Evidence of Correlated Mobility Fluctuations in p-Type Organic Thin-Film Transistors

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Abstract—We report on the results of noise measurements in p-type organic thin-film transistors (TFTs) extending from the subthreshold region into the strong accumulation region over four decades of drain current values. The low-frequency noise produced by the devices can be successfully interpreted in the context of a multitrapping correlated number fluctuation—mobility fluctuation (CMF) theory, while neither phonon-induced mobility fluctuation nor carrier number fluctuation mechanisms are capable of justifying the observed noise behavior. The Coulomb scattering parameter is found to be in the order of $10^7$ Vs/C, about three orders of magnitude larger with respect to crystalline silicon MOSFETs and comparable with what already reported in hydrogenated amorphous silicon TFTs, suggesting a much more relevant contribution coming from CMF in disordered materials.

Index Terms—Organic TFT, low frequency noise, low frequency noise measurements.

I. INTRODUCTION

ORGANIC thin film transistors (OTFTs) have gained considerable interest in the last decades thanks to their application in large-area/flexible electronics such as displays, sensor arrays and RFID tags [1]. Low frequency noise measurements (LFNMs) [2]–[9] and models [10] have been used to understand the dielectric quality and channel transport mechanisms in OTFTs showing, in all cases, a higher level of 1/f noise, and hence a higher defect density with respect to crystalline Silicon (c-Si) MOSFETs. There have been many efforts to understand the origins of 1/f noise in OTFTs. In most cases, either the empirical mobility-fluctuation (MF) [4], [5] or the number-fluctuation (NF) model [6], [7] has been used to interpret the measured noise. Only in a few works [8] it has been suggested that CMF could be at the core of the observed noise behavior. The relatively complex procedure required for the reliable estimate of the 1/f noise vs bias conditions is possibly the reason why in many published works the explored current range is limited to approximately two decades, and even when larger current ranges are explored [6], [9], the measurement resolution in terms of measurement points per decade is quite poor, especially in the sub-threshold region. Thanks to a high sensitivity measurement system, in this work we have been able to explore with great accuracy and unprecedented resolution a wide range of currents (over four decades) from the deep subthreshold to the strong accumulation region. The noise data extracted from many devices are well fitted by the CMF model in the entire explored current range, allowing us to estimate the Coulomb scattering parameter for the OTFTs under test.

II. DEVICE STRUCTURE AND MEASUREMENT SETUP

OTFTs (Fig. 1), with staggered top-gate configuration, were fabricated on flexible (125 μm thick) polyethylene-naphthalate (PEN) by using solution processed semiconductor and dielectric. After the definition of the source (S) and drain (D) gold contacts, self-assembled monolayer (SAM) 2,3,4,5,6-pentafluorobenzenethiol, small molecule organic semiconductor (SmartKem p-FLEX, 20 nm thick [11]) and amorphous fluoropolymer gate dielectric (poly(perfluorobutylvinylether) known as Cytop, 550nm thick, relative dielectric constant $\sim 2.1$) were sequentially deposited by spin coating. Finally, gate electrode (evaporated Al, 50 nm thick) and device islands were lithographically defined. Investigated devices have a gate width $W = 70 \mu m$ and gate length $L$ from 2μm to 100μm. Drain current-gate voltage ($I_D-V_{GS}$) characteristics are measured by the semiconductor parameter analyzer HP4155B. A typical $I_D-V_{GS}$ in the linear regime ($V_{DS} = -1V$) is shown in Fig. 1b.
III. NOISE DATA INTERPRETATION

Before noise data can be processed to extract trap parameters it is necessary to estimate the influence of contacts in terms of DC contact resistance \( R_C \) and contact resistance noise \( S_{RC} \) [9]. Fig. 3 shows the measured (top) total device resistance \( R_T \) and (bottom) the total device resistance noise \( S_{RT} = (S_{ID}/I_D^2) R_T^2 \) as function of the gate overdrive \( (V_0 = V_{GS} \text{ where } I_D \cdot L/V_{DS} = -4 \cdot 10^{-7} \Omega^{-1} \cdot \mu m) \) for \( L = 100 \mu m \) and \( L = 2 \mu m \). Since \( R_T(L = 100 \mu m) \gg R_T(L = 2 \mu m) > R_C \) and \( S_{RT}(L = 100 \mu m) \gg S_{RT}(L = 2 \mu m) > S_{RC} \) we can conclude that the contact effects are negligible for OTFTs with channel length of \( L = 100 \mu m \). In shorter devices contact effects cannot be neglected. For these reasons, in this work, we focus the noise analysis on OTFTs of \( L = 100 \mu m \).

For \( L = 100 \mu m \). The measured mobility is about 2 cm²/V.s. During LFNMs devices are biased by the HP4155B and drain current fluctuations are amplified by a custom-built transimpedance low noise amplifier (LNA) in order to ensure sufficient signal-to-noise ratio at the input of the spectrum analyzer system [12]–[14].

Fig. 2 shows the power spectral density (PSD) of current fluctuations \( S_{ID} \) as function of the frequency \( f \) in the linear regime for different values of the drain current, from the subthreshold to the strong accumulation region in a device with \( L = 100 \mu m \). A clear \( 1/f^\gamma \), \( \gamma \approx 1 \), behavior is observed at all investigated bias points. The increase of \( S_{ID} \) at higher frequencies is due to the LNA background noise (LNA-BN). In the following, PSD data have been evaluated at \( f = 1 \text{Hz} \).

Fig. 4 shows the normalized current PSD evaluated at \( f = 1 \text{Hz} \) as function of the drain current \( (-I_D) \) in 4 samples with \( L = 100 \mu m \) (different symbols refer to different devices).

Fig. 5 shows the normalized gate voltage PSD evaluated at \( f = 1 \text{Hz} \) as function of \( -I_D/g_m \) in 4 devices with \( L = 100 \mu m \) biased at \( V_{DS} = -1 \text{V} \). Two different trends are observed in the subthreshold and in the strong accumulation regimes.

In particular, a minimum is observed at \( |I_D| \approx 10^{-8} \text{ A} \). Neither the MF nor the carrier NF mechanisms can explain the observed behavior. A better understanding is possible considering the input referred voltage noise \( S_{VG} = (S_{ID}/I_D^2)/(g_m/I_D)^2 \), shown in Fig. 5. The measured \( S_{VG} \) can be successfully interpreted in the context of a multi-trap CMF model [10]:

\[
S_{VG} = \sum_i S_{VFB,i} \left[ 1 + a_i \mu_i C_{ox} \left( \frac{I_D}{g_m} \right) \right] ^2
\]

where the sum extends over the generic trap-type \( i \), \( S_{VFB,i} \) is the flat-band gate voltage PSD, \( N_{T,i} \) is the trap density,
\( \lambda \) is the tunneling parameter, \( \alpha_i \) is the scattering parameter, \( \mu_i \) is the effective mobility in the active layer and \( C_{ox} \) is the oxide capacitance. Since \( \lambda \) depends on quantities which are not exactly known, like effective mass and barrier height, we consider only the ratio \( N_{T,i} = N_{T,i}/\lambda \). Any combination of traps and parameters in Eq. 1 results in a quadratic form for \( \sqrt{S_V G} \). The shape of the measured noise in Fig. 5 is not compatible with the presence of a single type of trap.

In fact if \( \alpha > 0 \) (donors) the plot would be monotonic, while if \( \alpha < 0 \) (acceptors) the plot would have a null (unphysical). Fig. 5 shows also a quadratic fit over the entire noise data set that is in good agreement with the CFM model (Eq. 1). Since only three parameters are obtained from the fit, the extrapolation of the properties of each single trap-type is not possible. The influence of different traps is different depending on the gate bias point. In the subthreshold region the decrease of the measured noise suggests that acceptors are present but we cannot exclude significant contributions coming from different acceptors and/or donors. In the strong accumulation region we were able to linear fit \( \sqrt{S_V G} \) with respect to \(-I_D/\overline{g}_m\). This means that in the strong accumulation region the noise is mostly due to a single trap-type. Following this approach we extrapolated the values of \( N_T \) and \( \alpha \), equals to \( 3.2 \times 10^{12} \, \text{cm}^{-2} \, \text{eV}^{-1} \) and \(-1.6 \times 10^7 \, \text{Vs/C} \) respectively. It should be pointed out that even adopting different assumptions (for example the same \( \alpha \) for all traps) we obtained values for \( N_T \) and \( \alpha \) of the same order of magnitude as for the case of dominant trap approximation.

IV. SUMMARY AND CONCLUSION

From accurate and extensive noise analysis of the noise produced by OTFTs in the linear region we can conclude that, differently from the majority of the published results, the behavior of LFN can only be interpreted in terms of a multi-trap CFM model. The fact that noise measurements have been performed covering more than 4 decades of bias current with unprecedented resolution in terms of number of noise measurement points per decade and that the noise behavior is consistently reproduced among different devices strongly support our conclusions. Assuming the presence of a dominant trap-type in the strong accumulation region, we extrapolated a value of the trap density \( 3.2 \times 10^{12} \, \text{cm}^{-2} \, \text{eV}^{-1} \) which is much higher with respect to conventional c-Si MOSFETs, as notes in several publications on OTFTs [6], [7]. More importantly, we have been able to estimate the value of the scattering parameter \( \alpha \). Its value is much higher (in absolute value) with respect to the case of conventional c-Si MOSFETs \(( \sim 10^7 \, \text{Vs/C} \) vs. \( 10^7 \, \text{Vs/C} \)). It can be noted that similar \( \alpha \)-\( \mu \)-values found from the present analysis \(( \alpha \mu \sim 3 \times 10^7 \, \text{cm}^2/\text{C}) \) have been reported for hydrogenated amorphous silicon (a-Si:H) TFTs [15] \(( \alpha \mu = 2 \times 10^7 \, \text{cm}^2/\text{C}) \), suggesting that in disordered materials the CFM parameter \( \alpha \) can be relatively high when compared to c-Si MOSFETs.

REFERENCES