1.4: Effect of Monochromatic Illumination on Organic Polymer Thin-film Transistors

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Abstract

We present our study of the effects of monochromatic illumination on the electrical performance of organic polymer thin-film transistors (OP-TFTs). In the case of monochromatic light that is strongly absorbed by the polymer, the drain current of a device biased in the OFF-state is significantly increased. Light that is not strongly absorbed by the polymer has little effect on the electrical performance of the OP-TFTs. The OFF-state drain current can be increased by several orders of magnitude depending on the intensity and wavelength of the incident illumination. A relatively smaller effect on the drain current in the strong accumulation regime is observed, even for strongly absorbed illumination. The threshold voltage is decreased and the subthreshold slope is increased by the illumination. We explain these effects in terms of the photo-carrier generation in the channel region of the device.

1. Introduction

Organic thin-film transistors (OTFTs), based on semiconducting organic materials, both small molecule and polymer, have shown promise for use in various electronic and optoelectronic applications [1,2]. Possible applications include broad-area flat panel displays and arrays of photodetectors for image sensing [3,4]. Various types of all-organic displays have been demonstrated by several research groups [6-9]. It is important to understand the effect of illumination on the operation of OTFTs because in many applications, the OTFT will either be integrated with light-emitting devices (as part of the driving circuitry) or it will be used to detect light itself. The TFT structure is also a useful tool that allows us to investigate the charge carrier dynamics in the active region (in this case, the organic material). Studies of the effects of illumination on the operation of OTFTs help to investigate the physics of carrier generation and transport in these materials. In this paper, we present the results of our investigation of the electrical performance of our organic polymer thin-film transistors (OP-TFTs) under monochromatic illumination. We show the dependence of the electrical performance on illumination wavelength and intensity.

2. Experimental Details

2.1 Device Structure

Figure 1 shows a cross-section of the device we have used. The device is in an inverted, co-planar configuration with a defined gate and gate-planarization that we have previously described [10,11]. The source and drain contacts are sputtered indium tin oxide (ITO). Plasma enhanced chemical vapor deposition (PECVD) hydrogenated amorphous silicon nitride (a-SiN:H) was used as one layer of gate insulator and benzocyclobutene (BCB) was used as the gate-planarization layer and a second gate insulator layer. Chromium (Cr) was used for the patterned gate electrode. The organic semiconductor F8T2 [poly(9,9-dioctylfluorene-co-bithiophene) alternating copolymer from The Dow Chemical Company] was spin-coated from mesitylenes solution to be used as the active layer (channel region) of the device. Typical channel widths and lengths of our devices are 56 to 116μm and 6 to 56μm, respectively.

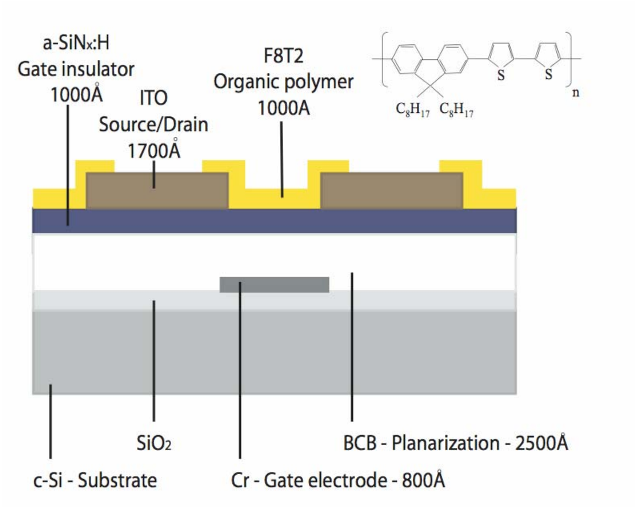

Figure 1. Cross-section of device and chemical structure of F8T2.

2.2 Device Operation and Parameter Extraction

Linear regime transfer characteristics of a typical device with the structure shown in Figure 1, are shown in Figure 2 and 3. From this figure, we can see that our devices show p-channel field-effect transistor operation. From the linear regime transfer characteristics we can extract the linear regime field-effect mobility and threshold voltage using the following equation, based on the MOSFET gradual channel approximation (for low drain-to-source voltage) [12]:

$$I_D = -\mu_{FElin} C_{ins} \frac{W}{L}(V_{GS} - V_{Tlin})V_{DS} \qquad (1)$$

where $\mu_{FE\ lin}$ is the linear regime field effect mobility (cm^2/Vs), C_{ins} is the gate insulator capacitance per unit area (F/cm^2), W is the channel width of the device, L is the channel length of the device, V_{GS} is the gate-to-source bias, $V_{T\ lin}$ is the linear regime

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threshold voltage and V_{DS} is the drain-to-source bias. We also extract the subthreshold swing from the linear regime transfer characteristics using the following equation:

$$S = \left(\frac{dLog(I_D)}{dV_{GS}} \right)^{-1} \tag{2}$$

where S is the subthreshold swing (V/decade) and the other parameters have been defined above. Typical values of the linear regime field-effect mobility, threshold voltage, and subthreshold swing are 4×10^{-3} cm^2/Vsec, -25V, and 3.0V/decade respectively.

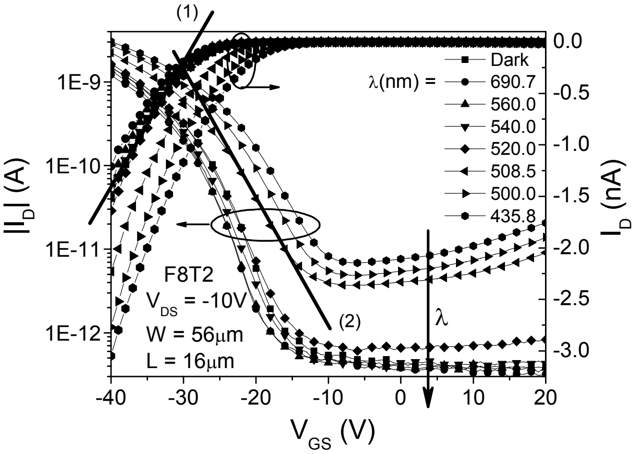

Figure 2. Linear regime transfer characteristics of OP-TFT in the dark and under monochromatic illumination at various wavelengths. The straight lines are fits using equations (1) and (2).

2.3 Experimental Set-up

The OP-TFT transfer characteristics (I_D vs. V_{GS}) and output characteristics (I_D vs. V_{DS}) were measured in the dark and under various levels of monochromatic illumination at room temperature using a Karl Suss PM8 probe station, an HP4156 semiconductor parameter analyzer, and Interactive Characterization Software (Metrics). A 200W mercury xenon (HgXe) arc lamp was used as the illumination source. The incident wavelength and light intensity from the HgXe lamp were controlled using optical interference filters (with FWHM < 10nm) and neutral density filters, respectively, providing wavelengths in the range of 435.8 to 690.7nm and intensities in the range of 0 to 0.13mW/cm^2 at the sample surface. The F8T2 polymer film strongly absorbs light in the range of wavelengths from 400 to 525nn. The filtered light from the HgXe source was passed through a Mitutoyo microscope and focused to a spot size approximately equal to the area of the device. The entire channel of the device was illuminated.

Several comments should be made about the nature of these experiments. It is well known that OP-TFTs exhibit shifts (sometimes severe) in their electrical characteristics due to measurement and other stresses (such as illumination). In order to compensate for these shifts, while allowing the experiments described below to be carried out in a reasonable manner, we used one device per experiment and annealed it between each measurement. This procedure removed the illumination-induced shifts and allowed the electrical characteristics of the device to return to their original state before proceeding with the next measurement. The annealing process we used was 15min at 90°C in a vacuum oven. The devices do exhibit full recovery at room temperature, however the elevated temperature speeds up the recovery.

3 Results

3.1 Dependence on Wavelength

The effect of monochromatic illumination on the electrical performance of our OP-TFTs has been investigated by measuring the transfer characteristics of a device in the dark and under monochromatic illumination at various wavelengths. Figure 2 shows the linear regime transfer characteristics of an OP-TFT illuminated at 7 wavelengths from 435.8 to 690.7nm with a constant optical flux of 1.3×10^{14} photons/cm^2s. From this figure, we can see that light with energy less than 2.4eV (corresponding to the optical gap of the F8T2 films we used) has little effect on the transfer characteristics, while light with higher energy (from 2.4 to 2.8eV) has a much larger effect.

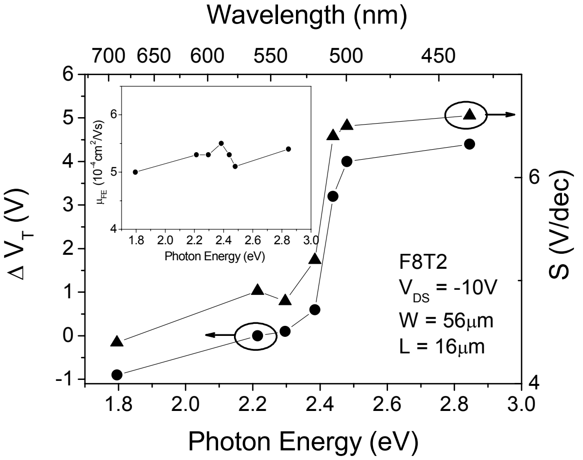

Figure 3. Change in threshold voltage and subthreshold swing [extracted from Figure 2 using equations (1) and (2)] versus photon energy for a device which was annealed between each measurement. Inset is field-effect mobility [extracted from Figure 2 using equation (1)] versus photon energy.

We extracted the field-effect mobility, threshold voltage, and subthreshold swing from the curves in Figure 2 using equations (1) and (2). The change in threshold voltage due to illumination and the subthreshold swing under illumination are shown in Figure 3. From this figure, we can see that the change in threshold voltage and the subthreshold swing increase for the strongly absorbed light, while the weakly absorbed light causes little change in the electrical characteristics. The field-effect mobility shows little variation with photon energy. We can explain these effects by photo-carrier generation in the polymer channel region. Strongly absorbed light causes the formation of an exciton (bound electron-hole pair) in the polymer. After formation, this exciton travels to a dissociation site (such as a defect, impurity, or surface) and dissociates into free carriers. These free carriers are separated by the source-to-drain field and move in opposite directions, to be collected at the drain or source electrodes. Some of the electrons become trapped by positively charged traps, thereby neutralizing the trap. This, in turn, reduces the threshold voltage, as we have observed for strongly absorbed light and is shown in Figure 3. Further evidence that carrier trapping is taking place is provided by the fact that we are able to shift the transfer characteristics back to the original state by annealing the devices at elevated temperature. The trapped carriers are detrapped faster at higher temperatures, causing the threshold voltage to return to its original value. The observed increase in subthreshold slope is caused by an increase in the conductivity of the channel due to the photo-carrier generation process. For the case of strongly absorbed light, the illumination provides a second means of controlling the density of carriers in the channel. Therefore, the control of the gate electrode over the channel is reduced, as evidenced by the increase in subthreshold swing. The field-effect mobility is not affected by the illumination. This shows that the light has negligible effect on the structure nor on the morphology of the polymer film, for which a change in the charge transport properties would be expected.

The drain current of a device under illumination (taken from Figure 2 at $V_{GS} = +5V$) and the absorption spectrum of the F8T2 film versus the photon energy of the incident illumination are shown in Figure 4. We can see from this figure that the OFF-state drain current under illumination follows the absorption spectrum. This is consistent with the proposed photo-carrier generation process in F8T2.

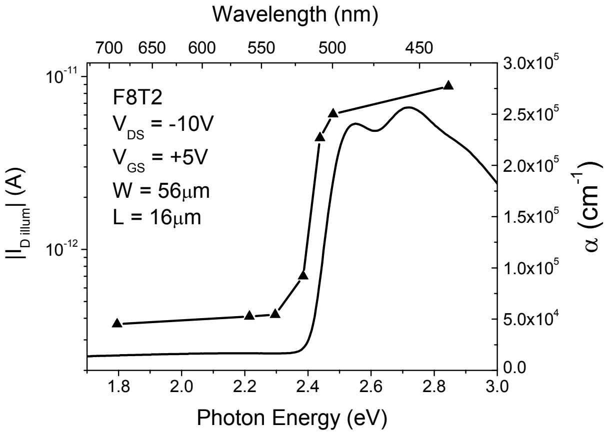

Figure 4. Drain current of OP-TFT illuminated at different wavelengths for constant optical flux and absorption coefficient of F8T2 versus photon energy.

3.2 Dependence on Intensity

To investigate the effects of monochromatic illumination further, we again measured the transfer characteristics of an OP-TFT under illumination at 460nm, at different intensities. 460nm was chosen because it lies in the absorption peak of F8T2 as can be seen from Figrure 4. We can see, from Figure 5, that the effects of the illumination increase (i.e. the OFF-state drain current increases and the threshold voltage is reduced) as the intensity is increased, similar to broadband illumination [11]. This is the expected effect, since as the intensity is increased, more photons are absorbed in the polymer film, thereby generating more charge carriers. The increased number of electrons causes a greater reduction of the threshold voltage, while the increased number of holes causes the channel to have a higher conductivity.

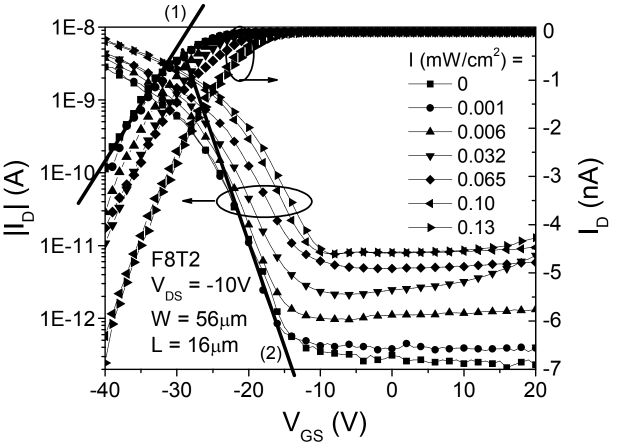

Figure 5. Linear regime transfer characteristics of OP-TFT in the dark and illuminated at different intensities at a wavelength of 460nm. The straight lines are fits using equations (1) and (2).

We have extracted the field-effect mobility, threshold voltage and subthreshold swing from Figure 5 using equations (1) and (2). The dependence of the change in threshold voltage and subthreshold swing on illumination intensity are shown in Figure 6. As stated above, we clearly see that the threshold voltage is reduced and the subthreshold swing increases as the intensity of the monochromatic illumination is increased. We observe little dependence of the field-effect mobility on the intensity of the illumination (for the range we have used here). This is again evidence that the illumination doesn't change the structure or morphology of the polymer film.

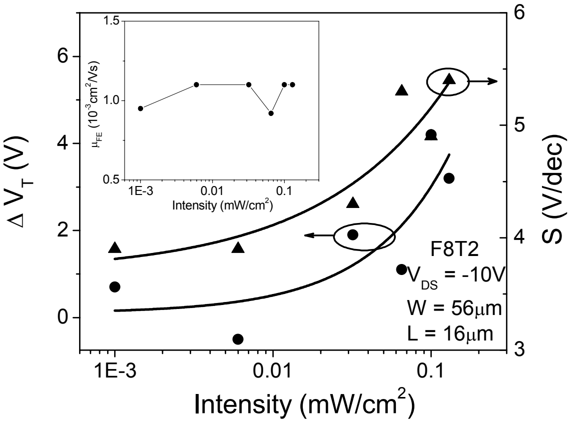

Figure 6. Change in threshold voltage and subthreshold swing [extracted from Figure 5 using equations (1) and (2)] of OP-TFT illuminated at different intensities at a wavelength of 460nm. Lines are provided as guides to the eye. Inset is field-effect mobility [extracted from Figure 5, using equation (1)] of same device.

The gate bias dependence of the ratio of drain current of an illuminated device to the drain current in the dark is shown in Figure 7 [10]. This ratio increases from approximately unity in the strong accumulation to several orders of magnitude in the OFF-state. In the OFF-state, this ratio is relatively independent of the gate bias. In the strong accumulation regime, the density of accumulated carriers is due mainly to the applied gate bias, as opposed to the illumination (for the range of intensities use here). In the OFF-state, the illumination is the major cause of free carriers in the channel, and we can see that the ratio is strongly dependent on the incident intensity. In fact, the ratio exhibits a power law dependence on the intensity. This is shown in Figure 8 and obeys the following equation:

$$\frac{I_{D\,Illum}}{I_{D\,Dark}} \propto I^{\gamma} \qquad (3)$$

where I is the incident intensity and γ is a material dependent parameter with a value of 0.6 here.

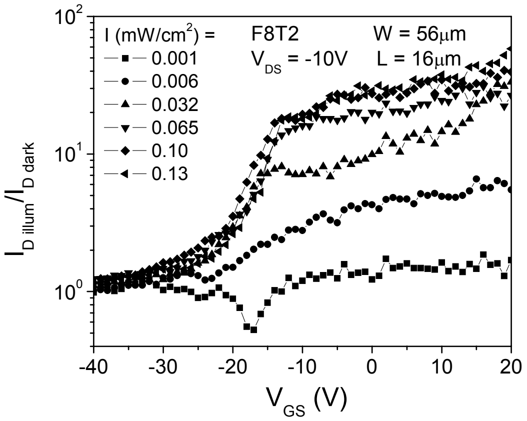

Figure 7. Ratio of drain current under illumination to drain current in the dark versus V_{GS} for OP-TFT illuminated at different intensities at a wavelength of 460nm.

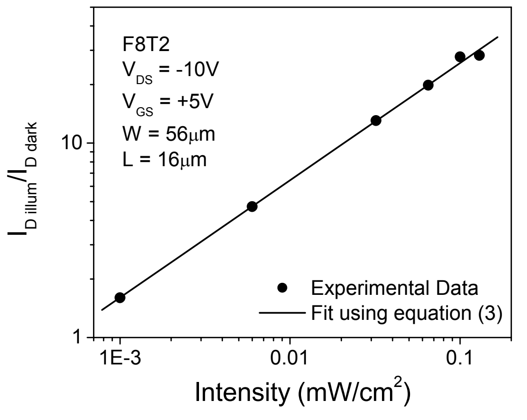

Figure 8. Ratio of drain current under illumination to drain current in the dark versus incident intensity for OP-TFT illuminated at different intensities at a wavelength of 460nm.

4. Conclusions

We have studied the electrical performance of our OP-TFTs under monochromatic illumination. In each case, the major effect of the absorbed light is a significant increase in the OFF-state drain current. For a device in strong accumulation, the drain current is relatively unchanged. The effects on the OFF-state drain current, threshold voltage, and subthreshold swing are strongly dependent on the wavelength and intensity of the incident illumination. Weakly absorbed light, with energy below the optical-gap, has almost no effect on the electrical characteristics of the OP-TFT. These effects have been explained in terms of the photo-carrier generation process. In the OFF-state, the response of the device to the illumination is gate voltage independent. Therefore, when operated in the OFF-state, this device could be used as a low power photosensor. In all cases, we have observed full recovery of the device after the illumination is removed. The recovery process is greatly enhanced by subjecting the devices to elevated temperature to anneal the polymer film. A study of these recovery processes is currently underway.

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