Estimation Of Charge Transport Parameters And Equivalent Circuit For Poly Alkyl Thiophene Field-Effect Transistors

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Abstract. The small signal ac response is measured across the source-drain terminals of organic field-effect transistors (OFET) under dc bias to obtain the equivalent circuit parameters of poly(2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-*b*]thiophene) (PBTTT) and poly(3-hexyl thiophene) (P3HT) based devices. The numerically simulated response based on these parameters is in good agreement with the experimental data for PBTTT-FET except at low frequencies, while the P3HT-FET data show significant deviations. This indicates that the interface with the metal electrode is rather complex for the latter, involving additional circuit elements arising from contact impedance or charge injection processes. Such an investigation can help in identifying the operational bottlenecks and to improve the performance of OFETs.

Keywords: Impedance, PBTTT, P3HT, organic field-effect transistor, contact resistance
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INTRODUCTION

Organic field-effect transistors (OFETs) based on semiconducting polymers have attracted considerable attention due to their unique advantages, which include low cost of fabrication, large area, ease of processing and mechanical flexibility.[1,2] Solution-processible organic semiconductors with high mobilities and air-stability allow not only a reasonable performance of OFETs but also the possibility of processing and operating all polymer devices under ambient conditions.[3,4] Impedance characterization of these devices can provide insight into the transport mechanism occurring at the bulk and the interfaces, and from this the circuit elements can be identified. However, only a few results have been reported on the ac impedance analysis of OFETs so far, while the dc characteristics have been widely investigated in this field.[5,6]

In the present work, we report the low frequency ac impedance measurements across the source-drain terminals of OFETs under dc bias, with poly(2,5-bis(3-tetradecylthiophen-2-yl)thieno[3,2-*b*]thiophene) (PBTTT) and poly(3-hexyl thiophene) (P3HT) as active materials. This is used to determine the equivalent circuit of the FETs, especially to identify the role of interfaces.

EXPERIMENTAL

The PBTTT-OFET was fabricated in bottom-gate, bottom contact configuration with heavily doped n-type silicon served as the back gate, covered with 400 nm silicon nitride as gate dielectric. The PBTTT solution in 1,2-dichlorobenzene was deposited by spin coating, followed by annealing at 150° C to induce the formation of liquid-crystalline phase. The details of the device fabrication and schematic can be found elsewhere.[6] The P3HT-OFET was fabricated in the top-gate geometry. The source-drain Au contacts were deposited at first on a clean glass substrate to form a channel 30-40 µm apart. The deposited P3HT film was annealed to 120° C prior to spin-coating of the PMMA dielectric layer (~ 1 µm).

The I-V characteristics of the devices were measured using Keithley source-meters (Model Ke-2400). A lock-in amplifier based technique was used to find the low frequency ac impedance across the source-drain channel (SDC) of the field-effect transistors under dc bias. In this method an appropriate dc bias (V_{DS}) together with a superposed ac small

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signal (50 mV) is applied across the SD electrodes of the OFET and the complex ac voltage response are measured using a lock-in amplifier (SR-830) and a resistor-divider.[5] Further the ac measurements were carried out at 200 K in a custom made cryostat.

RESULTS AND DISCUSSIONS

The transfer characteristics of the PBTTT and P3HT OFETs are plotted in Fig. 1(a) and 1(b), respectively. The transfer characteristics suggest hole transport in both the systems. The room temperature on-off ratio of the devices is 600 for the PBTTT-OFET and 450 for the P3HT-OFET. The mobility of PBTTT device (0.1 cm^2/Vs) is found to be slightly higher compared to that of P3HT device (0.065 cm^2/Vs), at room temperature, this may be due to the larger grain size.[7]

The impedance characterization of these devices under dc bias is essential for a comprehensive understanding of the equivalent circuit, and to develop theoretical models for injection and transport in polymer devices. The frequency dependence of the phase φ_O at different temperatures is shown in Fig. 2. The negative phase angle increases in magnitude while increasing the frequency. The impedance data are analyzed according to the electrical network theory and described by Bode Plot analysis as discussed elsewhere.[5]
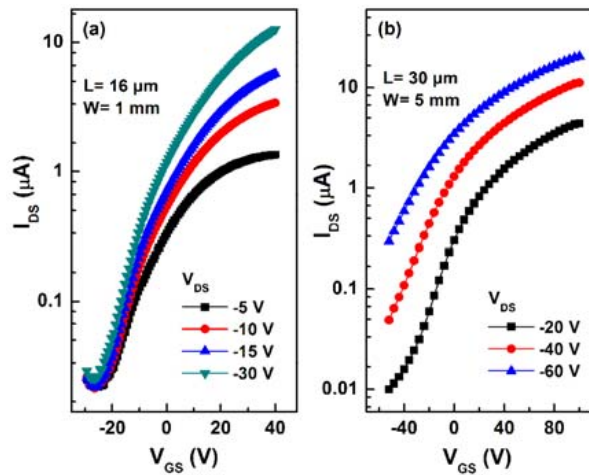

FIGURE 1. Transfer characteristics of (a) PBTTT-OFET and (b) P3HT-OFET.

The frequency response of the system $G(\omega)$ is measured by the complex source-drain impedance $Z_O(\omega)$, under assumptions of low-level input and linearity of system response. It is known that, time-invariant linear systems (i.e., the frequency response is independent of the amplitude and phase of the input

signal) often follow ordinary linear differential equations (OLDE) of the first order and its transfer function in polar form is as follows:

$$|G(\omega)| = \kappa / [1 + (\omega / \omega_c)^2]^{1/2}, \qquad (1)$$

$$\varphi_O(\omega) = \tan^{-1}\left(-\omega / \omega_c\right), \qquad (2)$$

where κ and ω_c are system dependent constants. Using the network theory developed by Bode, the above Eq. (1) is represented in units of decibels [i.e., $20\log|G(\omega)|$], and is plotted as a function of $\log\omega$, as shown in the insets of Fig. 2(a) and 2(b). The high frequency asymptote has a slope of nearly -20 db/decade, as known in linear time invariant system that follows OLDE of first order. The corner frequency ω_c could be determined by plotting φ versus ω (or f) and from such a plot the value of ω_c at $\varphi = 45^o$ [see Eq. (2)] can be obtained. Substituting the value of ω_c and $|G(\omega_c)|$ in Eq. (1), the value of κ can be estimated. Thus Bode plots can be used to determine the system dependent constants, κ and ω_c, in the analysis of the equivalent circuits of FETs.
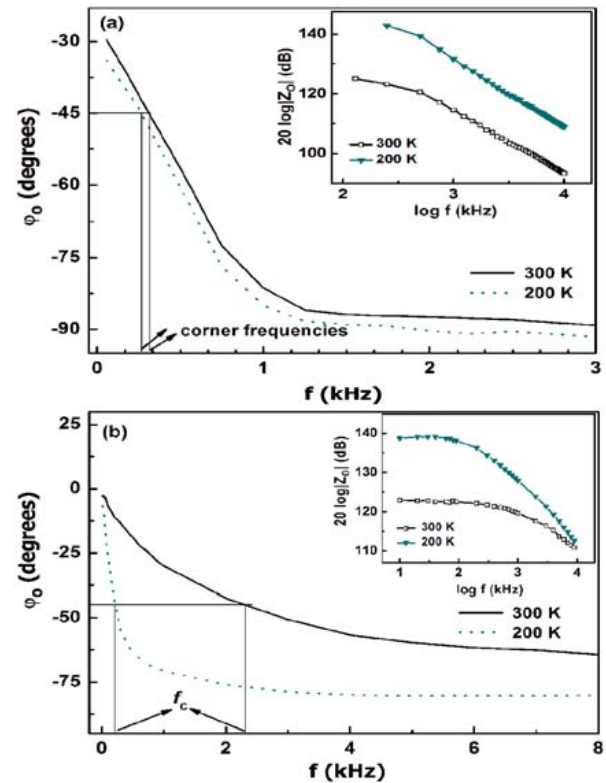

FIGURE 2. (a) Phase vs frequency for PBTTT-OFET, the corner frequency f_c is the frequency value at -45^0. Inset: Bode plot of output impedance. (b) Phase vs frequency for P3HT-OFET. Inset: Bode plot of output impedance.

The ac equivalent circuit of the SDC is determined from the complex form of impedance expressed in

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terms of complex current $I(\omega)$ and voltage $V(\omega)$, which upon simplification could be written as,

$$I(\omega) = (1/\kappa)\, V(\omega) + j\, \omega[1/(\kappa\omega_c)]\, V(\omega). \qquad (3)$$

Eq. (3) resembles the sum of current passing through a parallel network of R and C, for which the Kirchoff's current law yields, $R = \kappa$ and $C = 1/(\kappa\omega_c)$. Using these values and Eq. (1), the numerical form of $|Z_O(\omega)|$ can be generated, and it is plotted along with measured

polymer and metal. Both contact impedance and charge injection processes may be responsible for the presence of the additional circuit parameters. And the deviation becomes more significant at low temperatures as the contact resistance increases with lowering the temperature.

TABLE 1. The equivalent circuit parameters for PBTTT and P3HT OFETs.

Active material	ω_c (300 K) kHz	ω_c (200 K) kHz	R (300 K) MΩ	R (200 K) MΩ	C (300 K) pF	C (200 K) pF
PBTTT	0.30	0.26	1.68	13.56	313.9	45.6
P3HT	0.23	0.22	1.02	8.84	68.6	81.1

data at different temperatures for PBTTT [Fig. 3(a)] and P3HT [Fig. 3(b)] OFETs.

 In the case of PBTTT the numerically simulated curve matches with the measured data except at low frequencies. Table 1 summarizes the equivalent circuit parameters for both OFETs. The low frequency deviations to the channel impedance are possibly due to the contributions from contact resistance (R_c) and contact capacitance (C_c) and the deviations are modeled with additional parallel R_c-C_c element in series with the output resistance R as shown in the inset of Fig. 3(a).[5,6] The contact resistance increases upon lowering the temperature[7] and a significant low frequency deviation is observed at 200 K and thereby limiting the charge transport at low temperatures.
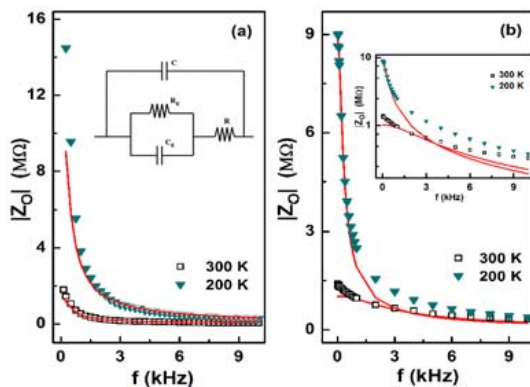

FIGURE 3. (a) Output impedance $|Z_O|$ vs f for PBTTT-OFET at different temperatures. Inset shows the equivalent circuit. (b) Output impedance $|Z_O|$ vs f for P3HT-OFET at different temperatures. Inset shows the deviation. Solid lines are the simulated curve derived from the equivalent circuit parameters.

 P3HT device data show significant deviations from the numerically simulated response at all temperatures, as shown in the inset of Fig. 3(b). The P3HT-OFET source drain channel likely involves additional circuit elements that may be correlated with the interface of

CONCLUSIONS

 In summary, the ac equivalent circuit parameters of the source drain channel for PBTTT and P3HT polymeric field effect transistors are determined, as summarized in Table 1. The numerically simulated response based on these parameters is in good agreement with the experimental data for PBTTT-OFET except at low frequencies, which is modeled as the contributions arising from the contact impedances. The P3HT-OFET data show significant deviations indicating that the additional circuit elements from contact impedance or charge injection processes play a major role.

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REFERENCES

1. G. Horowitz, *Adv. Mater.* **10,** 365 (1998).
2. C. D. Dimitrakopoulos and P. R. L. Malenfant, *Adv. Mater.* **14,** 99 (2002).
3. S. R. Forrest, *Nature* **428,** 911 (2004).
4. H. Sirringhaus, *Adv. Mater.* **17,** 2411 (2005).
5. M. Jaiswal and R. Menon, *Appl. Phys. Lett.* **88,** 123504 (2006).
6. C. S. S. Sangeeth, M. Jaiswal, and R. Menon, *Appl. Phys. Lett.* **95,** 093308 (2009).
7. I. McCulloch, M. Heeney, C. Bailey, K. Genevicius, I. MacDonald, M. Shkunov, D. Sparrowe, S. Tierney, R. Wagner, W. Zhang, M. L. Chabinyc, R. J. Kline, M. D. McGehee, and M. F. Toney, *Nat. Mater.* **5,** 328 (2006).