Invited Paper

Noise and Charge Transport in Polymer Thin-Film Structures

O. Marinov[1], M.J. Deen[1], J. Yu[2], G. Vamvounis[2], S. Holdcroft[2], W. Woods[3]

[1]Electrical and Computer Engineering Department, McMaster University
Hamilton, Ontario, Canada L8S 4K1 *E-mail*: *jamal@mcmaster.ca*

[2]Department of Chemistry, [3]School of Engineering Science
Simon Fraser University, Vancouver, BC, Canada V5A 1S6

ABSTRACT

The low frequency noise (LFN) properties of the field-effect transistors (FETs) using polymers as the semiconducting material in thin-film transistor (TFT) structures are investigated and discussed in terms of the charge carrier transport. Results obtained from several research groups are summarized. Injection-drift limited model (IDLM) for charge transport in amorphous PFETs is discussed. IDLM has some advantages in comparison to the commonly used metal-oxide-semiconductor (MOS) transistor models. A general trend of proportionality between noise power density and the DC power applied to the polymer FET's (PFET's) channel is observed in the data from several research groups. This trend implies mobility fluctuation in PFET as the dominant noise source.

Keywords: organic field-effect transistors, polymer TFT, low-frequency noise and fluctuation, charge transport, injection-drift-limited model, charge hopping, mobility noise.

1. INTRODUCTION

Organic- or polymer-based field-effect transistors (PFETs) have been increasingly investigated in the past three decades[1,2]. This is in an effort to realize inexpensive polymer thin-film transistors (PTFTs) that can be used in some niche commercial applications such as electronic tags, drivers in active matrix displays, or for sensing applications. Usually, the test structures of PTFTs are fabricated in two configurations, as shown in Figure 1, with the source/drain (S/D) contacts either below (a) or above (b) the semiconducting polymer film. The degenerately doped substrate serves as the gate electrode.

a) b)

Figure 1: Typical test TFT structures for PFETs: a) Bottom contact configuration; b) Top contact configuration

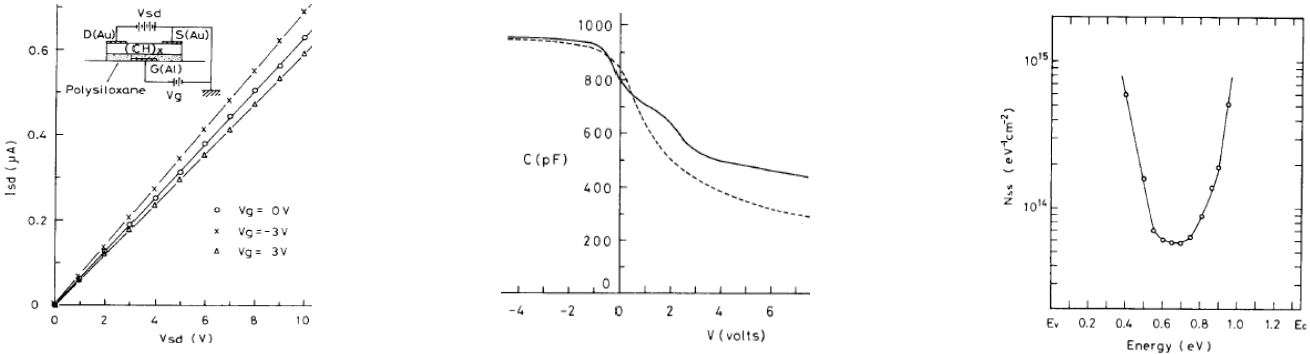
According to Ref. 2, the first polymer TFT with a gate-controlled drain-source current[3] was fabricated in 1983 using polyacetylene $(CH)_x$ as the semiconducting material in S/D top contact configuration. As shown in Figure 2, the gate dependence of the drain current I_D was small, as compared to the conductance between drain and source electrodes. However, from the C-V characteristics was deduced that the field-dependent part of I_D is due to carrier accumulation/depletion of the polymer at the gate-insulator interface, and the charge transport is similar to that in inorganic metal-insulator (oxide)-semiconductor (MIS or MOS) transistors.

This deduction was accepted in several succeeding investigations of PFETs, and researchers began using the MOS transistor theories for description and explanation of polymer transistor operation. For example, it is expected that the drain current I_D can be described as a function of the gate voltage (V_{GS}) and drain voltage (V_{DS}), as given by eqs. (1) and (2) for linear and saturation mode of PFET operation, respectively.

$$I_D = \frac{W}{L}\mu \cdot C_I\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}\text{ , for linear mode, if } V_{DS} \leq V_{GS} - V_T \tag{1}$$

$$I_D = \frac{W}{L}\,\frac{\mu \cdot C_I}{2}\left(V_{GS} - V_T\right)^2\text{ , for saturation mode, if } V_{DS} \geq V_{GS} - V_T \tag{2}$$

Here W and L are width and length of PFET's channel, μ is charge carrier mobility in the PFET's channel, C_I is the gate- insulator capacitance per unit area, and V_T is the threshold voltage.



a) b) c)

Figure 2: The first polymer TFT with gate-controlled drain-source current [3]: a) Output DC characteristic; b) C-V characteristic of gate; c) Density of polymer-insulator interface states

The deviation from these relations is attributed to imperfection of polymer material and TFT structure, and it is believed that it can be "worked-around" by introducing of additional terms, such as drain-source conductance $G_{DS,LEAK}$ for leakage in polymer bulk[4,5,8], drain and/or source resistance (R_D and/or R_S) for electrode-to-polymer access resistance [6,7,10], charge trapping and electric field enhancement for hysteresis in measured I-V curves [6,8] and bias-dependent variation of mobility [5,6,7,9] obtained from experimental data by using eqs. (1) and (2). Despite the complications of applying the MOS transistor theory to PFETs, much effort was devoted to finding appropriate polymers and electrode-insulator configurations. This is because it was observed that the type of polymer, the insulator and the electrode materials can result in PFET characteristics similar to those of MOS transistors. The experience from amorphous inorganic TFTs also "boosted" the research efforts. The results that were achieved and are discussed in next section indicate that the most of the complications arise due to hopping mechanism of charge transport in polymer.

The nature of charge transport in PFETs also results in some "anomalies" observed in their low frequency noise (LFN) characteristics when compared to LFN in MOS transistors. The general trend from the noise experiments on PFETs is illustrated in Figure 3. The slope 10dB/dec is consistent with the conclusion in Ref.11 that the noise is due to intergrain charge hopping in polymer, rather than due to interaction between carriers and gate insulator. The fluctuation of charge hopping causes a fluctuation in the conductivity of the semiconducting polymer and results in a proportionality between noise power and DC power, given by [12]

$$S_{I_D} = \frac{\alpha}{f \cdot N} I_D{}^2 = \frac{e \cdot \mu \cdot \alpha}{f \cdot L^2} V_{DS} \cdot I_D \, , \tag{3}$$

where S_{ID} is the noise spectral density of drain current I_D, α is the Hooge parameter, f is the frequency, N is the total number of carriers in PFET channel, and e is the electronic charge.

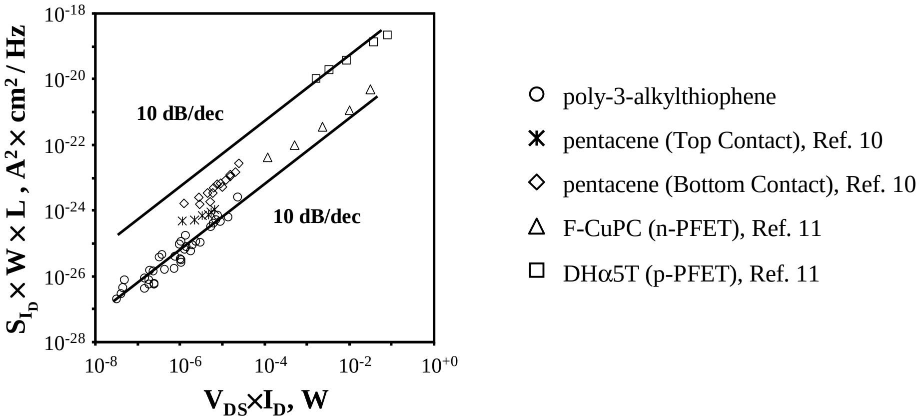


Figure 3: The level of the 1/f noise power density S_{ID} at 1Hz of the drain current I_D is proportional to the DC power applied on PFET channel. Data is normalized to the area of PFETs

Eq.(3) implies mobility fluctuation, which is in contrast to what is deduced by Martin *et al* [11]. However, in polymers the charge displacement is governed by charge hopping with random and long waiting time between consecutive hops, also resulting in dispersive carrier transport [13,14]. The carriers are occasionally able to move. Thus, both the carrier number N and hopping time fluctuate, or the mobility μ is just an effective parameter in the polymer thin film. Note that charge hopping is a completely different mechanism, as compared to thermal motion with scattering in crystal devices, and one should be alert when using the MOS sheet charge approximation in PFETs.

Considering the above discussion, charge transport in state-of-the-art PFET is discussed in next section. Then, the low-frequency noise (LFN) in PFETs is analyzed phenomenologically and in terms of charge hopping. In conclusion, some important findings are summarized in an attempt to “normalize” the discussion on LFN in PFETs.

2. STATE-OF-THE-ART AND CHARGE TRANSPORT IN POLYMER TFTs

Compared to the first attempt to make PFETs in Ref. 3 more than 20 years ago, there has been tremendous improvement in the PFETs electrical characteristics in the past 15 years. From the comprehensive review [2] on state-of-the-art PFETs, it is noted that both materials and fabrication processing and technology play important roles in the quality of PFETs. For example, the typical DC output characteristics of recently reported PTFTs indicate high on/off ratio (~10^3 and higher) and small leakage, as illustrated in Figure 4. The field-effect mobility, as defined by eqs. (1) and (2), is increased to values of ~1cm^2/V.s. However, some problems remain for PFET.

First, high mobilities in the range of 0.1 to 1cm^2/V.s have only been achieved in PFETs fabricated on polymer crystals[7,8,15,16]. However, the growth and processing of polymer crystals is neither simple nor inexpensive. Unfortunately, for amorphous polymer TFTs processed from solution, the estimated mobility is on the order of 10^{-4} to 10^{-3} cm^2/V.s. Intergrain traps are often cited as the cause for the drop in the mobility in amorphous PFETs[15,16] and appropriate theoretical models have been developed [5,7,9]. However intergrain effects are more reasonable for polymer bulk rather than for surface effects. The observation in Ref. 8 for high mobility in both bulk and surface conduction may indicate that a charge layer is not formed in the PFET structure and the transport mechanism remains in polymer bulk, rather than at surface. Instead, a high-quality of polymer-insulator interface is claimed in Ref. 8.

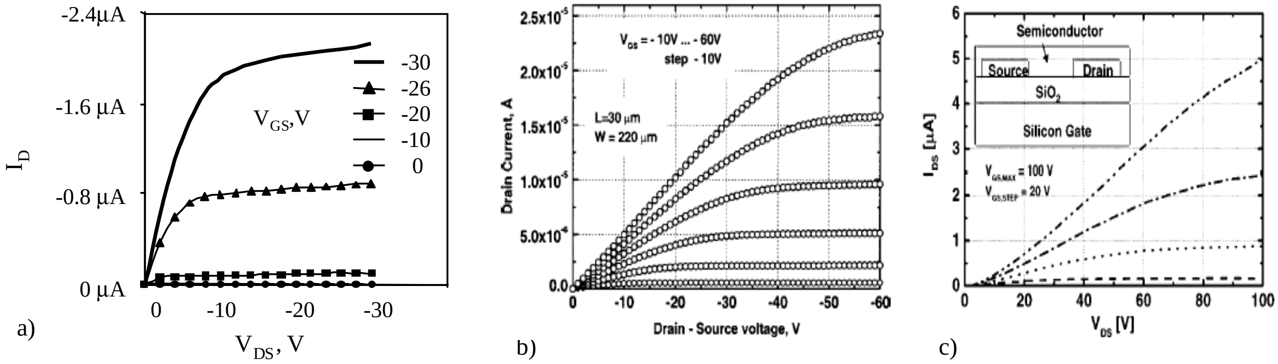


Figure 4: Typical DC output characteristics of recently reported PTFT: a) poly-3-alkylthiophene; b) pentacene (Top Contact) Ref. 10; c) F-CuPC (n-PFET), Ref. 11

Second, large dispersion of mobility values for the same polymer is observed, see Fig. 3 in Ref. 2, for example, and even for devices on the same wafer [17], as illustrated in Figure 5. The lack of repeatability can be attributed to incorrect method of using MOS transistor eqs. (1) and (2) for calculation of mobility in polymer TFT, although one may deduce the opposite from Ref. 9 where it is speculated that there are also intergrain traps at the polymer surface. Further, to the best of our knowledge, there is no reasonable explanation why the thickness of polymer film should change the surface mobility, as observed in Ref. 4 for a polymer thickness less than 100nm, and opposite to that in Ref. 7, where the accumulation layer thickness is calculated ~1nm, and found to be less than the thickness of one monolayer (~1.5 to 3nm) of a polymer molecule.

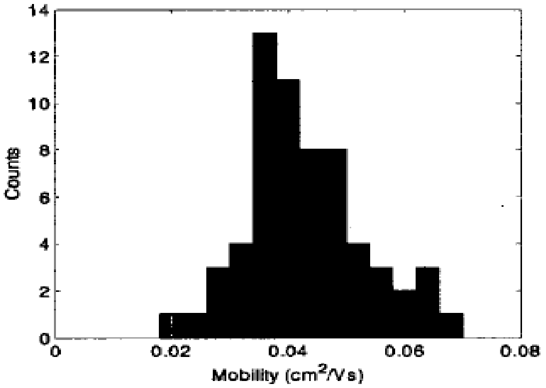


Figure 5: Histogram of mobility in identical pentacene transistors from polymer IC technology [17]

Third, problems due to access contact effects from source and/or drain terminals to the polymer, as well as gate bias dependence of mobility are reported in almost every paper for PFETs. For example, in Refs. 10 and 18, a parasitic Schottky barrier in series with contact is suggested in bottom contact PFETs. Special procedure for evaluation of source access resistance was developed in Refs. 6 and 7, and the mobility was estimated to be a linear function of gate voltage V_{GS}. Several contributions [7,11,18] using eqs. (1) and (2) for the DC modeling of a PFET suggested a power-law dependence of mobility on gate bias that is given by

$$\mu(V_{GS}-V_T)=\mu_o(V_{GS}-V_T)^p \tag{4}$$

Here, μ_o is initial mobility at low V_{GS}, and the exponent p is in the range of 0.5 to 1. Eq. (4) implies trap-aided enhancement of the mobility[7]. However, the Poole-Frenkel-like form for trap activated mobility [19,20,21] suggests an exponential dependence $\mu(E)\propto\exp(\gamma\sqrt{E})$, which we have observed in some of our experiments [12].

Considering these three complications when applying the MOS transistor model to polymer TFTs, and taking into account that electric field enhancement of mobility should be in the direction of the current flow, we suggested[22] the following for the charge transport in PFET. Three processes dominate in an amorphous polymer thin-film transistor, as depicted in Figure 6. The electric field at the source electrode injects carriers from the source into the polymer. Since the electric field of the drain-source bias is low (the drain electrode is far away), the carrier injection rate is primarily limited by V_{GS} because the gate insulator is thin and has a high permittivity. One part of the injected carriers occupies shallow energy states in the polymer, and the drain-source bias move these quasi-free charges toward the drain electrode, resulting in a drain current I_D due to V_{DS}. The other part of the injected carriers is captured for longer times in deeper polymer states, and this creates a space charge, recognized as a charge buildup at polymer-insulator interface or slow polarization of polymer. The charge injection from source electrode limits the rate of carrier number that can enter into polymer per unit time, while the mobility in polymer determines the time needed for the carriers to exit from drain electrode. The conduction layer of quasi-free charge does not contribute significantly as a limiting condition in charge transport, and this is the main difference between a MOS and a polymer transistor operation.

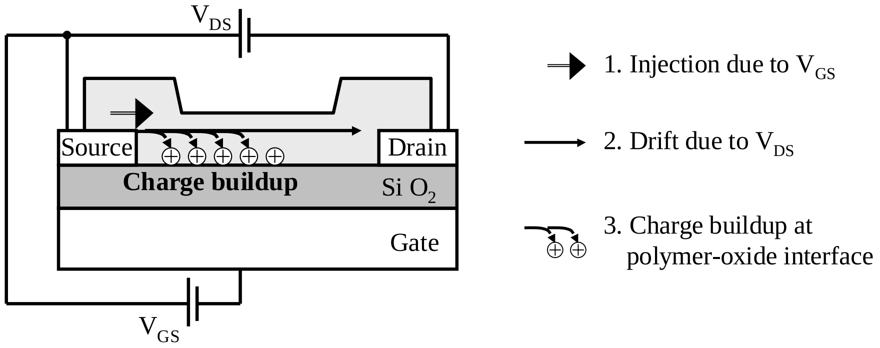
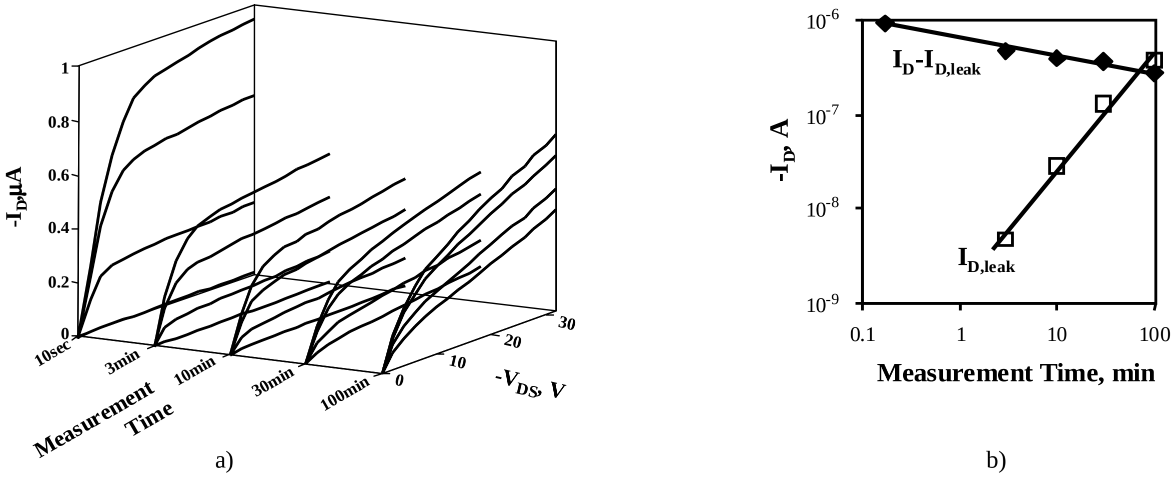


Figure 6: Injection-drift limited model (IDLM) of the charge transport in PFETs

As compared to the charge sheet approximation, the proposed injection-drift limited model (IDLM) for charge transport has several advantages when investigating PFETs. Some of these advantages are as follows.

- First, IDLM has been extensively used in two-terminal polymer devices (diodes). For instance, a threshold voltage exists due to the potential barrier at the metal-polymer interface. The variation of the slope of I-V characteristics can change from an exponential function if the barrier is sharp, through a power-law function if the barrier is distributed, to a linear function if the barrier is very low.
- Second, both the carrier injection into polymer and the drift of these carriers can be explained by charge hopping between energetically and spatially distributed states in polymer, rather than having to introduce conduction or valence bands in amorphous organic materials and a band-gap with traps.

- Third, “anomalous” behavior and “extraneous effects” in PFET can be easily understood by taking into account the properties of deep energy levels (traps) in polymer. An example for the charge buildup effect due to deep traps is illustrated in Figure 7. Since the deep traps are slow, the trapped charge increases gradually with time, and this decreases the electric field due to the gate bias. Therefore, the injection rate from source electrode drops with time and the field-effect current I_D-$I_{D,leak}$ also decreases. In addition, the leakage current $I_{D,leak}$ increases because the amount of trapped charge increases with time to high values, and even with low mobility, the large number of these charges is sufficient to provide a current comparable to the current of faster shallow polymer states. Thus, it is not necessary to introduce “mobile ions” [23] in the polymer in order to explain the slow transients observed in PFETs.



a) b)

Figure 7: Non-stationary DC characteristics of poly-3-alkylthiophene p-PFETs: a) degradation of characteristic with measurement duration; b) increase of leakage $I_{D,leak}$ and decrease of field-effect current (I_D- $I_{D,leak}$) due to charge buildup.

Although the IDLM is not fully developed, some ideas have already been introduced in several papers. Injection mechanism was argued as reason for gate bias dependence of drain current in Ref. 24, and lack of a saturation region in the PTFT’s characteristics with ambipolar charge conduction in Ref. 23. Also, in several contributions, for example in Ref. 25, it is concluded that the mobility in polymer is only governed by the nature of the organic active layer. In addition, the separation of polymer charge into mobile and trapped parts has already been proposed in Ref. 5. Therefore, the analysis in the next section is related to IDLM.

3. LOW-FREQUENCY NOISE IN POLYMER TFTs

The investigation of low-frequency noise in PFETs is still at a phenomenological stage and a solid theoretical explanation of the measured results is currently lacking. As well, for current transport in PFETs, most of researchers use measurement techniques and apply methods for analysis that were developed for MOS transistors and modifications known from heterostructure FETs. For example, Martin *et al*[11] used eq. (5), and proposed that the 1/f noise is due to surface trapping, since $A_F \approx 0.9 \sim 1$ in the PFET samples they studied. They deduced two-dimensional charge transport with scattering occurring as a surface mechanism, similar to that observed in MOS transistors, and expressed the drain current noise spectral density as.

$$S_{I_D} = \frac{K_F}{f \cdot C_{ox} \cdot L^2} I_D^{A_F} \tag{5}$$

Here, K_F and A_F are parameters for the popular SPICE-type 1/f noise model. However, as one can see from Figure 3, the data are also consistent with eq.(3), since V_{DS} was constant, and the deduced mechanism cannot be identified without the assumption of MOS transistor like operation.

Necliudov *et al*[10] used Hooge empirical relation (left terms in eq. (3)) to explain their measured data of PFETs in the linear mode of operation, and estimated α=0.045 for top contact configuration and between 5 and 20, depending on channel length, for bottom contact configuration. For the bottom contact configuration, it was found that that $S_{ID} \propto I_D^{1.3}$ and problems due to access contact resistance R_S are deduced from an analysis of the noise as a function of gate bias. However, numerical values for R_S and its noise were not presented. Despite this, one can see, the data are again consistent with the trend in Figure 3. Using a similar approach, Vandamme *et al* [26] obtained values α=0.01-0.08 for poly-thienylene vinylene, and 1-100 for pentacene. Later, it will be shown that these samples agree with the trend in Figure 3 too, but their data cannot be presented in the figure because the values for either I_D or V_{DS} are not stated in the paper. Also, "anomalous" behavior was observed in long channel pentacene samples, but the analysis in terms of V_{GS}, by assumption of MOS transistor-like operation in linear mode, did not give numerical values for the suggested four possible factors. Despite this, and on the basis of their experience, the authors pointed out that access series resistance R_S was the best candidate for the "anomalous" behavior, as Necliudov *et al*[10] had previously done.

Our previous investigation[12,27,28,29,30,31] on poly-3-alkylthiophene and other polymer p-PFETs with bottom contact configuration also used the MOS transistor model. We developed a physically based quantitative description for the noise level in terms of the mobility fluctuation theory, relating the Hooge parameter to the non-stationary field-dependent mobility. This was reasonable description since the spectral density S_{ID} of the PFET's drain current I_D was almost proportional to the DC power ($I_D \times V_{DS}$) applied onto the PFET's channel, with a slope of 9dB/dec. The slight decrease in the slope from the theoretical 10dB/dec, given by eq. (3), was explained by the enhancement of the mobility at increased electrical field, and it was found power-law dependences between carrier number N, mobility μ and Hooge parameter α. The interesting result is that the low-frequency noise (LFN) could be described by eq. (3) accurately in both linear and saturation mode of PFET operation. Therefore, the LFN could be assumed as a bulk effect in the polymer, and this was the first indication that MOS transistor-like operation could be inadequate for PFETs. In addition, the drain current I_D in some samples had an exponential dependence on V_{GS} and V_{DS}, instead of a linear or quadratic dependency. The DC characteristics of PFETs were similar to those of MOS transistor in weak inversion. Since no inversion layer is formed in weak inversion, the use of the MOS transistor charge transport can be inadequate for describing the PFETs electrical behavior. Finally, any attempt to refer the noise to (V_{GS}-V_T) has limied[10,11] or no success, as shown in Figure 8, when referring the noise to gate terminal using the relation for interface trap aided noise in MOS transistors [32], given by

$$\frac{S_{I_D}}{I_D^2} = \frac{g_m^2}{I_D^2} S_{V_G} \tag{6}$$

Here, g_m is transconductance of PFET, and S_{VG} is noise voltage due to traps, referred to the gate terminal. According to eq. (6), a positive slope is expected in Figure 8, because S_{VG} is weakly dependent on V_{GS}. However, this was not observed in our experiments.

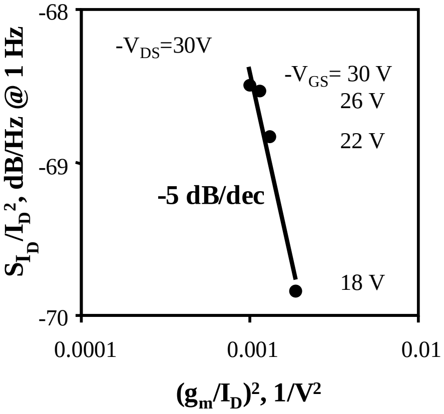


Figure 8: Negative slope in the dependence (S_{ID}/I_D^2) vs. $(g_m/I_D)^2$ indicates that the noise in PFET can not be referred to gate terminal

Since our attempts to describe the LFN in terms of MOS transistor theory met difficulties, we began investigating to injection-drift limited model (IDLM) of the charge transport in PFETs last year[22]. We suggested three possible noise sources for amorphous polymer TFTs, as illustrated in Figure 9. The effect of interface traps is attributed to gate electrode noise voltage source S_{VG}, although we suppose that S_{VG} is insignificant for PFETs, because the charge layer of quasi-free carriers is not a limiting phenomenon for the current transport in the amorphous polymer, as discussed previously.

The fluctuation of charge hopping in the polymer is attributed to $S_{G\mu}$. Since the waiting times between charge hops are random, $S_{G\mu}$ results in mobility fluctuation in the PTFT, and is consistent with eq. (3). For convenience, eq. (3) is rewritten[12] for the normalized current noise S_{ID}/I_D^2, as

$$\frac{S_{I_D}}{I_D^2} = \frac{\alpha}{f\cdot N} = \frac{e\cdot\mu\cdot\alpha}{f\cdot L^2}\,\frac{V_{DS}}{I_D} = \frac{e\cdot\mu\cdot\alpha}{f\cdot L^2}R_{DS} \tag{7}$$

where $R_{DS}=V_{DS}/I_D$ is the DC resistance of PFET channel. Vandamme *et al*[26] observed that the normalized current noise S_{ID}/I_D^2 scales inversely with carriers number N in PFET's channel. That is $S_{ID}/I_D^2 \propto 1/N$, and since N is proportional to the area of PFET's channel, we normalized the data for LFN, obtained by us and other researchers, with the areas W×L of the samples, and plot the results obtained in Figure 3 and Figure 10. From these two figures, consistent with eqs.(3) and (7), one can conclude that the low-frequency noise most likely originates from mobility fluctuation in amorphous polymer layer of the PFETs due to random waiting time between charge hops.

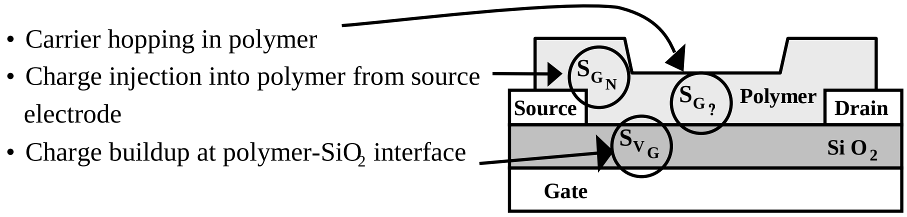


Figure 9: Low-frequency noise sources in PFET, relevant to injection-drift limited model (IDLM)

However, small deviation from slope 10dB/dec can be observed in Figure 3 and Figure 10, which can be attributed to access contact effects [10,32] and carrier injection through metal-polymer barrier [26]. Also, in two samples, we have observed the noise S_{GN} of carrier injection from source electrode into polymer, as shown in Figure 11.

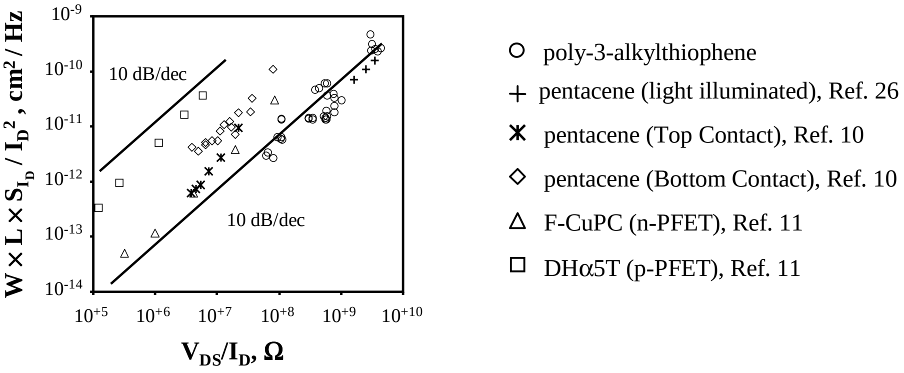
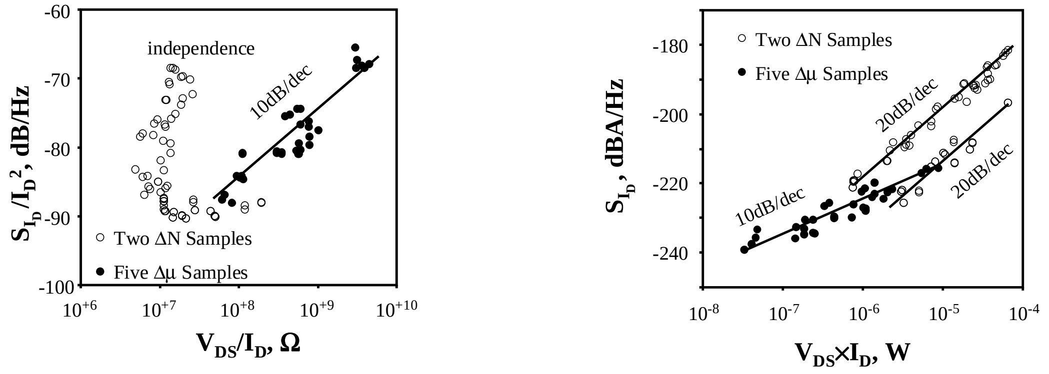


Figure 10: The level of the normalized 1/f noise power density S_{ID}/I_D^2 at 1Hz of the drain current I_D is proportional to the DC resistance R_{DS} of PFET channel. The data is normalized to the area of the PFETs

Here, S_{GN} is independent of the carrier number N in the PFET's channel, since no relation is observed in Figure 11a between normalized noise S_{I_D}/I_D^2 and channel resistance $R_{DS}=V_{DS}/I_D \propto 1/N$. This implies that S_{GN} is localized in a small area, most probably at source electrode of PFET, and it is due to disorder in polymer at metal-polymer interface. S_{GN} causes fluctuation in the rate of carrier injection, resulting in correlated number fluctuation ΔN in the channel current and channel conductance. Therefore, the power density S_{I_D} of the drain current noise becomes a quadratic function of the DC power $V_{DS}\times I_D$ applied onto PFET channel, and this can explain the experimental observation shown in Figure 11b.



a) b)

Figure 11: Injection noise source S_{GN} causes carrier number fluctuation ΔN in PFET channel conductivity: a) S_{GN} is localized in small area, since it is independent of carrier number $N \propto 1/R_{DS} = I_D/V_{DS}$; b) S_{GN} results in quadratic dependence of 1/f noise power density S_{I_D} of the drain current I_D on DC power $V_{DS}\times I_D$ applied onto PFET channel.

4. CONCLUSION

Much effort has been devoted last two decades to find appropriate materials and configurations to fabricate polymer field-effect transistors (PFETs) of thin-film transistor (TFT) structure with strong field-effect and small leakage. A significant improvement of PFET characteristics has been achieved in the past 15 years, however some important issues such as higher carrier mobility and improved reproducibility, stability and reliability are still to be resolved. Therefore, research continues in this field.

Our research shows that the charge transport in polymer TFTs is not easily understood in terms of metal-oxide-semiconductor (MOS) transistor theory. The deduction made 20 years ago that the field dependence of the PFET current is due to charge enhancement at polymer-insulator fails to explain many experimental findings. This is because the MOS transistor equations have to be modified significantly with "parasitic" terms, such as leakage conductance between drain and source electrodes, contact access resistances, and "fitting" field-dependent mobility. Although appropriate theories are developed in terms of the charge sheet approximation, the application of these theories is difficult. This is because the experimental data often deviate from the relations obtained for MOS transistors, and charge-trapping effects are introduced in order to get satisfactory agreement. However, trap states are attributed to intergrain structure of amorphous polymers, i. e. mostly to polymer bulk, rather than to the polymer surface. This conclusion is confirmed from the observed trend in noise experiments where there is mobility fluctuation in the bulk material.

As an alternative, the injection-drift limited model (IDLM) for charge transport in amorphous PFETs is introduced in this work. Three processes dominate in amorphous polymer thin-film transistor:

- carrier injection from source electrode into polymer, primarily due to gate-source voltage V_{GS};

- drift of quasi-free charges toward the drain electrode due to drain-source voltage $V_{DS;}$
- and charge trapping in deep states of the polymer.

The charge injection from source electrode limits the rate of carrier number that can enter into polymer per unit time, while the mobility in polymer determines the time needed for the carriers to exit from drain electrode. The conduction layer of quasi-free charge does not contribute significantly as a limiting condition in charge transport, and this is the main difference between the operation of a MOS transistor and a polymer transistor.

IDLM for charge transport has advantages when investigating PFETs.

- First, IDLM is in agreement to what is known for two-terminal polymer devices (diodes). For instance, a threshold voltage exists due to potential barrier at the metal-polymer interface. The variation of the slope of the I-V characteristics may occur as an exponential function, a power-law function, or a linear function depending on barrier height and its distribution.
- Second, both the carrier injection into the polymer and the drift of these carriers can be explained by charge hopping between energetically and spatially distributed states in polymer, rather than having to introduce conduction or valence bands in amorphous organic materials and a band-gap with traps.
- Third, the "anomalous" characteristics and "extraneous effects" in PFETs can be easily understood by taking into account the properties of deep energy levels (traps) in polymer. Since the deep traps are slow, the trapped charge increases gradually with time, and this decreases the electric field due to the gate bias. Therefore, the injection rate from source electrode drops with time and the field-effect current I_D-$I_{D,leak}$ also decreases. In addition, the leakage current $I_{D,leak}$ increases, because the large amount of trapped charge, even with low mobility, can provide current comparable to the current from the faster, shallow polymer states.

Three noise sources in PFET are associate with IDLM. Mobility fluctuation noise source is suggested for the charge hopping in polymer. This noise source is dominant in "good" PFETs, as indicated in the trend obtained from the published results of several research groups. Number fluctuation noise source is proposed for carrier injection from the source electrode into the bulk. This noise source is associated with a low quality metal-to-polymer contact at the source electrode. The third noise source is associated with traps at polymer-insulator interface, but it is found to be insignificant.

In conclusion, despite the dispersion in the published data, there is a trend of proportionality between noise power density and DC power applied to the PFET channel. The data from different research groups are within a factor of 10 of each other.

Acknowledgements

The authors would like to thank the School of Engineering Science, Simon Fraser University, for the use of the clean room facilities and to several of their colleagues at both McMaster University and Simon Fraser University for assistance and cooperation. This work was supported in part by a strategic grant and a research grant from the Natural Sciences and Engineering Research Council (NSERC) of Canada.

REFERENCES

1. M.J. Deen, "Organic Semiconductor Devices", *Wiley Encyclopedia of Electrical and Electronics Engineering*, Editor J.G. Webster, Vol. 15, 419-429, John Wiley & Sons Inc., New York, 1999.
2. A. Lodha, and R. Singh, "Prospects of Manufacturing Organic Semiconductor-Based Integrated Circuits", *IEEE Transactions on Semiconductor Manufacturing*, **14**(3), 281-296, 2001.
3. F. Ebisawa, T. Kurokawa, and S. Nara, "Electrical properties of polyacetylene/polysiloxane interface", *Journal of Applied Physics*, **54**(6), 3255-3259, 1983.

4. G. Horowitz, X. Peng, D. Fichou, and F. Garnier, “The Oligothiophene-Based Field-Effect Transistor: How it Works and How to Improve it”, *Journal of Applied Physics*, **67**(1), 528-532, 1990.

5. G. Horowitz, and P. Delannoy, “An Analytical Model for Organic-Based Thin-Film Transistor”, *Journal of Applied Physics*, **70**(1), 469-475, 1991.

6. G. Horowitz, R. Hajlaoui, D. Fichou, and A. El Kassmi, “Gate Voltage Dependent Mobility of Oligothiophene Field-Effect Transistors”, *Journal of Applied Physics*, **85**(6), 3202-3206, 1999.

7. G. Horowitz, M. Hajlaoui, and R. Hajlaoui, “Temperature and Gate Voltage Dependence of Hole Mobility in Polycrystalline Oligothiophene Thin-Film Transistors”, *Journal of Applied Physics*, **87**(9), 4456-4463, 2000.

8. J. Schon, C. Kloc, R. Laudise, and B. Batlogg, “Surface and Bulk Mobilities of Oligothiophene Single Crystals”, *Applied Physics Letters*, **73**(24), 3574-3576, 1998. (suspected for retraction).

9. J. Schon, and B. Batlogg, “Modeling of the Temperature Dependence of the Field-Effect Mobility in Thin Film Devices of Conjugated Oligomers”, *Applied Physics Letters*, **74**(2), 260-262, 1999. (suspected for retraction).

10. P. Necliudov, S. Rumyantsev, M. Shur, D. Gundlach, and T. Jackson, “1/f Noise in Pentacene Organic Thin Film Transistors”, *Journal of Applied Physics*, **88**(9), 5395-5399, 2000.

11. S. Martin, A. Dodabalapur, Z. Bao, B. Crone, H. Katz, W. Li, A. Passner and J. Rogers, “Flicker Noise Properties of Organic Thin-Film Transistors”, *Journal of Applied Physics*, **87**(7), 3381-3385, 2000.

12. M. J. Deen, O. Marinov, J. Yu, S. Holdcroft, and W. Woods, “Low-Frequency Noise in Polymer Transistors”, *IEEE Transactions on Electron Devices*, **48**(8), 1688-1695, 2001.

13. H. Scher, and E. Montroll, “Anomalous Transit-Time Dispersion in Amorphous Solids”, *Physical Review B*, **12**(6), 2455-2477, 1975.

14. P. Blom, and M. Vissenberg, “Dispersive Hole Transport in Poly(p-Phenylene Vinylene)”, *Physical Review Letters*, **80**(17), 3819-3822, 1998.

15. J. Schon, “On the Stability of Organic Field-Effect Transistor Materials”, *Applied Physics Letters*, **79**(25), 4163-4164, 2001. (suspected for retraction).

16. J. Schon, and C. Kloc, “Charge Transport Through a Single Tetracene Boundary”, *Applied Physics Letters*, **78**(24), 3821-3823, 2001. (suspected for retraction).

17. D. de Leeuw, T. Geuns, E. van Veenendaal, E. Cantatore, and B. Huisman, “Polymeric Integrated Circuits”, *IEEE-IEDM*, **78**(24), 293-296, 2002.

18. P. Necliudov, M. Shur, D. Gundlach, and T. Jackson, “Modeling of Organic Thin Film Transistors of Different Design”, *Journal of Applied Physics*, **88**(11), 6594-6597, 2000.

19. P. Murgatroyd, “Theory of Space-Charge-Limited Current Enhanced by Frenkel Effect”, *Journal of Physics D: Applied Physics*, **3**,151-156, 1970.

20. L. Bozano, S. A. Carter, J. C. Scott, G. G. Malliaras, and P. J. Brock, “Temeperature- and Field Dependent Electron and Hole Mobilities in Polymer Light-Emitting Diodes”, *Applied Physics Letters*, **74**(8), 1132-1134, 1999.

21. H. Martens, J. Huiberts, and P. Blom, “Simultaneous Measurement of Electron and Hole Mobilities in Polymer Light-Emitting Diodes”, *Applied Physics Letters*, **77**(12), 1852-1854, 2000.

22. O. Marinov, M. J. Deen, G. Vamvounis, J. Yu, S. Holdcroft, and W. Woods, “Instability of the Noise Level in Polymer Field-Effect Transistors with Non-Stationary Electrical Characteristics”, *Proc. Unsolved Problems of Noise (UpoN 2002),* September 2002*, in press*.

23. X. Chen, Z. Bao, J. Schon, A. Lovinger, Y. Lin, B. Crone, A. Dodabalapur and B. Batlogg, “Ion-Modulated Ambipolar Electrical Conduction in Thin-Film Transistors on amorphous Conjugated Polymers”, *Applied Physics Letters*, **78**(2), 228-230, 2001. (suspected for retraction).

24. X. Peng, G. Horowitz, D. Fichou and F. Garnier, "All-organic Thin-Film Transistors Made of Alpha-Sexithienyl Semiconducting and Various of Polymeric Insulating Layers", *Applied Physics Letters*, **57**(19), 2013-2015, 1990.

25. G. Velu, C. Legrand, O. Tharaud, A. Chapoton, D. Remiens and G. Horowitz, "Low Driving Voltages and Memory Effect in Organic Thin-Film Transistors with a Ferroelectric Gate Insulator", *Applied Physics Letters*, **79**(5), 659-661, 2001.

26. L. Vandamme, R. Feyaerts, and G. Trefan, "1/f Noise in Pentacene and Poly-Thieylene Vinylene Thin Film Transistors", *Journal of Applied Physics*, **91**(2), 719-723, 2002.

27. M.S.A. Abdou, X. Lu, Z.W. Xie, M.J. Deen and S. Holdcroft, "The Nature of Impurities in π-Conjugated Polymers Prepared by Ferric Chloride and Their Effect of the Electrical Properties of Metal-Insulator-Semiconductor Structures", *Chemistry of Materials*, **7**(4), 631-641, 1995.

28. M.S.A. Abdou, F.P. Orfino, Z.W. Xie, M.J. Deen and S. Holdcroft, "Reversible Charge Transfer Complexes Between Molecular Oxygen and Poly(3-Alkylthiophenes)", *Advanced Materials*, **6**(11), 838-841, 1994.

29. Z. Xie, M.S. Abdou, A. Lu, M.J. Deen and S. Holdcroft, "Electrical Characteristics of Poly(3-Hexylthiophene) Thin Film MISFETs", *Canadian Journal of Physics (Special Issue for CSTC 1991)*, **70**(10-11), 1171-1177, (Oct-Nov) 1992.

30. X. Lu, Z. Xie, M.S.A. Abdou, M.J. Deen and S. Holdcroft, "Studies of Polymer-Based Field Effect Transistors", *Proc.of the Canadian Conference on Electrical & Computer Engineering*, 814-816, (Vancouver, 14-17 Sep) 1993.

31. O. Marinov, M.J. Deen, J. Yu, S. Holdcroft and W. Woods, "Low Frequency Noise in Polymer Transistors with Non- Stationary Mobility", Proc. 16th International Conference on Noise in Physical Systems and 1/f Fluctuations (ICNF 2001), Ed. G. Bosman, *World Scientific*, New Jersey, 277-280, (Gainesville, Florida, October 22-25), 2001.

32. G. Ghibaudo, O. Roux, C. Nguen-Duc, F. Balestra, and J. Brini, "Improved Analysis of Low Frequency Noise in Field-Effect MOS Transistors", *Phys. Stat. Sol. (a)*, **124**, 571-581, 1991.

33. M.J. Deen, S.L. Rumyantsev, D. Landheer and D.-X. Xu, "Low Frequency Noise in Cadmium Selenide Thin-Film Transistors", *Applied Physics Letters*, **77**(14), 2234-2236, (2 October) 2000.