Doping and Illumination Dependence of $1/f$ Noise in Pentacene Thin-Film Transistors

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***Abstract*—We characterize the influence of interfacial trap sites on carrier scattering and subsequent contribution to channel noise by taking $1/f$ noise measurements on pentacene organic field-effect transistors (OFETs). The noise dependence on drain current from OFETs with UV-ozone treated parylene gate dielectric before the deposition of the semiconductor is compared to that of otherwise identical OFETs with no air exposure during fabrication. Our studies indicate a different noise characteristic in the two samples, which is further confirmed by increasing the carrier density under illumination and comparing the noise spectrum for photogenerated charges with gate-field-induced carriers.**

***Index Terms*—Charge carrier mobility, field-effect transistors (FETs), organic compounds, thin-film transistors.**

I. INTRODUCTION

ORGANIC field-effect transistors (OFETs) operate in accumulation [1] with a trap-dominated hopping conduction mechanism [2], [3]. Because of the larger aggregate density of scattering sites among molecules and transport-related trapping events, flicker noise ($\sim 1/f^{\beta}$, $\beta \cong 1 \pm 10\%$) is present at a higher power level than at silicon-based MOSFET devices with comparable current drive [4]. It has been shown that the flicker noise power in OFETs depends on the semiconductor properties [4]–[6], device structure [4], [5], deposition conditions [7], semiconductor microstructure [8], and bias condition [4] and [7]. OFETs can be intentionally [9] and unintentionally doped by electronegative oxygen-containing groups on the surface of polymer gate dielectrics. These groups are responsible for shifted turn-on voltage [9], [10]. Wavelength-resolved photocurrent spectrum in OFETs [11] confirmed these extra trapping states formed at the interface of semiconductor and dielectric layers in UV-treated OFETs. However, the influence of these charged sites on carrier scatter and subsequent contribution to channel noise is not well understood.

This study examines the noise contribution of the interfacial states by comparing the noise characteristics of OFETs whose polymer gate dielectric is exposed to UV ozone prior to semiconductor deposition with control OFETs whose semiconductor/gate dielectric interface is produced in a nearly oxygen-free environment.

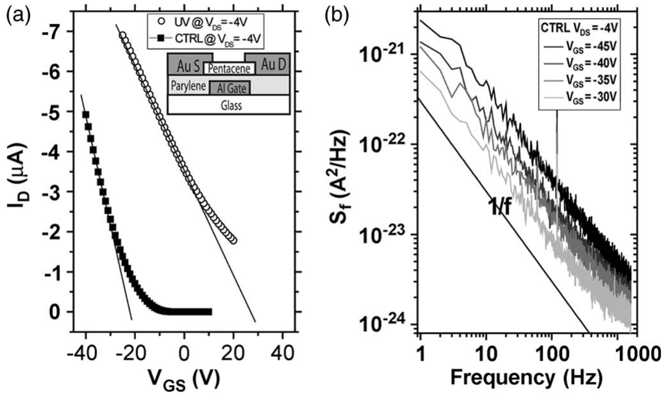

Fig. 1. (a) I_D as a function of V_{GS} in the linear region for devices whose dielectric is exposed to UV ozone prior to the deposition of pentacene (UV: Empty circles) and control devices that see no exposure to air (CTRL: Solid squares). The threshold voltage of the UV-ozone sample is shifted toward positive voltage with respect to the control sample. Inset: Cross-sectional schematic for pentacene OFET. (b) Noise power spectra for a control device show that noise power increases with more negative gate voltages or larger drain current.

II. EXPERIMENT

The devices used are pentacene OFETs with a parylene-C gate dielectric fabricated on glass substrates using a bottom-gate top-contact structure (Fig. 1(a) inset). The gate, semiconductor, and source–drain contacts are patterned using shadow masking. Thermal evaporation of 60-nm-thick Al gate electrodes is followed by the deposition of a blanket layer of 200-nm parylene-C as a gate dielectric in a custom chemical vapor deposition (CVD) system. Some 25 nm of pentacene is vacuum evaporated at a rate of 0.1–0.2 A/s with the substrate held at room temperature at a pressure $< 5 \times 10^{-7}$ torr. Au source and drain contacts are then thermally evaporated. All of the evaporation and CVD systems open and vent into the same glovebox cluster which is continuously scrubbed for oxygen and water ($<$ 0.1 ppm for both). The control OFETs are fabricated without any significant exposure to oxygen or water vapor. At the same time, the parylene dielectric on another sample set is both exposed to air and treated with air-generated mercury lamp UV-ozone system for 20 min prior to the pentacene deposition [9]. The control and UV-treated samples are placed into the pentacene evaporator at the same time to avoid any process variation, and more than 100 devices are fabricated on each sample with a representative sample set examined on both.

We employ the noise measurement configuration from the study in [12], and all the experiments are done in air. A semiconductor parameter analyzer (Agilent 4155C) provides the gate voltage and a low-noise transimpedance preamplifier (Stanford Research 570), which is battery powered, provides the drain bias, and measures the drain current. The two units

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share a common ground which is also connected to the source contact of the device. A spectrum analyzer (Agilent 35670A) is used to record the noise power spectrum in the frequency range of 1 Hz–1.6 kHz. Each spectrum is the result of the rms averaging of 30 measurements.

III. RESULTS AND DISCUSSION

Fig. 1(a) shows drain current I_D as a function of gate voltage V_{GS} under drain–source voltage $V_{\mathrm{DS}} = -4$ V, for both UV-treated (empty circles) and control (solid squares) OFETs in the linear region of operation. The two devices have identical geometries $(W/L = 860\ \mu\mathrm{m}/50\ \mu\mathrm{m})$ and structure, but the turn-on voltage in the UV-treated sample is shifted positive relative to the control due to the trapped negative charge layer at the semiconductor–dielectric interface [9]–[11]. The voltage shift value depends on the ozone exposure time [13].

It is generally believed that flicker noise in OFETs is generated by the hopping of carriers between trap sites. However, there is no agreement [4], [7], [14] on whether the noise generation mechanism in OFETs is caused by a carrier number fluctuation (as in the McWhorter model: trapping–detrapping of carriers in traps situated in the gate oxide, near or at the semiconductor/dielectric interface) or mobility fluctuation (as in the Hooge model: a bulk scattering phenomenon and cross-sectional fluctuations) [15], [16]. Martin *et al.* [4] and Ke *et al.* [14] suggest the number fluctuation model, although both believe that the interaction between carriers and gate oxide is very unlikely. Despite the difference of transport and noise mechanisms in OFETs and Si MOSFETs, we take the empirical expression describing the noise power density in a transistor [4]

$$S_f = \frac{K_F}{C_{\mathrm{OX}} L^2} \cdot \frac{I_D^{\alpha}}{f_{\beta}} \tag{1}$$

where K_F is the fractional flicker noise coefficient, I_D is the drain current, L is the channel length, C_{OX} is the dielectric capacitance per unit area, and f is the frequency (in hertz). α and β are constants which relate to the energy distribution of noise-inducing states with $\alpha \sim 1 - 2$ and $\beta \sim 1 \pm 10\%$.

Fig. 1(b) shows the noise power spectrum (S_f) from a control OFET as the gate bias varies. The noise increases as the gate biases become more negative (when the device is more accumulated). This is also true for UV-treated samples (data not shown). All the spectra follow $1/f$ trend, and specifically, $\beta \sim 0.95 \pm 0.05$ for control OFETs and $\beta \sim 1.00 \pm 0.05$ for UV-treated OFETs. $|\beta|$ tends to increase slightly with more negative gate bias in all samples. In control samples under less negative gate bias, noise spectra bend up slightly in the high-frequency region since thermal noise ($\sim 4k_B T/R$, where k_B is the Boltzmann constant, T is the absolute temperature, and R is the resistance. For our devices, $4k_B T/R \sim 10^{-26} - 10^{-25}$) becomes more apparent at higher frequencies.

For convenience, we define $K' = (K_F/C_{\mathrm{OX}} L^2) \cdot I_D^{\alpha}$. By fitting the spectra with $S_f = K'/f$, K' can be extracted and plotted as a function of $I_D(V_{\mathrm{GS}})$ for two representative UV-treated OFETs and two control OFETs [Fig. 2(a)]. There are two main differences. First, the noise level in UV-exposed devices is one order of magnitude higher than that in the control devices at the same drain current. Second, the dependence of K' on drain current is different: $\alpha \sim 1.21 \pm 0.03$ and 1.14 ± 0.03 for UV1 and UV2 (UV-treated samples), respectively; $\alpha \sim 1.63 \pm 0.06$ and 1.56 ± 0.05 for CTRL 1 and CTRL 2 (control samples), respectively.

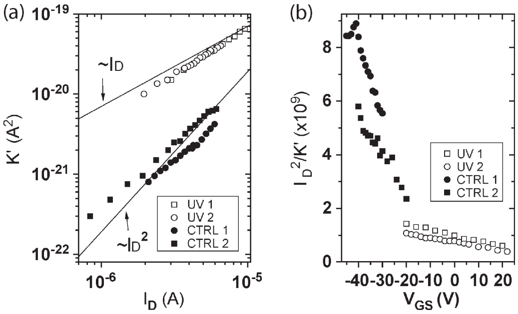

Fig. 2. (a) Plot of K' as a function of varied drain current (I_D, as a result of varied gate bias V_{GS}) for two UV-exposed devices and two control devices. The lines are guidelines of I_D^2 and I_D dependence. Please refer to text for the exact fitting slopes. (b) Plot of I_D^2/K' as a function of V_{GS} for the same devices. The linear dependence indicates a mobility fluctuation model.

Ishigami *et al.* [17] pointed out that, in the linear regime, $I_D^2/K' \propto |V_{\mathrm{GS}}|$ if noise is due to mobility fluctuations and $I_D^2/K' \propto |V_{\mathrm{GS}}|^2$ if noise is due to number fluctuations. Fig. 2(b) shows that all of our samples follow $I_D^2/K' \propto |V_{\mathrm{GS}}|$ with slopes of $(-2.07 \pm 0.06) \times 10^7$ (UV1), $(-1.59 \pm 0.04) \times 10^7$ (UV2), $(-2.8 \pm 0.1) \times 10^8$ (CTRL1), and $(-1.45 \pm 0.09) \times 10^8$ (CTRL2), respectively. Thus, there is no strong evidence of difference in noise generation mechanism between UV-treated and control samples, and the result implies a mobility fluctuation model. According to the empirical Hooge's relation, $S_f = (\alpha_H/N) \cdot (I_D^2/f)$, where N is the total number of carriers and $N = C_{\mathrm{OX}} WL(V_{\mathrm{GS}} - V_{\mathrm{th}})/e$, where W is the channel width, V_{th} is the threshold voltage, e is the charge unit of 1.6×10^{-19} C, and α_H is the Hooge's parameter. Comparing this work $S_f = K'/f$, we have $\alpha_H = N/(I_D^2/K')$. Based on Fig. 2(b), the Hooge's parameter α_H for UV-treated samples is around 1–3, and α_H for control samples is around 0.1–0.3.

UV ozone forms electron-accepting sites—COOH and OH groups—at the surface of dielectric [18], [19], which extract electrons from pentacene and induce holes in pentacene [10], [11]. The trapped electrons form a layer of fixed negative charges, which shifts the threshold voltage [9]. These fixed charges further appear to serve as scattering sites for induced and accumulated holes, leading to a higher noise level.

The UV-induced traps lie outside the HOMO-LUMO gap, and the Fermi level cannot access these states through gate biasing [11]. One possible explanation for the power-law dependence of the UV-treated devices is that a constant number of scattering sites is responsible for the noise, and as a consequence, the noise increases nearly linearly with the available density of carriers to scatter $(\alpha = 1.1)$. The control device, by contrast, is able to access a different density of traps as the Fermi level moves with increasing gate bias, allowing an increasing density of accessible scattering states together with an increased number of carriers. This gives a superlinear response in the noise characteristic $(\alpha = 1.6)$. The ability of states outside the HOMO-LUMO gap to influence transport is a characteristic of disordered semiconductors; carriers are localized and are not thermalized to the frontier gap energies [11].

Photocurrent excitation was also studied as an approach to inject charge into the samples. Photocurrent excitation allows the introduction of charge without changing the Fermi level, permitting probing of the noise characteristic without changing

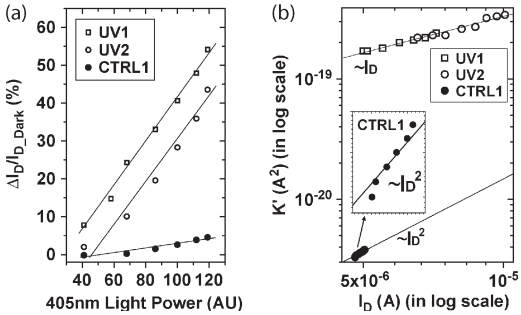

Fig. 3. (a) Drain current change under 405-nm LED illumination as a function of illumination power. The drain current change is calculated as $\Delta I_D/I_{D\_\mathrm{Dark}} = (I_D - I_{D\_\mathrm{Dark}})/I_{D\_\mathrm{Dark}}$. The control sample (solid dots) is under $V_{\mathrm{GS}} = -40$ V and $V_{\mathrm{DS}} = -4$ V. The UV-treated samples (open squares and spheres) are under $V_{\mathrm{GS}} = 0$ V and $V_{\mathrm{DS}} = -4$ V. (b) Plot of K' for control and UV OFETs as a function of varied I_D resulted from illumination. Inset is the zoomed plot of control sample data. The lines in all plots are guidelines of I_D^2 and I_D dependence. Please refer to text for the exact fitting slopes.

the applied bias. It has been shown that 405-nm illumination selectively excites carriers from interfacial states at the interface of pentacene and gate dielectric and is absorbed weakly by pentacene due to its low-absorption cross section above the HOMO-LUMO gap [11], [20]. The OFET channel was illuminated by 405-nm light from a regulated LED, and the drain current before (I_{D_Dark}) and during (I_D) was measured and plotted as $\Delta I_D/I_{D\_\mathrm{Dark}} = (I_D - I_{D\_\mathrm{Dark}})/I_{D\_\mathrm{Dark}}$ [Fig. 3(a)]. The control sample was under $V_{\mathrm{GS}} = -40$ V and $V_{\mathrm{DS}} = -4$ V. The UV-exposed sample is under $V_{\mathrm{GS}} = 0$ V and $V_{\mathrm{DS}} = -4$ V. In the UV-treated OFETs, the illumination excited more carriers than the control device and led to a greater photocurrent magnitude.

The $1/f$ noise spectrum for the UV-treated device follows $K' \sim I_d^{\alpha}$ with $\alpha \sim 0.96 \pm 0.05$ for UV1 and 1.1 ± 0.1 for UV2 [Fig. 3(b)]. The noise level is generally higher than that without light exposure (Fig. 2). For the control device, the noise level is comparable to that in Fig. 2 but with an $\alpha \sim 2.8 \pm 0.2$. When 405-nm light is applied to the channel, photons (3.1 eV) appear to transfer excess energy to excited pentacene molecules, making the electron transfer more effective from pentacene to O and O–O bonds at the dielectric surface, which is treated by UV ozone and generating holes into the channel [10], [11], [20]. We observe that the noise level from these photogenerated carriers is higher than that from the gate-accumulated carriers. The significant increase in the slope of the noise characteristic in the control device is possibly caused by the photoexcitation of carriers from filled states, leading to an increase in available scattering sites. Further investigation of this effect is underway.

IV. CONCLUSION

We have examined the influence of gate dielectric surface groups introduced by UV-ozone treatment on the $1/f$ noise characteristics of OFETs. Devices with a UV-ozone treated gate dielectric were compared to otherwise identical control devices fabricated without an air break. Noise power in the control devices is one order of magnitude lower than that in UV-treated OFETs and proportional to $I_D^{1.6}$. Noise in the UV-treated samples is proportional to $I_D^{1.1}$. We attribute the main noise source in the UV OFETs to acceptorlike traps at the interface of the semiconductor and dielectric introduced by UV treatment of the dielectric. We also confirmed that the same noise spectrum, and therefore mechanism, holds for photogenerated charges in the UV-treated samples. An increased noise slope is observed in the photogenerated charges in the control samples, possibly because of an interaction with available trap states in those devices.

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