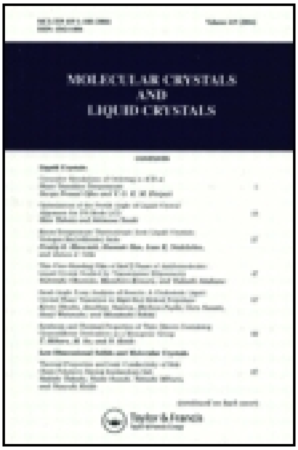

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Effect of Electrode Area on High Speed Characteristics over 1 MHz of Poly(3-hexylthiophene-2,5-diyl) Diode with Inkjet-Printed Ag Electrode

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We report the electrode-area dependence of the high-frequency characteristics of polymer diodes fabricated on a flexible poly(ether sulfone) (PES) substrate with inkjet-printed Ag electrode as an anode. Active layer of poly(3-hexylthiophene-2,5-diyl) (P3HT) layer was spin-coated on the Ag anode and then Al cathode was evaporated on the P3HT layer. The rectifying characteristics of P3HT diodes with different area sizes were compared, and their frequency response was analyzed for the sinusoidal input of different frequencies. The diode with smaller area exhibited higher breakdown voltage and operating frequency: The diode with a small area of 0.05 mm^2 *showed a 3 dB point at 1.8 MHz.*

Keywords: electrode area dependence; flexible polymer diode; high-frequency operation; inkjet printing

INTRODUCTION

Polymer electronic devices can be fabricated on flexible substrates through low-temperature solution processes such as spin coating and inkjet printing [1,2]. In particular, inkjet printing has advantages of direct patterning, low material wastage and low cost compared with vacuum evaporation [3,4]. Thus, polymer devices fabricated by inkjet printing can be an attractive alternative for

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low-cost, high-performance flexible electronic applications such as radio-frequency identification (RFID) tag or displays. In addition, high speed operation is an important issue for transistor or diodes.

Polymer diode based on inkjet-printed layer of poly (3-hexylthiophene-2,5-diyl) (P3HT) was reported, but its diode characteristics was not good enough and frequency response was not measured [5]. There were other reports of polymeric or organic diodes with good rectifier characteristics, but they were not fabricated through solution-processes nor flexible [6–8]. In this work, we fabricated the P3HT diodes with inkjet-printed Ag anodes on flexible poly(ether sulfone) (PES) substrates. We found that the diode with smaller area exhibited higher breakdown voltage and operating frequency.

EXPERIMENTAL

Fabrication of P3HT Diode

The P3HT polymer diode was fabricated in sandwich geometry using inkjet-printed Ag electrode as the anode and Al as the cathode, as shown in Figure 1. The silver ink with a metal content of 34.68%, purchased from ANP, was patterned using an inkjet printer (UJ200, Unijet) on hexamethyldisilazane (HDMS)-treated PES substrate which was maintained at 100°C. After inkjet-printing, the Ag electrode was cured at 120°C for 1 h in an N_2 atmosphere. Thickness of silver electrodes was about 2000 Å. On top of the Ag anodes, P3HT layer was spin coated from 2-wt % solution of regioregular P3HT (Sigma-Aldrich) in monochlorobenzene (MCB) with spin rate of 500 rpm for 30 s and then dried at 120°C for 30 min in an N_2 atmosphere. Under this condition, we obtained

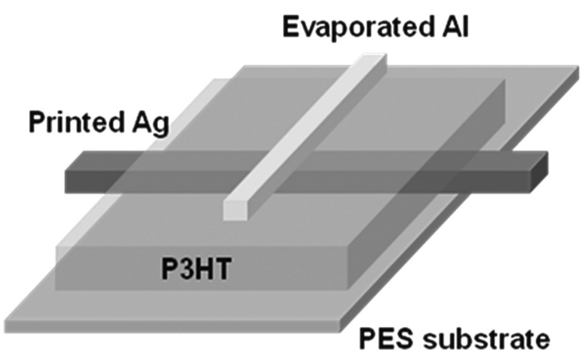

FIGURE 1 Schematic diagram of the structure of a P3HT diode.

P3HT thickness of about 1000 Å. Finally, Al cathodes (thickness ~ 1000 Å) were evaporated at the pressure $\sim 5 \times 10^{-6}$ Torr. The overlap area of Ag and Al electrodes were 0.050 mm^2 and 0.225 mm^2.

Measurement of Diode Characteristics

The current density vs. input voltage (J-V) characteristics were measured using a source measure unit (Keithley 236). For the characterization of the frequency response, a sinusoidal input voltage was applied to the diode using a function generator (Tektronix AFG310) and the output voltage was measured with an oscilloscope (Tektronix TDS5054B).

RESULTS AND DISCUSSION

Figure 2 shows the current density vs. voltage characteristics and breakdown voltages of P3HT diodes with different areas (0.05 mm^2 and 0.225 mm^2). The J-V characteristics of P3HT diodes shown in Figure 2(a) show the rectifying behavior with the forward bias defined as the positive voltage applied to the Ag electrode. The diode with the larger area (0.225 mm^2) shows an order of magnitude lower current density in the negative bias voltage compared to the diode with the smaller area (0.050 mm^2), while both diodes show similar current density in the positive bias voltage. Therefore, the rectification ratio (current density ratio at the same absolute value of voltage) is larger for the P3HT diode with the larger area. Table 1 compares the rectification ratio for both diodes. We consider that poor interfacial property between Ag and P3HT may cause lower rectification ratio for the small-area diode. Since the width of an Ag electrode was similar to the diameter of just one ink droplet for the device with area of 0.050 mm^2, the P3HT layer may not be formed uniformly on the narrow Ag electrode.

Although the diode with larger electrode area shows better rectifying characteristics, the breakdown voltage is lower. Figure 2(b) shows that breakdown occurs at 9.8 V for the 0.225 mm^2 device while it occurs at 13.2 V for the 0.05 mm^2 device. This difference in the breakdown voltage can be mainly attributed to different heat dissipation capability [9]. For the small area device, Joule heat can be effectively dissipated from the active device area to surrounding layers, i.e., electrodes, and substrate. However, heat dissipation can be less effective for the large area device. The current density of the small area device, therefore, reaches the highest point at higher voltage compared with the large area device.

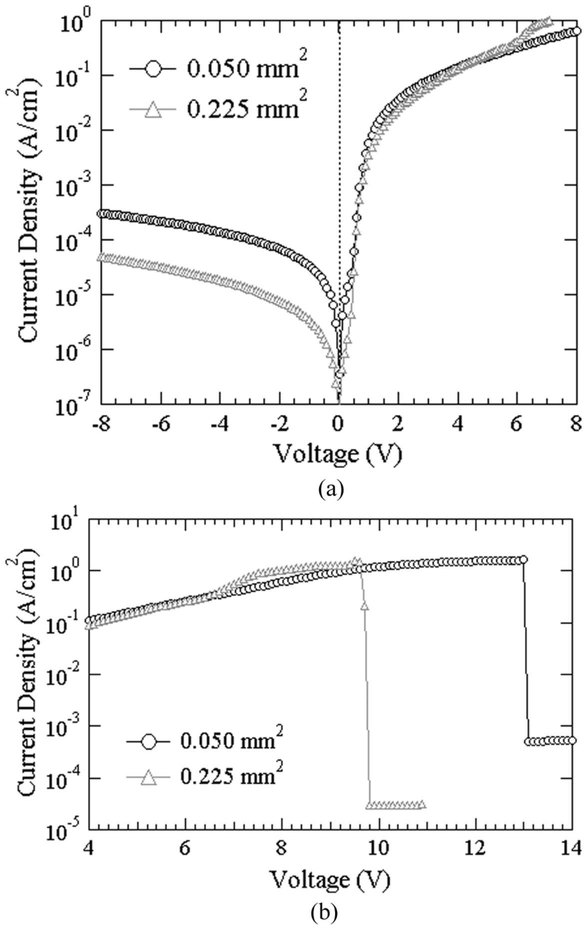

FIGURE 2 (a) Current density vs. voltage characteristics and (b) breakdown voltages of P3HT diodes with different electrode areas: $0.050\,mm^2$ (circle) and $0.225\,mm^2$ (triangle).

TABLE 1 Rectification Ratio of P3HT Diodes with Different Active Device Areas

Diode area	$0.050\,mm^2$		$0.225\,mm^2$
$\|V+\| = \|V-\|$	5 V	10 V	5 V
$\|I+\|$ (μA)	110	610	550
$\|I-\|$ (μA)	0.089	0.21	0.055
Rectification Ratio	1200	2900	9900

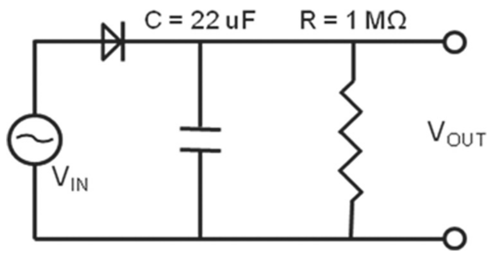

FIGURE 3 Circuit diagram for the frequency response measurement of the P3HT rectifier.

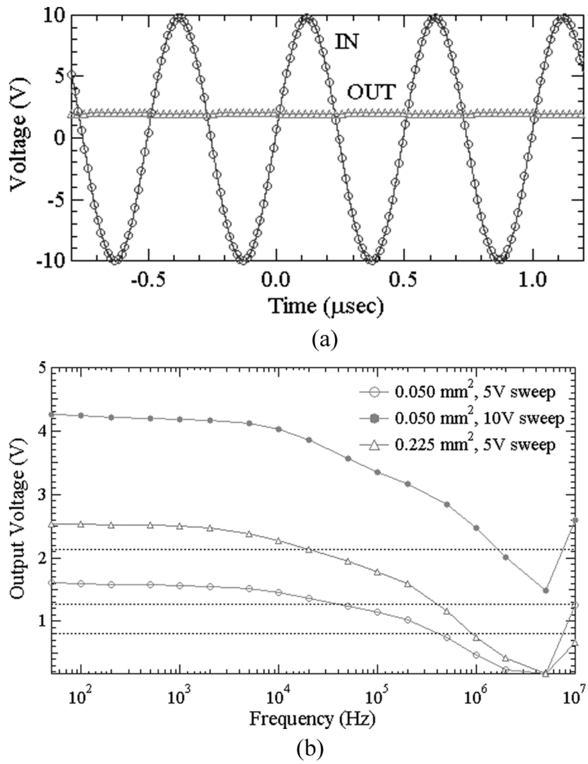

FIGURE 4 (a) The rectified output voltage of the P3HT diode with area of 0.050 mm^2 for the sinusoidal.input voltage of 10 V at 2 MHz. (b) Output voltage vs. frequency for the P3HT diodes. The horizontal dash lines indicate 3 dB points of diodes.

Because of the difference of breakdown voltage, input signal with high amplitude over 10 V can be applied only for the small area device. For rectifying characteristics measurement, sinusoidal input wave of the peak-to-peak voltage of 5 V (both devices) and 10 V (0.050 mm^2 device only) was applied to the input terminal of P3HT diodes in the circuit of Figure 3. Figure 4(a) shows the rectified output voltage for the sinusoidal.input of 10 V at 2 MHz in the P3HT diode with an area of 0.05 mm^2. Figure 4(b) shows the variation of rectified output voltage with frequency for P3HT diodes with the area of 0.050 mm^2 and 0.225 mm^2. The output voltage decreases gradually at the high frequency range. For the 5 V peak-to-peak input, both devices show almost same 3 dB point ($\sim$500 kHz) but the output voltage of the larger diode (0.225 mm^2) is almost 2 times larger than the small diode (0.050 mm^2). For the diode with the area of 0.050 mm^2, the 3 dB point increases when the input voltage increases. Figure 4(b) shows that its 3 dB point is 1.8 MHz and It works well as a rectifier when input frequency is 2 MHz as shown in Figure 4(a).

CONCLUSIONS

We demonstrate that P3HT diodes with inkjet-printed Ag anodes fabricated on flexible PES substrate shows a good rectifying behavior and works well in high frequency region over 1 MHz. The operating frequency of the diode increases as the active device area decreases because high input voltage can be applied. The diode with a small area of 0.05 mm^2 showed a 3 dB point at 1.8 MHz.

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