1/f noise in pentacene and poly-thienylene vinylene thin film transistors

L. K. J. Vandamme,[a)] R. Feyaerts, and Gy. Trefán
Department of Electrical Engineering EH 5.15, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

C. Detcheverry
Philips Research Laboratories, 5656 AA Eindhoven, The Netherlands

We investigate low frequency conductivity noise in the drain-source channel of organic material field-effect transistors by measuring the spectra of current fluctuations for several values of the gate voltage V_{gs} and drain voltage V_{ds} and find that it is 1/f. The samples are biased in the ohmic range of the applied V_{ds}. The relative current 1/f noise is inversely proportional to the charge carrier numbers N generated by illumination or by varying the gate-source voltage. Hooge's empirical relation for the 1/f noise is validated for these organic semiconductors with an $\alpha \cong 0.01$ for poly-thienylene vinylene and about 100 for pentacene thin film transistors. From geometry dependence of the noise we conclude that series resistance can be ignored for poly-thienylene vinylene field-effect transistors. However, some pentacene samples suffer from a noisy series resistance to the channel resistance. From the 1/f noise dependence on geometry and gate voltage bias we conclude that it can be used as a diagnostic tool for device quality assessment. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1423389]

I. INTRODUCTION

Electrical characteristics[1–3] and noise[4–6] in organic materials has been studied to improve the knowledge of the electrical properties. Here we test again if the empirical relation for the 1/f noise used for metal and semiconductors[7] is also applicable for organic materials as was shown already in Refs. 4–6. Our aim is to test if 1/f can be used as a diagnostic tool for device quality assessment. In most conductive materials submitted to homogeneous fields one observes a 1/f noise if the number of free carriers is less than 10^{14}. According to Hooge's empirical relation under constant voltage conditions, the current fluctuations S_I/I^2 are for homogeneous samples submitted to homogeneous fields

$$\frac{S_I}{I^2} = \frac{\alpha}{Nf} \tag{1}$$

with the number of free charge carriers given by $N = l^2/q\mu R$ where R is the sample resistance, l the length of the resistor and μ the mobility of free charge carriers and q the elementary charge.

To achieve these objectives we do noise measurements by varying channel lengths, the biasing and illumination, to check whether the relative noise is inversely proportional to the number of free carriers N. Here we discuss the noise properties of poly-thienylene vinylene (PTV) and pentacene samples produced by Philips Research Laboratories.[1–3] The low frequency noise analysis turns out to be a superior diagnostic tool for quality problems with some devices.

II. SAMPLES AND MEASUREMENT SETUP

Samples are designed as field-effect transistors (FET) and constructed in a bottom drain and source contact thin film transistor layout.[3] The polysilicon on top of a glass substrate forms the gate electrode (first layer), topped with an about 0.25-μm-thick oxide layer that forms the gate oxide (second layer). Gold source and drain electrodes are defined with conventional lithography (third layer). The top layer (channel) is made from a spin coated organic material that is PTV or pentacene. The FETs have p-type channels, with widths $W \approx 500$ or $1000 \ \mu$m and lengths $L = 1.25$, 2.5, 5, 10, 20, and 40 μm, respectively. The FETs operate in accumulation. To contact the drain and source we scratch through the polymer layer. To measure the noise we use a shielded probe station. Due to the low conductivity of polymers the sample resistances R_{ds} are in the GΩ range. Noise due to conductance fluctuations in sample impedances higher than the input resistance R_{iV} of a low noise voltage amplifier can be better observed with a low-noise current (transconductance) amplifier (Brookdeal 5002) in series with the impedance. Then the current fluctuations S_I are measured under a constant voltage bias as is shown in Fig. 1 with R_V short circuited. With a current amplifier the corner frequency between the thermal noise and the 1/f noise of the sample is higher and conductance fluctuations can be investigated better over a larger bandwidth.[8] The conductance between source and drain is changed either by applying a gate voltage or illumination. The pentacene samples were illuminated from a distance of about 50 cm using a 12 V dc, 100 W halogen lamp of which we vary the current in steps of 2 A.

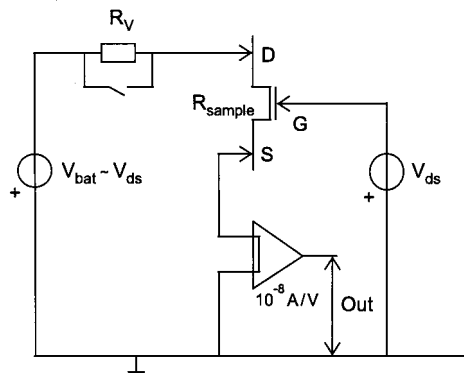[a)]Electronic mail: L.K.J.Vandamme@tue.nl

FIG. 1. On-wafer level measurement setup. The drain-source current is set by a battery for the drain with voltage $V_{bat} \sim V_{ds}$ and another battery for the gate with voltage V_{gs}, both can be changed in steps. The current fluctuations in I_{ds} are amplified by a Brookdeal 5002 low-noise current amplifier whose output is lead in an HP 3566A or Advantest R9211E spectrum analyzer in a bandwidth from 1 Hz up to 100 kHz.

III. RESULTS

A. PTV

PTV samples have a spaghetti-like microstructure. They are easily damaged by high fields ($E > 18$ kV/cm) and electrostatic discharge. Their drain and source resistances in dark are between 5 MΩ and 10 GΩ for gate voltages of about -9 to -22 V. Settling times after changing the bias conditions are rather short, and therefore the drift during the measurements is relatively small. This is important in order to suppress the $1/f^2$ drift contributions in the spectrum at low frequencies.

We measured the spectra of current fluctuations at a fixed gate-source voltage while changing drain voltages ($V_{ds} = -1.5, -3.0, -4.5$ V). We found that they are $1/f$ (see Fig. 2) except at $f < 3$ Hz where the spectra suffer from a drift contribution. Since $I \propto V_{ds}$ and $S_I \propto I^2$ the sample is ohmic in the range of applied V_{ds}. We investigated for a given geometry S_I/I^2 vs V_{gs} and found $S_I/I^2 \propto 1/V_{gs}$ in

FIG. 3. The relative noise S_I/I^2 taken at $f = 1$ Hz dependence on the gate voltage V_{gs}. The inverse proportionality with V_{gs} is expected, because the relative noise in Ohmic samples is inversely proportional to the number of free carriers ($N \propto V_{gs}$) and $S_I/I^2 = \alpha/Nf$ at least if α is V_{gs} independent.

agreement with Eq. (1). We measured the dependence of the relative noise on the gate voltage V_{gs}. We found that $S_I/I^2 \propto 1/V_{gs}$ as is expected and shown in Fig. 3. We also investigated how the noise depends on the geometry since the samples have different lengths $L = 5, 10, 20, 40$ μm (FETs with channel length of $L \leq 2.5$ μm often were detected to be short circuits), respectively. We measured the low frequency current noise S_I at $V_{gs} = -9$ to -22 V and $V_{ds} = -1.5$ to -4.5 V. We found $S_I/I^2 \propto 1/L$ which is in agreement with the empirical relation for ohmic samples (see Fig. 4). Calculated α values using Eq. (1) are in the range of 0.01-0.08 using mobilities $\mu = 10^{-4} - 10^{-3}$ cm^2/V s. These are observed mobilities calculated from a relation $\mu = L^* g_m/(WC_i V_{ds})$ where $g_m = dI/dV_{gs}$ the transconductance and C_i the oxide capacitance per unit area.
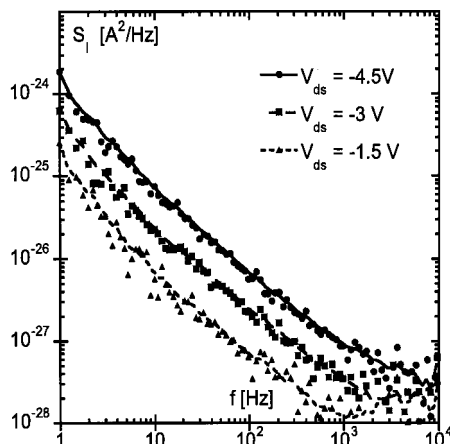

FIG. 2. Current noise spectra S_I in a PTV sample for drain-source voltages $V_{ds} = -1.5, -3,$ and -4.5 V, respectively. The spectra show $1/f$ and background noise. The spacing indicates different drain-source current levels.
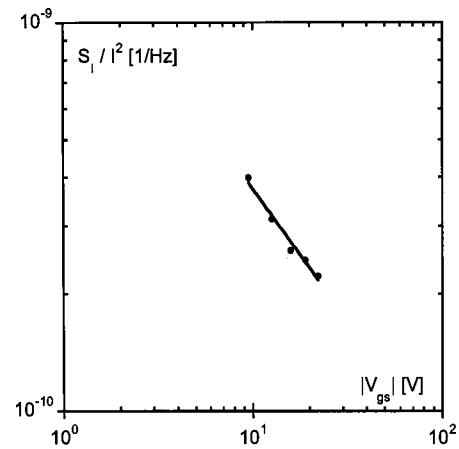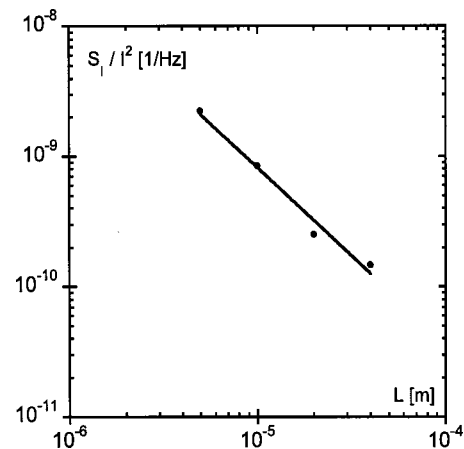

FIG. 4. Geometry dependence of the relative current $1/f$ noise on a PTV sample. S_I/I^2 (taken at 1 Hz with $V_{ds} = -3$ V and $V_{gs} = -15.9$ V) is inversely proportional with channel length L because $S_I/I^2 \propto 1/N \propto 1/L$ for samples biased at the same V_{gs} and having the same width. This fact indicates an ohmic sample without serious contact noise contributions and proves the validity of the empirical relation of Eq. (1).
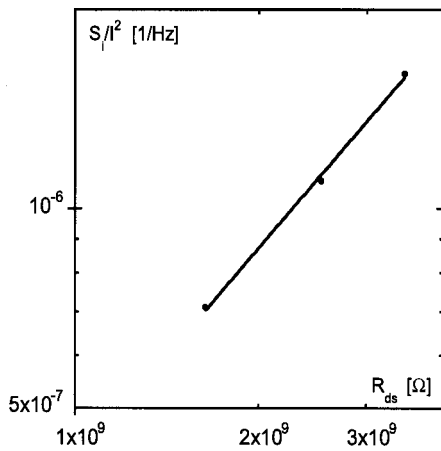
FIG. 5. Illumination effects on the relative noise on a pentacene sample. The relative noise S_I/I^2 measured at 1 Hz varies linearly with the channel resistance R because $S_I/I^2 \propto 1/N \propto q\mu R/L^2$ where μ is mobility, q elementary charge and R channel resistance, respectively. The resistance changes are due to the generation of free carriers by illumination.

B. Pentacene

The pentacene samples are more robust than PTV samples with respect to aging. However, their impedance in dark is even higher ($10^9 - 10^{11}$ Ω) which leads to noise detection problems even with low noise current amplifiers. However, by shining light on pentacene samples extra charge carriers are generated so illumination decreases the sample resistance ($R \propto 1/N$) down to 1/3 of the dark value and also the relative noise S_I/I^2. This kind of optical suppression of $1/f$ noise was also observed in silicon, GaAs and GaAlAs which is in support of the empirical relation.[9–11] Through resistance measurements we found that measured at 1 Hz $S_I/I^2 \propto R_{ds}$ (see Fig. 5). This result shows the validity of the empirical relation for the current $1/f$ noise in pentacene as was found already in semiconductors under illumination.[9–11] The calculated α values from Eq. (1) were of about 1–100 using mobilities $\mu = 10^{-5} - 10^{-4}$ cm^2/V s. The mobilities were calculated for PTV from measuring transconductance and the oxide capacitance. Our mobility values $10^{-5} - 10^{-4}$ cm^2/V s are typical for granular pentacene[12] and 3–4 orders of magnitude lower than mobilities of single crystal pentacene.[13]

IV. ON CALCULATING THE RESISTANCE AND α IN RADIAL FIELDS

Doing $1/f$ noise measurement with the aim of obtaining a reliable α value for quality assessment of material one has to analyze the measurement data carefully.[14] Our samples have concentric circular source and drain electrodes which leads to radical fields between the electrodes. The inner circle with radius r_1 functions as drain, the outer circle with radius r_2 functions as source. In our analysis for resistance and noise dependence on geometry the radial field between the concentric electrodes is approached as homogeneous. We will now investigate if this is a correct approximation. The relative noise S_R/R^2 in such a structure is not given by Eq. (1) but N has to be replaced by an N_{eff} and for the relative noise we find[15]
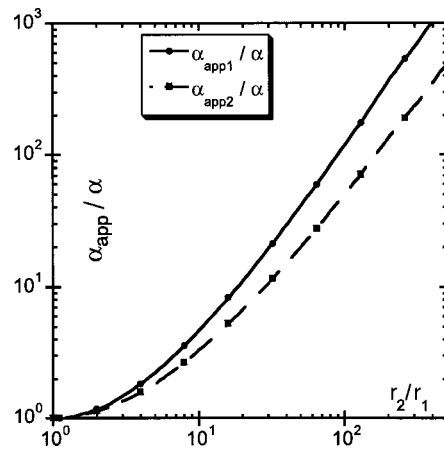

FIG. 6. Differences between the apparent α and the real α due to ignoring radial field effect by treating the sample as if it were submitted to a homogeneous electric field.

$$\frac{S_R}{R^2} = \frac{\alpha[1/r_1^2 - 1/r_2^2]}{4\pi tn[\ln(r_2/r_1)]^2 f} \quad (2)$$

with t being the thickness of the layer and n the free carrier concentration. If the α parameter is calculated by overlooking the nonhomogeneity of the field and is calculated from the experimentally observed relative noise at 1 Hz (fS_R/R^2) given by Eq. (2) and by multiplying it with $N = \pi(r_2^2 - r_1^2)tn$, it results in an apparent α_{app1} which is always larger than the real α like

$$\frac{\alpha_{\text{app1}}}{\alpha} = \frac{(r_2^2 - r_1^2)(1/r_1^2 - 1/r_2^2)}{4[\ln(r_2/r_1)]^2} \quad (3)$$

The continuous line of Fig. 6 shows the error in terms of the ratio $\alpha_{\text{app1}}/\alpha$ as a function r_2/r_1. If α is calculated by overlooking the radial field but thus applying $N = L^2/q\mu R$ which holds for homogeneous samples submitted to homogeneous fields, then we find an error $\alpha_{\text{app2}}/\alpha$ which is expressed by

$$\frac{\alpha_{\text{app2}}}{\alpha} = \frac{(r_2 - r_1)^2(1/r_1^2 - 1/r_2^2)}{2[\ln(r_2/r_1)]^3} \quad (4)$$

This error $\alpha_{\text{app2}}/\alpha$ is shown by the dashed line in Fig. 6. Figure 6 shows that in the range of $1.01 < r_2/r_1 < 1.5$ $\alpha_{\text{app1}} \approx \alpha_{\text{app2}} \approx \alpha$, within an error of less than 10%.

The resistance in a radial field is given by

$$R = \frac{\rho}{2\pi t} \ln(r_2/r_1) \quad (5)$$

instead of our approximation $R_a = \rho(r_2 - r_1)/2\pi tr_1$. However, all discussions about geometry dependence in terms of $L = r_2 - r_1$ are correct because the error $R_a/R = (r_2/r_1 - 1)/\ln(r_2/r_1)$ is negligible in the range $1.01 < r_2/r_1 < 1.5$. Hence overlooking the complication due to the radial fields in the calculations of resistance and α does not result in large errors for our samples.
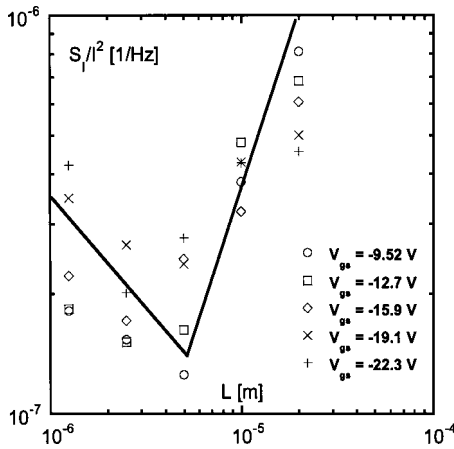
FIG. 7. Some anomalies in $S_I/I^2(L)$ in pentacene. In high quality samples the proportionality $S_I/I^2 \propto 1/L$ should be observed as in Fig. 4.

V. ON 1/f NOISE AS A DIAGNOSTIC TOOL

Sometimes we face a situation when current–voltage characteristic indicates a normal device but the low frequency noise analysis indicates quality problems with that device.[16] In these cases the low frequency noise analysis turns out to be a superior diagnostic tool. For instance, in a normal device the relative noise $S_I/I^2 \propto 1/L$ and $1/V_{gs}$. If this proportionality does not hold we consider the device noise anomalous. In some of our pentacene samples we observed that the relative noise S_I/I^2 grows with the length L (see Fig. 7) for FETs whose channel length $L > 5$ μm. We also observed that in some pentacene samples the relative noise S_I/I^2 grows with the gate voltage V_{gs} (see Fig. 8). In both of the above cases the noise is anomalous. Here we offer four possible explanations for the origins of anomalous noise: (i) a parasitic conductance situated parallel with the channel, (ii) a parasitic resistance in series with the channel, (iii) the dependence of carrier mobility on the gate voltage V_{gs} and (iv)
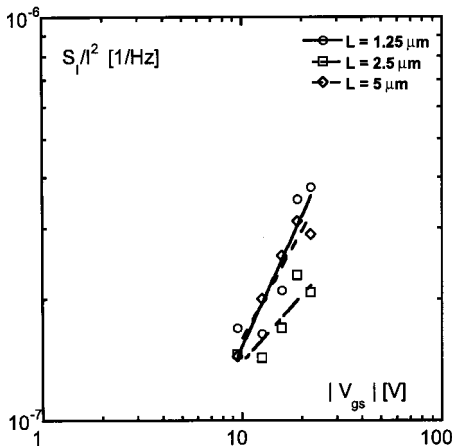

FIG. 8. Some anomalies in $S_I/I^2(V_{gs})$ in pentacene. In a high quality sample the proportionality $S_I/I^2 \propto 1/V_{gs}$ should be observed as in Fig. 3. The increase in relative noise with gate voltage is typical for samples which have a small series resistance with respect to the channel resistance, but the noise of this series resistance is much larger than the noise in the channel resistance as in Ref. 18.

TABLE I. Complications that explain anomalous relative noise dependence $S_I/I^2 \propto L^x$ with $x \neq -1$ and $S_I/I^2 \propto V_{gs}^y$ with $y \neq -1$.

Dominant term in G or R	Dominant term in S_G or S_R	$S_I/I^2(L)$	$S_I/I^2(V_{gs})$
$G \approx G_{ch} \propto L^{-1}$	$S_G \approx S_{G_p}$	L^2 if $S_{G_p} \propto L^0$, V_{gs}^0	V_{gs}^{-2}
$G \approx G_{ch} \propto L^{-1}$	$S_G \approx S_{G_p}$	L^{-1} if $S_{G_p} \propto L^{-3}$, V_{gs}^0	V_{gs}^{-2}
$R \approx R_{ch}$	$S_R \approx S_{R_s}$	L^{-2}	V_{gs}^2

the noise generated by an injection-type current–voltage characteristic, respectively. We note here that in investigating the noise as a function of geometry in an L array (a set of devices all having the same width but different length L) we assume that the conductance G and noise parameter α are uniform over the set. If this is not the case then the L-array analysis is not applicable.

When considering the complications [case (i)] due to a parasitic parallel conductance G_p to the channel conductance G_{ch} with total conductance is $G = G_{ch} + G_p$ and noise $S_G = S_{G_{ch}} + S_{Gp}$ we assume that the conductance is normal and dominated by the channel, i.e., $G \approx G_{ch} \propto L^{-1}$ but the emerging noise is dominated by the parasitic conductance, i.e., $S_G \approx S_{G_p}$ that does not depend on the gate voltage V_{gs}. Our experiments suggest that the parasitic conductance noise S_{G_p} must be independent of the channel length L for $L < 5$ μm and inversely proportional to it for $L > 5$ μm in order to obtain a relative current noise shown in Fig 7. This noise is anomalous since normally it should be $S_{G_{ch}} \propto L^{-3}$.

The complication [case (ii)] takes into account a parasitic noisy resistance R_s in series with the channel generating noise S_{R_s}. Both R_s and S_{R_s} are considered to be independent of L as in Refs. 17 and 18. For parasitic series resistance problems we have $R = R_{ch} + R_s$ and $S_R = S_{R_{ch}} + S_{R_s}$ with a dominating channel resistance ($R = R_{ch}$) and parasitic resistance noise ($S_R = S_{R_p}$). Then the anomalous relative noise derives from a length independent parasitic resistance with noise S_{R_s} becomes proportional to L^{-2}. Table I summarizes the abovementioned considerations to explain anomalous trends in the relative current noise.

The type of complication [case (iii)] to explain x and y different from -1 is the 1/f noise parameter α dependence on mobility μ.[7,19] The mobility is weakly dependent on the gate voltage.[3] If $\alpha \propto \mu^x$ with $x \approx 2$ and $\mu \propto V_{gs}^y$ we find $S_I/I^2 \propto V_{gs}^{xy-1}$. Here we took into account how the channel resistance R depends on the gate voltage V_{gs}, i.e., $R \propto 1/n\mu \propto 1/V_{gs}V_{gs}^y$. Now we consider $xy = 1$ with $x = 2$ and $y = \frac{1}{2}$ which means that we use a well established dependence of α on μ observed in semiconductors and a weak dependence of μ on V_{gs} as suggested in Refs. 2 and 3. Such a behavior results in a $S_I/I^2 \propto L^{-1}$ that was observed for short channels (see Fig. 7) and $S_I/I^2 \propto V_{gs}^0$ which was not observed (see Fig. 8).

The last complication [case (iv)] considered explaining at the same time a nonohmic current–voltage characteristic and a $S_I/I^2 \propto V_{gs}^y$ with $y \neq -1$ is the injection type of behavior on a microscopic scale between two pentacene single crystals grains. For the current–voltage characteristic then

holds[20] a proportionality in the current–voltage characteristic as $I \propto V^2$. For the noise then holds[20] the proportionality $S_I \propto I^2/V$. So the relative noise for a fixed gate voltage then becomes $S_I/I^2 \propto V^{-1} \propto I^{-1/2}$. Some of our experimental results are in agreement or at variance with the abovementioned trends.

The best candidate to account for the anomalous noise seems to be (ii) when we assume a noisy series resistance in the channel dominating the noise of the channel but not its resistance. This has often been observed in submicron metal-semiconductor transistors, high electron mobility transistors[17] and metal-oxide-semiconductor (MOS) transistors.[18,21,22]

VI. ON BIAS AND GEOMETRY DEPENDENCE AS SHOWN IN LITERATURE

Necliudov *et al.* found[6] in bottom contacted samples which have similar contacts to our pentacene samples, there is a nonlinearity of the injection diode type for small values of the V_{ds}. They suspected that it was caused by poor contact edge coverage due to shadowing of the source and drain contacts. This would explain high local fields and the injection-like behavior in the $I_d - V_{ds}$ curves. From their noise results we can derive a dependency of $S_I/I^2 \propto V_{ds}^{-1/2}$ and the rather normal dependence $S_I/I^2 \propto V_{gs}^{-1}$, which is also present in our longest pentacene samples. The α values that they present for bottom contacted samples are in the range 5–20, which is again in agreement with what we found in pentacene.

The existence of series resistance contributions in organic thin film transistors can be observed as well from the results by Martin *et al.* in Ref. 4. From their survey we observe that the relative noise is proportional to L^{-3} in samples with channel lengths of $L \geqslant 12$ μm which point to a channel without series resistance contributions. This is true since: $S_I \propto I^2 * \alpha/N \propto (W/L)^2 * 1/(WL) \propto W/(L^3) \propto L^{-3}$. However, for lower values of the channel length as often occurs this proportionality no longer holds, indicating a limit caused by a series resistance.

VII. CONCLUSIONS

The low frequency noise in PTV samples is due to conduction fluctuations and has the typical $1/f$ spectrum. In the ohmic region under a constant gate voltage S_I/I^2 remains constant with I and with an increasing gate voltage the number of free carriers (holes) increases and the relative $1/f$ noise drops as predicted in the empirical relation $S_I/I^2 \propto 1/N \propto 1/V_{gs}$. The pentacene samples have a lower concentration of free carriers than PTV samples and they are more sensitive to light. Under constant bias voltage at drain (-4.5 V) and gate (-22 V) the relative noise S_I/I^2 drops with increasing light illuminations (Φ) as by the empirical relation

$S_I/I^2 \propto 1/N \propto R_{ds}(\Phi)$. Our PTV thin film transistors show no contact noise contributions, as it was observed from the noise versus geometry (W/L) relations. However, pentacene samples suffered from series resistance contact noise, while the resistance between source and drain was still dominated by the channel resistance which was under control of the gate voltage.

From our noise under illumination investigations it becomes clear that the free carrier transport process in PTV and pentacene is quite different. On one hand, PTV has a behavior considering the $1/f$ noise as in normal MOS transistors except of the much lower mobility. Pentacene FETs, on the other hand, suffer from a low but noisy series resistance. It has been proved again that the $1/f$ noise van should be used as a diagnostic tool for quality assessment of prototype devices.

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