A Static Model for Electrolyte-Gated Organic Field-Effect Transistors

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A static model for electrolyte-gated organic field effect transistors

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***Abstract*—We present a DC model to simulate the static performance of electrolyte-gated organic field effect transistors. The channel current is expressed as charge drift transport under electric field. The charges accumulated in the channel are considered being contributed from voltage-dependent electric double layer capacitance. The voltage dependent contact effect and short channel effect are also taken into account in this model. A straightforward and efficient methodology is presented to extract the model parameters. The versatility of this model is discussed as well. The model is verified by the good agreement between simulation and experimental data.**

***Index Terms*—static model, electric double layer capacitance, field effect transistors, parameter extraction, polymer electrolyte**

I. Introduction

POLYMER semiconductors have attracted highly notable attention and been widely studied for their potential applications in electronic devices and circuits, since the discovery of electrical conduction in plastics [1]. Towards flexible, low-cost, and large-area integrated circuits, polymer transistors have been known as an ideal candidate with their unique features, such as printability and tunable functionality [2]. Among all various transistors based on polymer materials, field effect transistors are the most promising and deeply explored, due to their similarity with traditional silicon thin-film transistors [3]. However, it has been quite challenging to make polymer or organic field effect transistors work at low voltage with conventional silicon dioxide [4] or polymer insulator [5] as gate dielectric. Therefore, tremendous effort has been devoted to the engineered of gate dielectrics, in order to lower the control voltage for field effect transistors [6~10]. The solutions include but are not limited to high-κ inorganic materials [6, 7], self-assembled molecular monolayer [8], and ion-gel gate [9, 10]. Particularly, the devices with ion-gel gate dielectric have an excellent turn-on conductance at low operating voltage (< 2 V), but suffer from extremely slow switching speed (approximately in seconds) [10], which is comparable with electrochemical transistors [11, 12].

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Recently, a polymer electrolyte (copolymer of vinyl phosphonic acid and acrylic acid, P(VPA-AA)) has been demonstrated as a gate dielectric in polymer field effect transistors, achieving an operating voltage less than 1 V [13~15]. With the capability to form electric double layer capacitors (EDLCs), P(VPA-AA) indicates a new generation of organic field effect transistors (OFETs), named electrolyte-gated organic field effect transistors (EGOFETs) or EDLC-OFETs. The formation of EDLCs is a complex electrochemical process, which results nonlinear and voltage-dependent capacitance, and pretty crucial to device's performance. So far, no device model, taking this effect into account, has been published.

Here, we propose a model to describe the static electrical behaviors of EGOFETs. The model is based on charge drift in presence of accumulated charges in the channel, covering subthreshold, linear and saturation regimes of the EGOFETs. The charges accumulated are contributed from the field effect caused by electric double layer capacitance dependent voltage biased. Dynamic equilibrium of the electrochemical process in EDLCs is discussed to interpret the nonlinearity and voltage dependence of the capacitance. Contact barrier dependent on gate voltage and short channel effect are taken into account in this model. The extraction of physical parameters from experimental results is demonstrated. With the extracted parameters, good agreements have been found between model simulation and experimental data.

II. EDLCs and EGOFETs

With huge capacitance and high charging rate, EDLCs, also known as supercapacitors, have been widely investigated as energy-storage devices [16]. The extraordinary capacitance per unit area of EDLCs is up to 500 μF/cm^2 [17], over three orders higher in magnitude than that of 100-nm-thick hafnium oxide (κ=25, 0.22 μF/cm^2) [18], which is the best known high-κ dielectric applied in traditional silicon-based metal-oxide-semiconductor field effect transistors. This implies that EDLC is an efficient solution to lower the operating voltages for organic or polymer field effect transistors. Driven by potential bias, the anions/cations in the electrolyte are attracted to the charged electrode, forming an electric double layer, composed of a Helmholtz layer and a diffuse layer, schematically shown in Fig. 1(a). In this paper, the charge contribution to transport in the channel of the Helmholtz layer is considered as a non-neglectable part. Specifically, the polymer electrolyte referred to here is a random copolymer, P(VPA-AA), with the chemical structure as presented in Fig. 1(b). The protons in P(VPA-AA) are mobile ions, capable of travelling under electric field or diffusion. A top-gate bottom-contact configuration of field effect transistors was chosen for the discussed EGOFETs [13], sketched in Fig. 1(c). In the initial state of polymer electrolyte gate dielectric, we assume that the protons are uniformly distributed in the polymer matrix. When a negative voltage is applied to the gate, the protons are pulled to the gate, causing a concentration gradient of ions, which drives protons away from the gate. When these two opposite movements of protons in the polymer gate dielectric reach equilibrium, a layer of protons close to the gate contact is established. Since polymer chains as anions are considered to be immobile, the negative charges are accumulated at the interface between the gate electrolyte and semiconductor. This charge contribution of the electric double layer capacitor is taken into account in this model, although there is probably a part of ions penetrating into the bulk

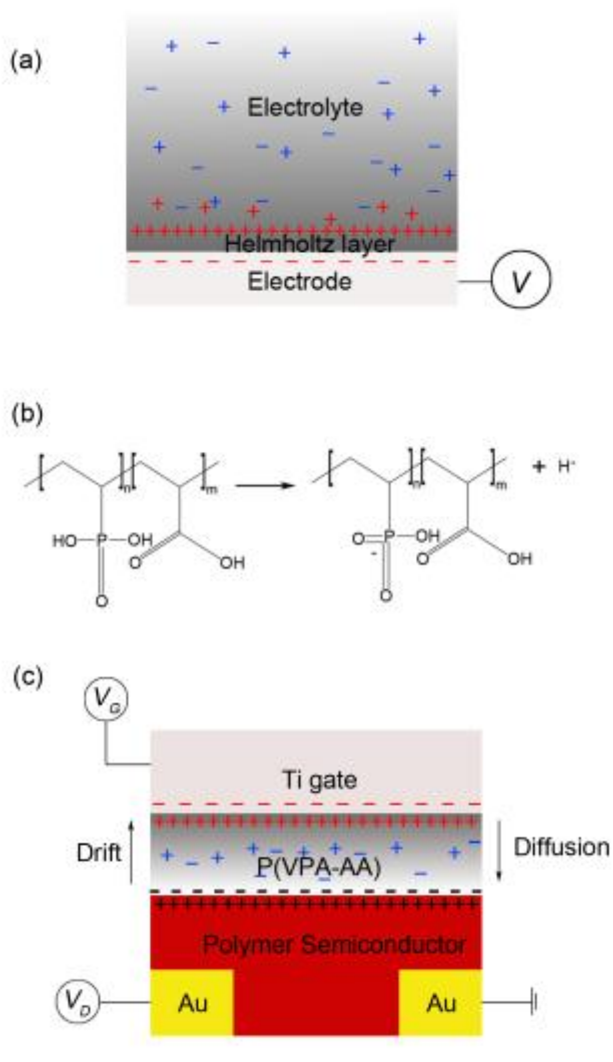

Fig. 1. (a) Schematic of electric double layer at electrolyte and electrode interface, when the electrode is applied a potential. (b) The molecular structure of P(VPA-AA) and its deprotonated process under a negative bias. (c) The sketched device structure of EGOFETs discussed in this work. The arrows indicate directions of proton movements driven by electric field or diffusion.

polymer semiconductor layer [13]. The undesired ion doping leads to very slow switching speed and huge hysteresis, making EGOFETs like electrochemical transistors. At certain voltage bias, EGOFETs can be operated only in field effect mode. Therefore, the ion penetration into semiconductor channel is neglected in this work.

III. Model Theory and Derivation

Despite that many theories are proposed and reported to describe behaviors of various organic field effect transistors, the widely known ones are based on charge drift [19] in presence of tail-distributed traps [20] and variable range hopping [21]. For the charge drift model, a critical point is to figure out the quantity of charges at the dielectric-semiconductor interface. In our model, the charge contribution is considered to be provided by electric double layer capacitance, which is nonlinear and voltage dependent. Moreover, a very important common point among different theories is the voltage dependent mobility, which has to be taken into account. Here, we consider a few common points in the modeling of organic field effect transistors, including charge drift transport, voltage dependent mobility, contact effect and gate leakage current, as well as the contribution of EDLCs to propose an EGOFET-exclusive compact model. The detailed derivation is shown below. To simplify the derivation, all equations are given for the n-type field effect transistors first. In our case, the P(VPA-AA)-gated transistors are p-type and polarity of voltages and currents will be reversed.

A. Electric double layer capacitance

The electric double layer is created at the interfaces between electrolyte and metal gate and between the electrolyte and the/semiconductor. Since the dimension of a proton is much smaller than the dimension of the anionic group in P(VPA-AA), the overall capacitance is actually limited by the smallest electric double layer located at the polyelectrolyte -semiconductor interface. At this interface, the electrolyte is divided into two zones: a compact layer constituted of the first monolayer of polyanions in contact with the semiconductor and, and a diffusion layer composed of polyelectrolyte chains partially depleted from the protons. The compact layer is modeled by Helmholtz [22], giving a capacitance dependent on the distance between the metal surface and a plane of ions. In the diffusion layer, the two motions of mobile protons, drift by electrical field and diffusion by concentration gradient, reach equilibrium at steady state. This complicated process is described by the Gouy-Chapman theory, which was revised by Stern later, yielding a correlation between surface charges and electric surface potential to determinate the nonlinear capacitance [23]. Interestingly, for low ion concentrations, the capacitance is expected to change abruptly around the potential of zero charge [24], while for high concentration of ions, as it is the case in the polyelectrolyte used for the transistor, the ideal model leads to a constant capacitance versus voltage. From theory, the capacitance versus voltage in the polyelectrolyte used for the transistor is expected to be small. Actual electric double layers however, always display a smooth evolution of the capacitance versus voltage at high ion concentration [25].

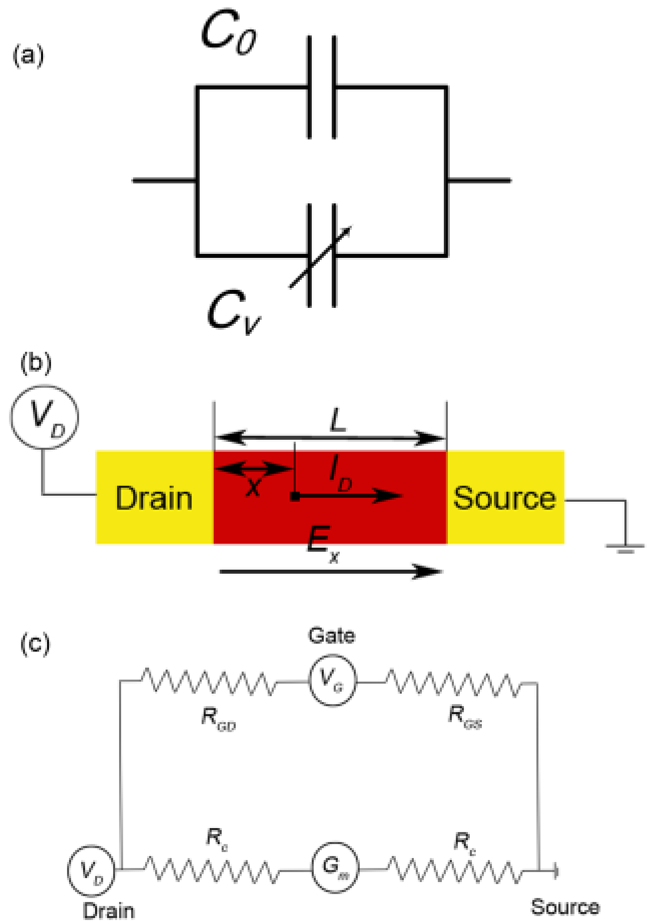

Fig. 2. (a) The circuit diagram of revised Two Branches Model of EDLCs. Voltage-dependent capacitor C_v and voltage-independent capacitor C_0 are connected in series. (b) Schematic of transistor channel, the accumulated charges in channel drift under electrical field, forming the channel current. (c) A static equivalent circuit of EGOFETs, parasitic capacitance is neglected. The G_m is gate voltage-dependent channel conductivity, and R_{GD} or R_{GS} is the negligible resistance between gate and drain or source, respectively.

Such deviation from ideal models is here included in the following model. We consider this voltage-dependent capacitance summed of two parts, one is proportional to a certain power of voltage but the other is constant, for this model. The equivalent circuit of the revised two branches model for electric double layer capacitor is presented in Fig. 2(a). So, the capacitance of electric double layer $C(V)$, at a certain position x in the channel is given by $C(V)=C_0+C_v(V_{GT}-V(x))^{\chi}$ $(0<x<L,\ \chi>0)$, where C_0 is the voltage-independent of capacitance, C_v is the voltage-dependent capacitance, V_{GT} is the gate voltage V_G minus the threshold voltage V_T, $V(x)$ is the potential at position x between source and drain, χ is the EDLC voltage-dependent factor, and L is the channel length.

B. Charge drift model

To describe the DC behavior of charge transport in the device channel, a widely-accepted charge drift model [19] is presented here. As shown in Fig. 2(b), the channel current at point x per unit width (I_D/W) is given by $I_D/W=\mu(x)Q(x)|E(x)|$, and $\mu(x)$ is the voltage-dependent charge mobility, $Q(x)$ is the accumulated charges and $E(x)$ is the electric field given by the drain voltage along the channel, at point x in the channel. The current is considered to be consistent along the channel.

From the theories of organic field effect transistors [20, 21], the mobility $\mu(x)$ is related to the voltage potential at that location and can be written as $\mu(x)=\mu_0(V_{GT}-V(x))^{\gamma}$ $(\gamma>0)$, where μ_0 is the low-field mobility and γ is the mobility enhancement factor.

With this capacitance of EDLCs, the charge accumulated at the position x in the channel is rewritten as

$$\begin{aligned} Q(x) &= C(V)(V_{GT}-V(x)) \\ &= C_0(V_{GT}-V(x)) + C_i(V_{GT}-V(x))^{\chi+1} . \end{aligned} \quad (1)$$

In addition, $|E(x)|$ is $\partial V(x)/\partial x$.

Here, the channel current can be rewritten as follows,

$$\begin{aligned} I_D(x)/W &= \mu_0(C_0(V_{GT}-V(x))^{\gamma+1} \\ &+ C_i(V_{GT}-V(x)^{\gamma+\chi+1}))\frac{\partial V(x)}{\partial x} . \end{aligned} \quad (2)$$

Integrating along channel length x, an intermediate equation is given as

$$\int_0^L (I_D(x)/W)dx = \int_0^L [\cdots\frac{\partial V(x)}{\partial x}]dx = \int_{V_S}^{V_D}[\cdots]dV(x) . \quad (3)$$

Usually, the source terminal is grounded in most organic field effect transistor instances and so we assume here. The potential of source V_S is set to 0 V to simplify equation derivation and the current is considered to be consistent along the channel. Therefore, the first channel current formula of EGOFET model is obtained from (3) as

$$\begin{aligned} I_{D,lin} &= \frac{W}{L}\mu_0[C_0\frac{V_{GT}^{\gamma+2}-(V_{GT}-V_D)^{\gamma+2}}{\gamma+2} \\ &+ C_i\frac{V_{GT}^{\gamma+\chi+2}-(V_{GT}-V_D)^{\gamma+\chi+2}}{\gamma+\chi+2}] \end{aligned} . \quad (4)$$

This equation covers DC behaviors of EGOFETs in linear regime. Furthermore, the saturation regime, subthreshold regime and a few detailed supplements are discussed below to make the model solid and versatile, based on this equation.

C. Saturation regime

For saturation regime, the V_D is superior to V_{GT}, and then the V_{GT}-V_D is considered to be zero, approximately. When downscaling the channel length of field effect transistors to less than a few microns, short-channel effects [26] can be observed, which can cause a series of issues to the device characteristics, such as non-saturation, threshold voltage shift, fall of on/off ratio, and so on. Here, a channel length modulation factor $1+\lambda(V_D-V_{GT})$ is introduced to address a short channel effect in the saturation current equation, where λ is the channel length modulation coefficient [27]. Hence, the (4) can be rewritten for the saturation regime in this form

$$I_{D,sat}=\frac{W}{L}\mu_0(C_0\frac{V_{GT}^{\gamma+2}}{\gamma+2}+C_i\frac{V_{GT}^{\gamma+\chi+2}}{\gamma+\chi+2})\times[1+\lambda(V_D-V_{GT})] \quad . (5)$$

D. Subthreshold regime

Most of the induced charges are trapped in the subthreshold regime, and the charge transport in the channel is not dominated by drift but by diffusion. The charge drift-based model is not accurate to describe device behaviors in the subthreshold regime. The channel current can be presented as in [19], with a similar expression to conventional transistors,

$$I_{D,sub}=\frac{W}{L}\mu_0 C_0 V_{SS}^2\exp(\frac{V_{GT}}{V_{SS}})[1-\exp(\frac{-V_D}{V_{SS}})] \quad ,(6)$$

where V_{ss} is a voltage parameter, reflecting the steepness of the subthreshold characteristics, which can be approximately estimated with the subthreshold slope [28]. The electric double layer capacitance is considered to be negligible, since the gate voltage is rather low in subthreshold regime.

E. Contact effect

For ideal transistor operation, the contact resistance between source/drain electrodes and semiconductor channel is generally negligible. This contact is named Ohmic contact. However, contact resistances for organic field effect transistors are often quite substantial and play an important role in the charge transport. Fig. 2(c) presents an equivalent circuit of EGOFETs for DC performance without parasitic capacitances. The contact resistances at the source and drain are considered to be symmetric. If the contact resistance R_C is considered, the effective drain voltage V_D', excluded the voltage drop on contact resistance, will be $V_D'=V_D-2I_DR_C/L$.

As reported [29], contact resistance in organic field effect transistors is highly dependent on gate voltage. To take this dependence into account, a power law dependence on V_{GT} is given to the contact resistance in this form $R_C(V)=R_{C0}V_{GT}^{-(\gamma+1)}$ [30], where R_{C0} is the contact resistance at V_{GT}=1 V. Here, the contact resistance shares the same factor γ as the voltage dependent mobility and this is due to the contact resistance is reciprocal to the amount of accumulated charge carriers times their voltage dependent mobility [30].

F. Threshold voltage shift

Although electrolyte gate has suppressed short channel effects, we still observe the trend when the channel length shrinks [14]. As referred above, one of short channel effects is the shift of V_T, which is also called threshold voltage roll-off [31]. This is due to the shrinking channel length lowers the required gate voltage to make the channel conductive, hence the threshold voltage shifts toward the reverse direction of gate voltage switching on the transistor. If the channel length is long enough, the threshold voltage is consistent along the channel length. To address the impact of short channel effect, the shift of V_T from the long channel value is reciprocal to the channel length [32], so the V_T dependence on channel length is expressed as $V_T(L)=V_{T,L}(1-\zeta/L)$, where ζ is a coefficient, $V_{T,L}$ is the threshold voltage of the long channel transistors, without short channel effect.

The variation of threshold voltage with biasing is another factor which makes the V_T shift [33]. The sensitivity of this dependence is expressed as $\delta_{VT}=\partial V_T/\partial V_G$.

Including this parameter, the threshold voltage can be modified to $V_T(L)=V_{T,L}(1-\zeta/L)+V_G\delta_{VT}$. In this modification, we have considered the influence of both channel length and voltage bias on threshold voltage.

IV. Results and Discussion

To verify the above model, EGOFETs with polymer electrolyte P(VPA-AA) were fabricated and characterized as reported [13]. Two kinds of polymer semiconductors were used respectively, including PTTTT and P3HT. The devices had Au source/drain bottom electrodes with channel length L=2 to 50.5 µm and width W=1000 µm. The thickness of spin-coated P3HT/PTTTT layer was around ~30 nm and P(VPA-AA) gate dielectric layer was 100 nm, capped by a Ti gate electrode. The measurements were carried out with a Keithley 4200-SCS semiconductor characterization system in ambient air at room temperature. Here, PTTTT transistors with L=50.5/20.5/10.5/5.5/3.5/2 µm are presented as example to extract parameters in this model, and then the comparison of

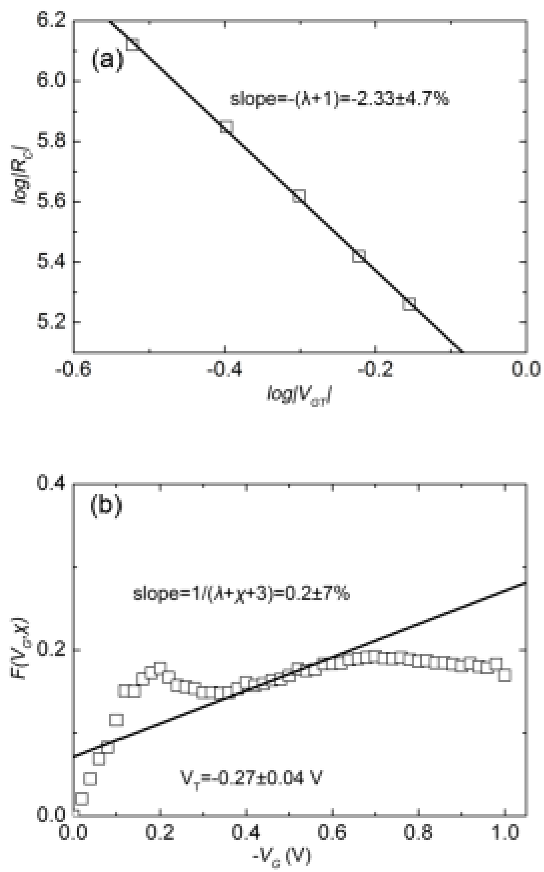

Fig. 3. (a) The contact resistance dependence on voltage is graphed with $logR_C$ versus $logV_{GT}$. (b) $F(V_G,\chi)$ plot of EGOFET with 50.5-µm channel length. The slope of linear fitting gives the coefficient χ.

simulation results and experimental data at various channel length is followed in this discussion.

A. Extraction of mobility enhancement factor γ

The power law dependence of contact resistance on voltage can be rewritten as $logR_C=logR_{C0}-(\gamma+1)logV_{GT}$.

Unlike the method in [28], this equation provides an alternative way to extract the mobility enhance factor γ. Here, we extract contact resistance at V_G = 0.6/0.7/0.8/0.9/1 V with the method discussed below, respectively. Then the γ can be calculated from the relation between R_C and V_G. The $logR_C$ versus $logV_{GT}$ is plotted in Fig. 3(a) and a linear fitting gives a slope of -2.33. Hence, we can obtain the mobility enhance factor γ, which is around 1.33, comparable with those conventional organic field effect transistors [28].

B. Extraction of EDLC factor χ

To simplify the extraction, we use the saturation equation to obtain the voltage-dependence coefficient χ. In addition, the data are from the transistor with 50.5-µm channel length, so the short channel effect is negligible. A function $F(V_G, \chi)$, consisting of V_G and χ, is written as

$$F\left(V_G,\chi\right)=\frac{\int_{V_T}^{V_G}\left(\frac{1}{\gamma+2}\frac{\partial I_D}{\partial V_G}V_{GT}-I_D\right)dV_G}{\frac{1}{\gamma+2}\frac{\partial I_D}{\partial V_G}V_{GT}-I_D}=\frac{V_{GT}}{\gamma+\chi+3}. \quad (7)$$

In this equation, $F(V_G, \chi)$ becomes a linear function of gate voltage with only another two coefficients γ and χ, and the γ is 1.33, as extracted above. From the slope of linear fitting in Fig. 3(b), presenting the plot of the function $F(V_G, \chi)$, the electric double layer capacitance coefficient χ is calculated to be 0.67.

C. Extraction of L modulation coefficient λ

From (5), we can see that the increasing current is proportional to the difference of V_D and V_{GT} in saturation regime and the slope is λ. Here, we extract λ at fully-on state of transistors, although it is usually related to gate voltage in silicon CMOS transistors [34]. Fig. 4(a) presents the current curves in saturation regime versus V_D-V_{GT} and their linear fittings at V_G=-1 V, obtained from transistors with channel length from 2 to 50.5 µm. The dependence of λ on channel length is plotted in Fig. 4(b). Look into Fig. 4(b), we can see the λ is dramatically increasing when the channel length is below 5µm, indicating an evident short channel effect. From this figure, the coefficient λ is denoted as *0.83/L*, where *L* is in µm.

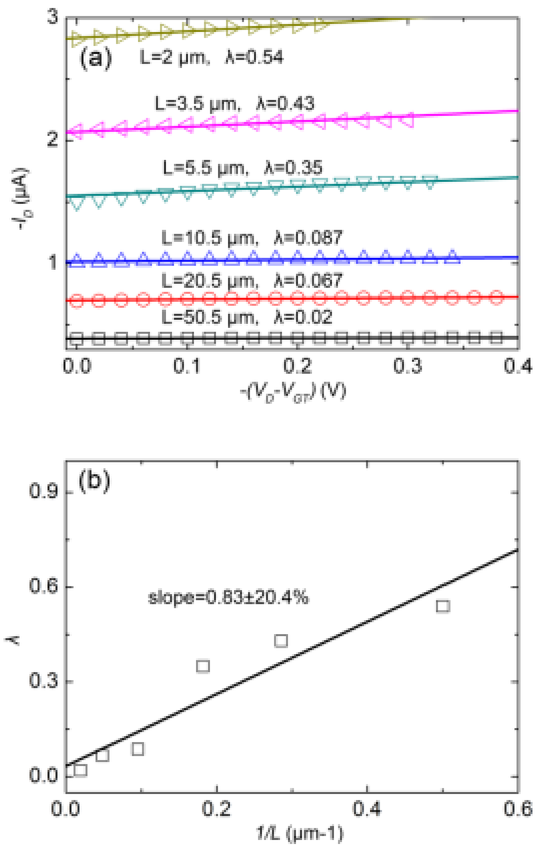

Fig. 4. (a) The output curves of EGOFETs with various channel length in saturation regime at V_G=-1V. The channel length modulation factor λ is extracted from the linear fitting. (b) The dependence of λ on the channel length *L*.

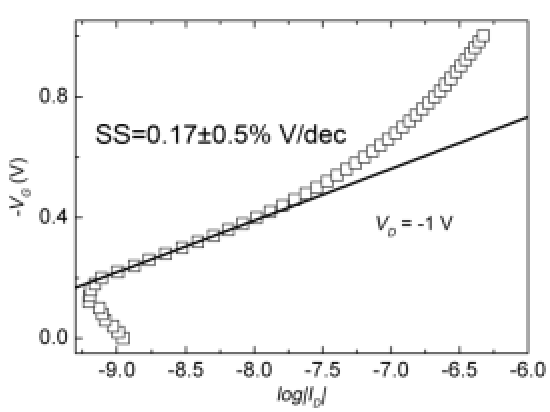

Fig. 5. The subthreshold slope is extracted to estimate the parameter V_{SS}.

D. Extraction of subthreshold slope SS

In subthreshold regime, the subthreshold slope *SS* is defined as $SS=V_G/log|I_D|$. The *SS* is extracted from the transfer curves of the 50.5-µm channel length transistor, shown in Fig. 5. For this device, the *SS* is as low as 0.17V/dec, implying a fast transition between off state and on state in EGOFETs. In this model, the *SS* is used to estimate the parameter $V_{SS}=SS/2$ [28].

E. Extraction of contact resistance R_{C0}

To give the contact resistance referred above, the PTTTT transistors at six channel lengths from 2 to 50.5 µm were presented here. The channel resistance of each device at $V_G=V_D$=-1 V is graphed in Fig. 6(a) as the hollow squares. A linear fitting of these resistances indicates an $R_C\times W$ of 0.019 MΩ•cm at $V_G=V_D$=-1 V, corresponding R_{C0}=0.12 MΩ at W=1000µm. As expected [14], the contact resistance in EGOFETs in much lower than that of SiO_2-dielectric organic transistors [29].

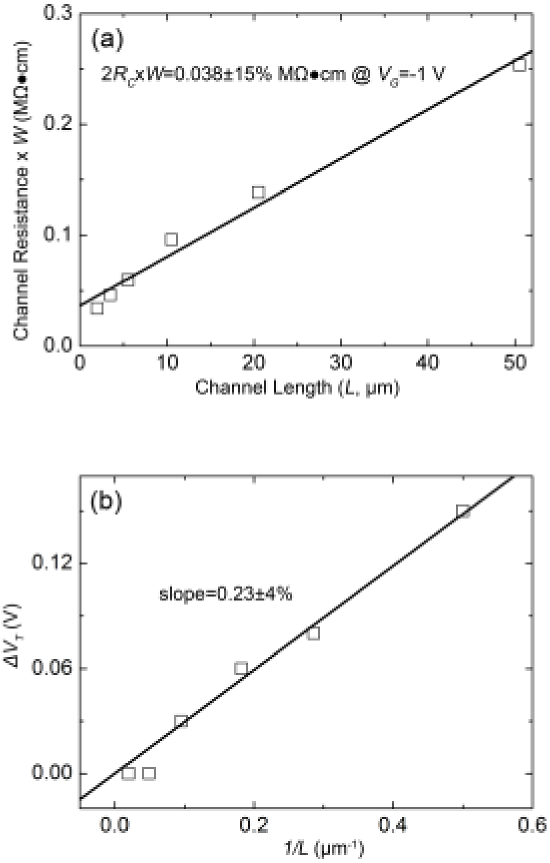

Fig. 6. (a) The channel resistance of EGOFETs at $V_D = V_G$ = -1 V with various channel lengths. (b) The threshold voltage V_T shifts with the channel length L, caused by short channel effect.

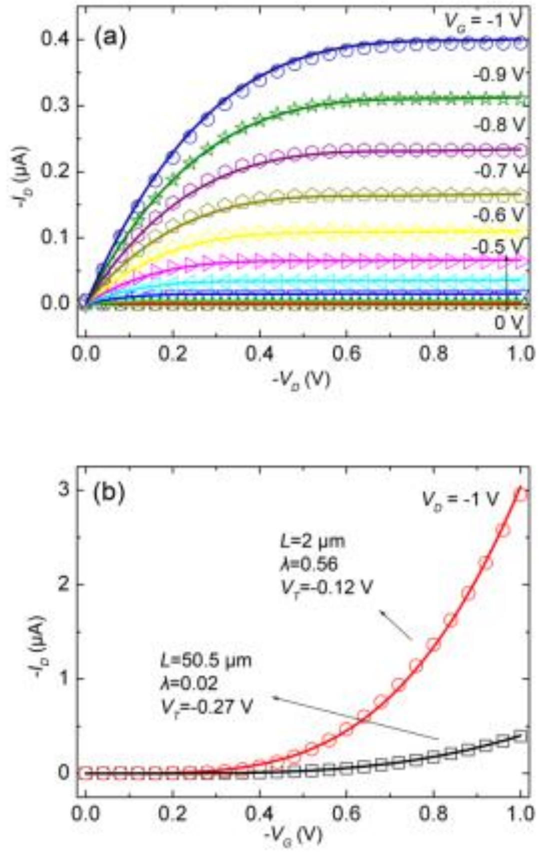

Fig. 7. (a) The comparison between calculation and experimental data for output characteristics of EGOFETs. (b) The comparison between calculation and experimental data for transfer characteristics of EGOFETs with L=2 and 50.5 μm. The symbolic circles are experimental, while the curves are simulated results given by the model.

F. Extraction of V_T shift coefficient ζ and δ_{VT}

Here, the threshold voltage of the 50.5-μm channel length transistor is considered to the long channel threshold voltage $V_{T,L}$. The threshold voltage shift $V_{T,L}$-V_T versus $1/L$ is shown in Fig. 6(b). The slope of the linear fitting in Fig. 6(b) is $V_{T,L}\zeta$, so the threshold voltage shift coefficient ζ is obtained to be 0.77. The magnitude of is δ_{VT} usually very small [33], here we have δ_{VT} =0.1, by linear fitting the threshold voltage extracted at different bias.

G. Comparison between calculation and experimental data

Fig. 7(a) shows the output characteristics (I_D-V_D) of the transistor with L=50.5 μm mentioned above. The drain voltage was swept from 0 to -1 V with a -0.02 V step, while the gate voltage was varied from 0 to -1 V with a step of -0.1 V. The simulated curves given by our model match well with the symbolic circles from experimental data. The model parameters and their values in the simulation are summarized in Table I. The transistor parameters W=1000 μm and L=50.5 μm are given by the experimental conditions, while the parameters V_T=-0.27 V, V_{ss} =0.085 V, R_{C0}=0.12 MΩ, γ=1.33, χ=0.67, λ=0.02, ζ=0.77, and δ_{VT}=0.1 are extracted from the experimental data, as discussed above. Only three parameters are obtained from fitting and they are C_0=5 μF/cm^2, C_v=1.5 μF/cm^2 at $|V_{GT}|$= 1V, and μ_0=0.028 cm^2/Vs. The ratio C_0/C_v is around 3.3, which is comparable in the electric double layer capacitance modeled by two branches method [35]. Besides the magnificent low operation voltage, the capacitance is over 5 μF/cm^2, which is much higher than ordinary organic field effect transistors with gate dielectric. This implies a superior capability of polymer electrolyte as a gate dielectric. The transfer characteristics of the 50.5 and 2-μm transistors are presented in Fig. 7(b) to show a further verification of our model. Their parameters share almost the same values except those listed in the figure. For both of them, we can find good agreements between experimental data (circles) and theoretical curves.

To investigate the validation of this model on different polymer semiconductor, sixty P3HT transistors at the same six channel length are presented here. The P3HT transistors shared the same fabrication processes with the PTTTT devices except different polymer semiconductors. In the same way, we extract the parameters V_T=-0.2 V, R_{C0}=0.06 MΩ, λ=0.6/L for the P3HT transistors and the fitted mobility is given as 0.1 cm^2/Vs. By fixing all the other parameters but channel length, we plot the channel current dependence on the channel length for P3HT transistors in Fig. 8(a), where a good agreement we can see. The black squares with error bars are the currents from experimental data, which are matched well by the simulated

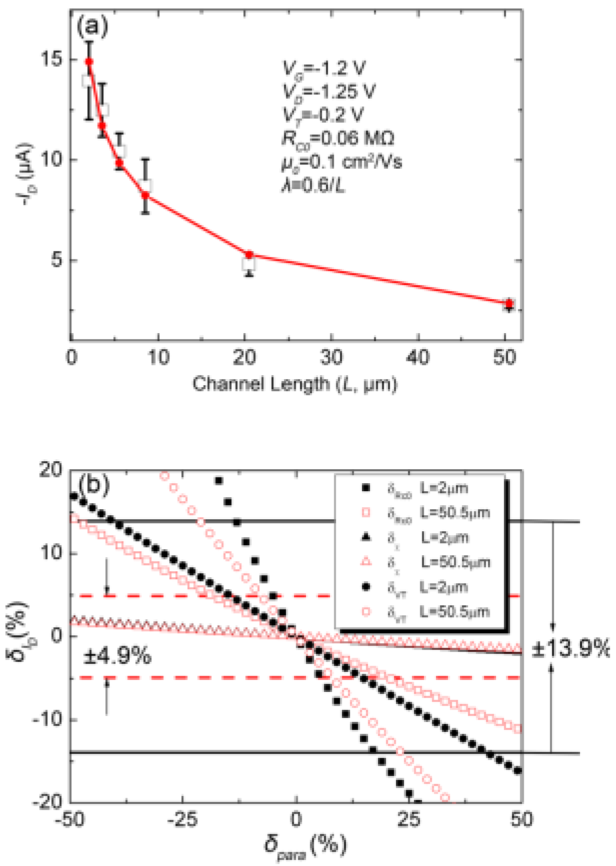

Fig. 8. (a) The channel currents at V_D =-1.2 V and V_G = -1.25 V of P3HT EGOFETs with various channel lengths. The circles are given by this model and the hollow squares are the mean value of measurement results. (b) The drain current variations caused by parameter variations.

current represented by red circles. This agreement indicates that the model is valid for devices fabricated in different batches.

We analyze the model sensitivity to parameter variation (δ_{para}), which leads to a drain current variation (δ_{ID}), and the results are presented in Fig. 8(b). Three parameters are analyzed here, including contact resistance (R_{C0}), EDLC voltage dependent factor (χ), and threshold voltage (V_T). From the statistic experimental data, the current of 2-µm-*L* P3HT EGOFETs exhibits a variation of ±13.9% (solid line in Fig. 8(b)), which is higher than that of 50.5-µm-*L* devices (±4.9%, dash line in Fig. 8(b)). When R_{C0} varies from -13% to 17% or -19% to 20%, the model results stay in the interval of experimental data, for the P3HT EGOFETs with channel length of 2 or 50.5µm, respectively. The long channel devices exhibit a better tolerance to contact resistance variation slightly. On the contrary, the long channel devices are quite sensitive to threshold voltage variation. The variation of ±8% in V_T leads a current variation of ±4.9% for 50.5-µm-*L* P3HT transistors, while the currents are agreed with experiment data even though V_T varies from -40% to +42% for 2-µm-*L* P3HT transistors. The current variation caused by variation of χ is less than ±2% for all the devices in this case, when χ varies in ±50%. This is expected as the discussed voltage dependence of EDLC above.

TABLE I
MODEL PARAMETERS AND THEIR VALUES FOR 50.5-µM-*L* EGOFET

Model parameters	Notation	Unit	Value
Type of transistor	p,n	-	p
Channel width	W	µm	1000
Channel length	L	µm	50.5
Threshold voltage	$V_{T,L}$	V	-0.27
Steepness of subthreshold regime	V_{SS}	V	0.085
Contact resistance	R_{C0}	MΩ	0.12
Mobility enhancement factor	γ	-	1.33
EDLC factor	χ	-	0.67
Channel length modulation factor	λ	V^{-1}	0.02
Threshold voltage shift factor	ζ	µm	0.77
Sensitivity of V_T on bias	δ_{VT}	V^{-1}	0.1
Voltage-independent capacitance	C_0	µF/cm^2	5
Voltage-dependent capacitance	C_v	µF/cm^{2}V	1.5
Low field mobility	μ_0	cm^2/Vs	0.028

Although this model is proposed and verified for EGOFETs, it is quite general. For ordinary organic field effect transistors with gate dielectric, our model is still valid as long as we cut off the contribution from the electric double layer capacitance, by removing the part of voltage-dependent capacitance. This is quite reasonable if we consider the gate dielectric as a plate capacitor in absence of electric double layer.

V. CONCLUSION

In summary, we have developed a DC model for EGOFETs. This model is based on charge drift in presence of electric double layer capacitor. The voltage-dependent charge contribution of the electric double layer is considered and contact resistance is taken into account as well as short channel effect, which leads to non-saturation and threshold voltage shift. The model parameters and coefficients are extracted for the device simulation. Comparisons between experimental data and model theoretical simulations exhibit good agreements. The model is also applicable for conventional organic field effect transistors with insulating gate dielectrics.

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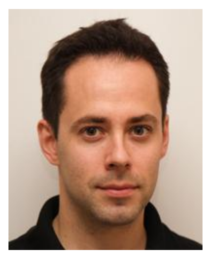

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