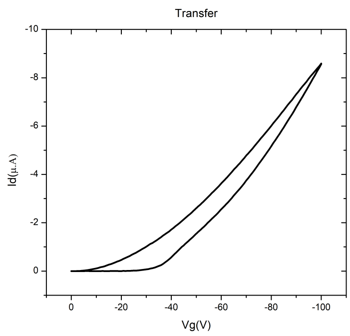
5 Observations

5.1 Dielectric: PMMA (Polymethyl methacrylate)

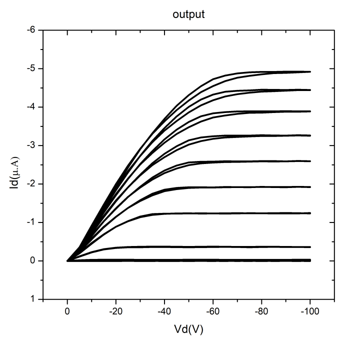
1. Dielectric thickness corresponding to 1000 rpm acceleration rate (Device 1)



(a) I-V Characteristics



(b) Transfer Characteristics



(c) Output Characteristics

Figure 4

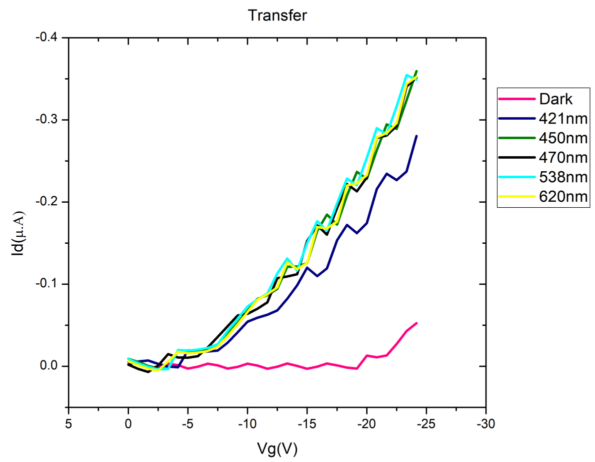
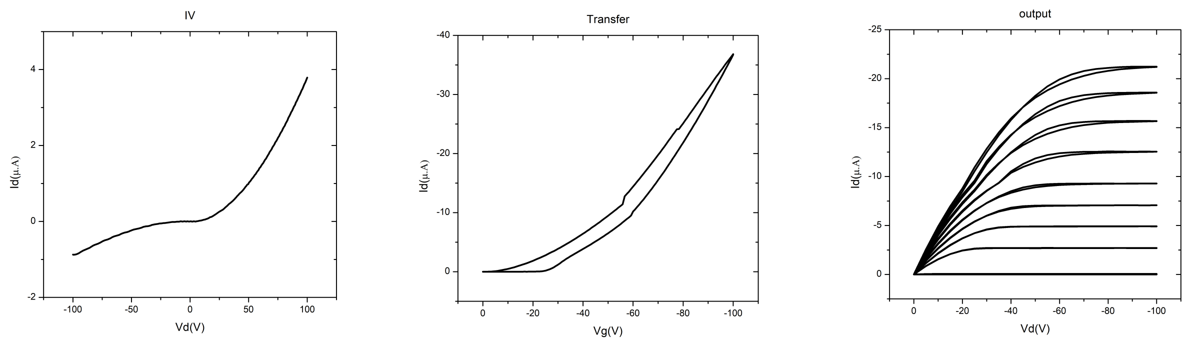


Figure 5: Transfer Characteristics for a varying wavelength of incident light

2. Dielectric thickness corresponding to 2000 rpm acceleration rate (Device 2)



(a) I-V Characteristics (b) Transfer Characteristics (c) Output Characteristics

Figure 6

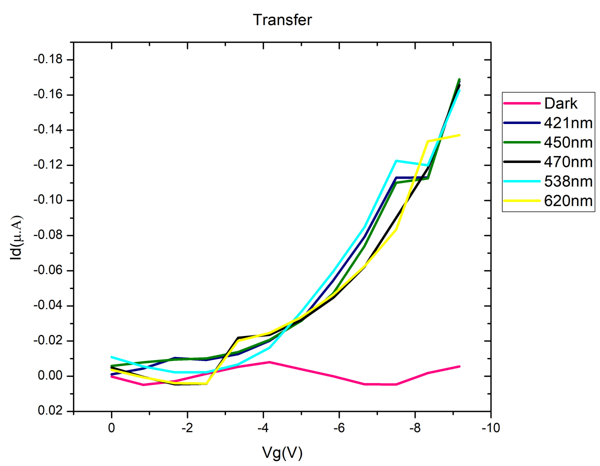
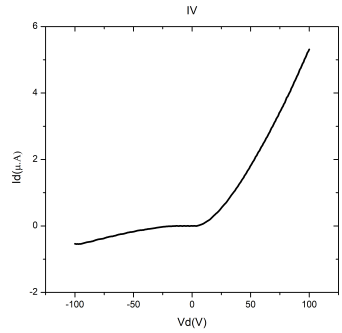
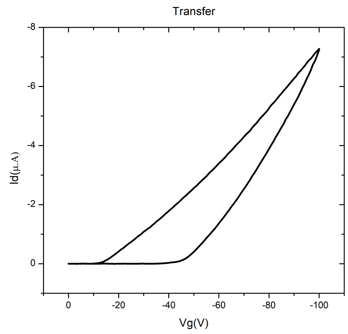


Figure 7: Transfer Characteristics for a varying wavelength of incident light

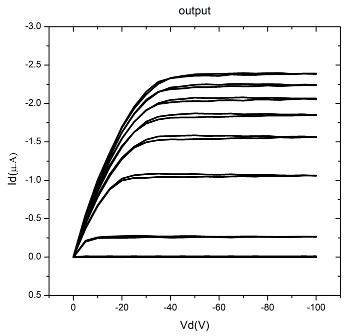
3. Dielectric thickness corresponding to 3000 rpm acceleration rate (Device 3)



(a) I-V Characteristics



(b) Transfer Characteristics



(c) Output Characteristics

Figure 8

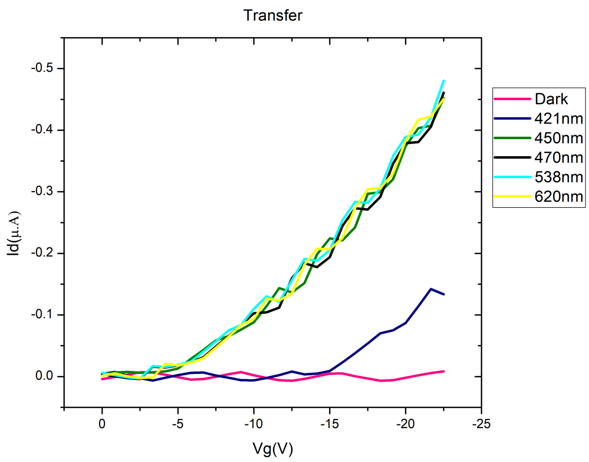
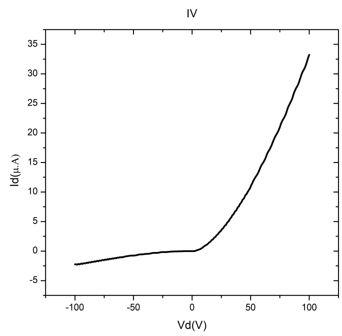
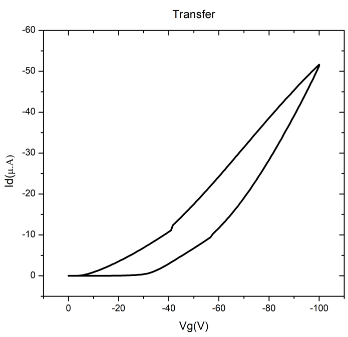


Figure 9: Transfer Characteristics for a varying wavelength of incident light

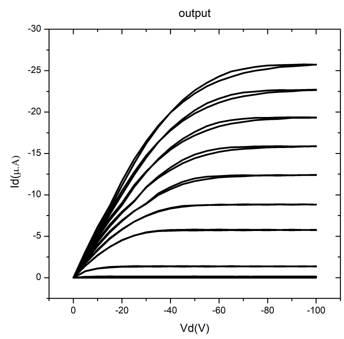
4. Dielectric thickness corresponding to 4000 rpm acceleration rate (Device 4)



(a) I-V Characteristics



(b) Transfer Characteristics



(c) Output Characteristics

Figure 10

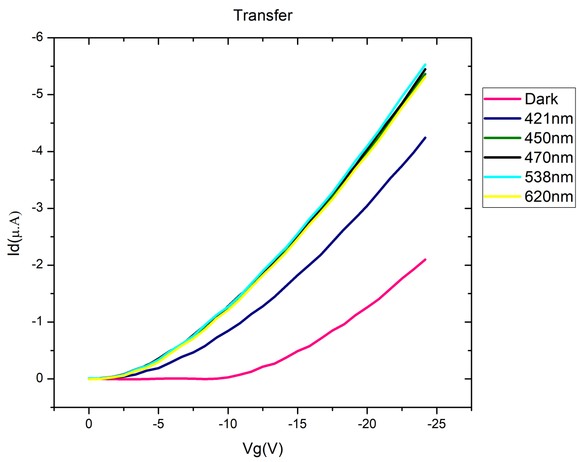
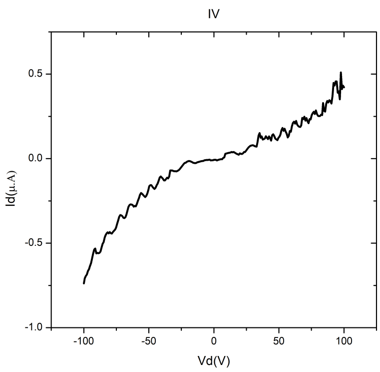


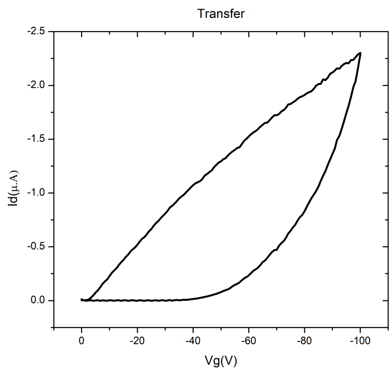
Figure 11: Transfer Characteristics for a varying wavelength of incident light

5.2 Dielectric: PS (Polystyrene)

1. Dielectric thickness corresponding to 1000 rpm acceleration rate (Device 1)



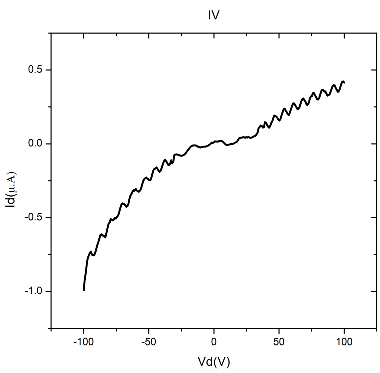
(a) I-V characteristics



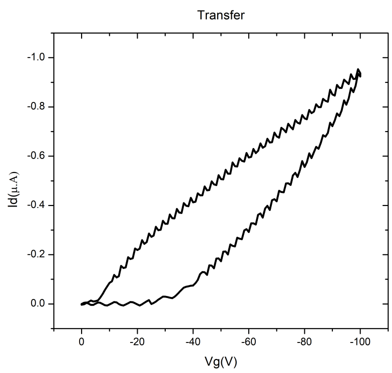
(b) Transfer characteristics

Figure 12

2. Dielectric thickness corresponding to 3000 rpm acceleration rate (Device 2)



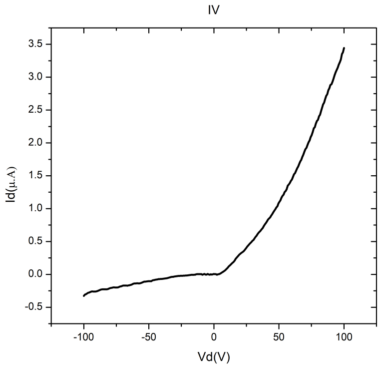
(a) I-V characteristics



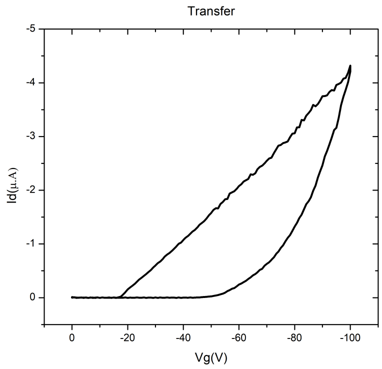
(b) Transfer characteristics

Figure 13

3. Dielectric thickness corresponding to 4000 rpm acceleration rate (Device 3)



(a) I-V characteristics



(b) Transfer characteristics

Figure 14

6 Results and Data Analysis

The devices are characterized based on the formulae as mentioned in section 3.3.

1. PMMA

For wavelength **421 nm**	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Responsivity	0.00554	0.01614	0.03608	0.13686
Photosensitivity	23.33646	248.30	4.39	393.70
EQE	3.73*10^-4	3.74*10^-4	3.59*10^-4	3.24*10^-4
For wavelength **450 nm**	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Responsivity	0.00108	0.01405	2.12*10^-4	0.02354
Photosensitivity	48.934	48.934	6.8	2035.4
EQE	2.84*10^-4	2.84*10^-4	3.04*10^-4	1.35*10^-4

Figure 15: Table 1

For wavelength **470 nm**	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Responsivity	0.0017	0.01474	2.84*10^-4	0.02661
Photosensitivity	55.01	55.00	8.38	2029.75
EQE	3.08*10^-4	3.08*10^-4	3.25*10^-4	3.07*10^-4
For wavelength **538 nm**	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Responsivity	5.89*10^-4	0.00506	1.17*10^-4	0.05972
Photosensitivity	54.782	54.78	6.63	2012.18
EQE	8.33*10^-5	8.33*10^-5	3.73*10^-4	4.30*10^-4
For wavelength **620 nm**	**Device 1**	**Device 2**	**Device 3**	**Device 4**
Responsivity	8.5*10^-4	0.00634	1.55*10^-4	0.06835
Photosensitivity	71.141	71.141	17.94	1809.20
EQE	9.16*10^-5	9.16*10^-5	8.71*10^-4	8.14*10^-5

Figure 16: Table 2

	Device 1	Device 2	Device 3	Device 4
Mobility	1.057	0.94011	0.04998	2.354
Threshold	-14.28	-13.35	-25.96	-4.64

Figure 17: Table 3

2. PS

	Device 1	Device 2	Device 3
Mobility	0.064	2.341	0.267

Figure 18: Table 4

Analysis for tables:

1. For PMMA: Device 4 shows the highest responsivity, photosensitivity, and mobility, whereas Device 2 shows the highest EQE. Environmental factors, the quality of the silver paste, and noise can have an influence on the results. As we have not done the actual capacitance measurement it is very difficult to explain the significance of this trend. Each rubrene crystal has a different capacitance which changes according to channel length and width.

2. For PS: We determined that mobility and the quality of silver paste also determine the presence of noise in the curve. Device 2 has the highest mobility, while Device 3 is next.

3. Typically, the mobility decreases with increasing wavelength due to increased phonon scattering.

4. The photosensitivity, responsivity, and external quantum efficiency can vary with the incident wavelength due to variations in the absorption and quantum efficiency of rubrene. Typically, these can be highest for wavelengths near the absorption peak of the rubrene layer. The relationship between these parameters and incident wavelength will depend on the specific materials and device design used in the phototransistor.

Analysis for graphs:

1. **I-V**: Slow increase in the current in the initial voltage range, followed by a rapid increase, can be attributed to the presence of traps and defects in the organic semiconductor material, which initially hinders the flow of charge carriers through the material. As the voltage is increased, more charge carriers are injected into the material, which can fill up some of the traps and defects, leading to an increase in the current. Once a sufficient number of traps have been filled, the current increases rapidly, leading to the characteristic steep rise in the I-V curve. The shape of the I-V curve can also be influenced by the geometry and materials used in the device, as well as the presence of any surface or interface effects.

2. **Transfer**: The hysteresis in the transfer curve of a rubrene-based phototransistor can be attributed to the trapping and de-trapping of charge carriers in the organic semiconductor material, which can occur as the gate voltage is swept back and forth. During the forward sweep of the gate voltage, charge carriers can be injected into the organic semiconductor material, leading to an increase in the drain current. As the gate voltage is swept back to its original value, some of the injected charge carriers may become trapped in localized energy states or defects within the material, leading to a decrease in the drain current. During the reverse sweep of the gate voltage, some of the trapped charge carriers may become detrapped and contribute to the drain current, leading to a higher current than during the forward sweep.

3. **Output**: The drain current versus drain voltage graph of a rubrene-based phototransistor shows the relationship between the drain current (ID) and the drain voltage (VD) under different gate voltages (VG) and incident light intensities. The graph generally shows an increasing linear region at low drain voltages, followed by a saturation region where the current plateaus. In the linear region, the current increases linearly with voltage, and the slope of the curve (transconductance) is related to the mobility of the charge carriers

in the semiconductor. In the saturation region, the current plateaus because the semiconductor is fully depleted and the flow of charge carriers is limited by the number of available carriers. The graph can also show the effect of different gate voltages and incident light intensities on the drain current. As the gate voltage increases, the current at a given drain voltage will increase, indicating a larger number of charge carriers available to flow.

4. **Photoresponse**: The drain current of a rubrene-based phototransistor typically increases with increasing incident light intensity (photocurrent) and with increasing gate voltage. For different wavelengths of light, the relationship between drain current and gate voltage can vary, depending on the absorption properties of the rubrene semiconductor. In general, the absorption of rubrene increases with decreasing wavelength, so the device will have a higher response to shorter wavelength light. This means that for a given gate voltage, the drain current will be higher for shorter wavelength light than for longer wavelength light. However, the actual relationship between drain current and gate voltage for different wavelengths will depend on the specific design and properties of the rubrene-based phototransistor.

7 Conclusion

The thickness of the gate dielectric layer in a rubrene-based phototransistor can have a significant impact on the device's electrical and optoelectronic properties.

The thickness of the dielectric layer can affect the mobility of the charge carriers in the rubrene semiconductor layer. A thicker dielectric layer can lead to lower field-effect mobility, which is a measure of how easily charge carriers move through the semiconductor layer in response to a gate voltage. This is because a thicker dielectric layer can increase the density of interface traps, which are localized states at the interface between the dielectric layer and the semiconductor layer that can trap charge carriers and reduce their mobility.

Furthermore, the thickness of the dielectric layer can affect the response of the phototransistor to light. A thicker dielectric layer can lead to reduced photoresponsivity, which is a measure of the ability of the device to convert incident light into an electrical signal. This is because a thicker dielectric layer can reduce the electric field in the semiconductor layer, leading to a lower generation and separation of charge carriers in response to light. Therefore, the choice of the dielectric layer thickness in a rubrene-based phototransistor should be carefully optimized to balance the trade-offs between the threshold voltage, field-effect mobility, and photoresponsivity. The optimal thickness of the dielectric layer can depend on factors such as the fabrication process, the specific dielectric material used, and the desired device performance. Also, the spectral response curve shows which wavelengths of light the device is most sensitive to and how the device's sensitivity changes with wavelength. If the spectral response curve shows high sensitivity to green light, it may be useful for applications in green light photodetection or green light harvesting in photovoltaic devices. Summarising:

1. Mobility (cm^2/Vs): The mobility of the rubrene semiconductor can be affected by the dielectric layer thickness, with thinner dielectric layers typically resulting in higher mobilities due to improved charge injection and transport. Capacitance measurement might have influenced the results.

2. Photosensitivity: The photosensitivity of the phototransistor can also be affected by the dielectric layer thickness, with thicker dielectric layers resulting in higher photosensitivity due to increased light absorption and charge separation. This is in line with the results we observed.

3. Responsivity (A/W): The responsivity of the phototransistor can vary with different dielectric thicknesses, depending on the trade-off between light absorption and charge collection efficiency. Thicker dielectric layers can improve light absorption and hence increase the responsivity, but it may also increase the resistance of the device and reduce the collection efficiency. This is in line with the results we observed.

4. External quantum efficiency (EQE): The EQE of the phototransistor can also vary with different dielectric thicknesses, with thicker dielectric layers typically resulting in higher EQEs due to improved light absorption and charge separation.

8 Possible Extensions and Applications of Phototransistors

This project can be further extended for

1. To Investigate different dielectric materials
2. To characterize device stability
3. For optimization of device performance
4. Also, Rubrene graphene-based phototransistors can be fabricated which is basically an organic phototransistor that incorporates graphene as the electrode material. The use of graphene electrodes in rubrene-based phototransistors can have several advantages over traditional metal electrodes. Graphene has high transparency in the visible and near-infrared regions, allowing a larger fraction of incident light to reach the active layer and be absorbed. It also has a low work function, which can reduce the energy barrier for charge carrier injection from the electrodes into the rubrene layer. Additionally, graphene has high mechanical flexibility, which can enable the fabrication of flexible and stretchable phototransistors.
5. We can also use several other techniques like epitaxial growth in which, the crystals are grown directly on the substrate using a process called epitaxy or growing the crystals on a separate substrate using a thermal evaporator, and then transferring onto the final substrate using a process called "pick and place." The crystals can then be lifted off the original substrate using a sticky tape, and then transferred onto the final substrate using a special tool. This improves the quality of devices produced.

Applications

1. Phototransistors are electronic devices that can detect light and convert it into an electrical signal. They have a wide range of applications in various fields, some of which are listed below:
2. Optical Sensing: Phototransistors are used in optical sensing applications such as light detection, color recognition, and proximity sensing. They are commonly used in automatic brightness control systems, streetlight control, and ambient light sensing applications.
3. Communication: Phototransistors are widely used in fiber-optic communication systems as photodetectors to convert optical signals into electrical signals.
4. Imaging: Phototransistors are used in imaging applications such as cameras, photocopiers, and scanners. They detect light reflected from an object and convert it into an electrical signal to produce an image.
5. Medical Devices: Phototransistors are used in medical devices such as pulse oximeters, blood glucose monitors, and oxygen sensors. They detect light transmitted through or reflected from a sample and convert it into an electrical signal to monitor vital signs and health parameters.
6. Industrial Automation: Phototransistors are used in industrial automation applications such as machine vision, robotics, and quality control. They can detect changes in light intensity or color and trigger a response to control the process.
7. Automotive: Phototransistors are used in automotive applications such as automatic headlights, rain sensors, and lane departure warning systems. They can detect changes in ambient light or weather conditions and trigger a response to enhance safety and comfort.

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