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Scanning Kelvin probe microscopy on organic field-effect transistors during gate bias stress

S. G. J. Mathijssen[a)]
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands and Philips Research Laboratories, High Tech Campus 4, 5656 AE Eindhoven, The Netherlands

M. Cölle and A. J. G. Mank
Philips Research Laboratories, High Tech Campus 4, 5656 AE Eindhoven, The Netherlands

M. Kemerink and P. A. Bobbert
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

D. M. de Leeuw
Philips Research Laboratories, High Tech Campus 4, 5656 AE Eindhoven, The Netherlands

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The reliability of organic field-effect transistors is studied using both transport and scanning Kelvin probe microscopy measurements. A direct correlation between the current and potential of a *p*-type transistor is demonstrated. During gate bias stress, a decrease in current is observed, that is correlated with the increased curvature of the potential profile. After gate bias stress, the potential changes consistently in all operating regimes: the potential profile gets more convex, in accordance with the simultaneously observed shift in threshold voltage. The changes of the potential are attributed to positive immobile charges, which contribute to the potential, but not to the current. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2737419]

Field-effect transistors with an organic semiconductor as the active layer have been studied for several decades. Applications are foreseen in the field of large-area electronics, where numerous discrete devices are integrated on low-cost substrates such as plastics. The mobility of the charge carriers in organic field-effect transistors (OFETs) is already comparable to amorphous silicon based transistors. Values of 1 cm^2/V s have been demonstrated not only for evaporated organic semiconductors,[1] but also using solution processed semiconductors.[2,3] The reliability of OFETs is the final bottleneck for integration in large-area applications, yet the microscopic mechanism affecting the reliability is unknown. So far, reliability studies have mainly been focused on the charge carrier transport by investigating the current as a function of time for different bias conditions.[4]

Here we use scanning Kelvin probe microscopy (SKPM) to measure the surface potential.[5] For field-effect transistors based on unintentionally doped semiconductors, this potential is a measure for the potential at the semiconductor gate dielectric interface.[6] Scanning Kelvin probe microscopy can therefore be used to determine the potential profile within the transistor channel. For unipolar transistors, SKPM has shown to be a powerful method to characterize grain boundaries and contact resistances.[7,8] In this letter we present a direct correlation between the current and potential profiles in the channel for all operating regimes of a transistor. Time dependent SKPM is used to monitor the potential during gate bias stress. In this way, additional local information on the effect of gate bias stress in the channel of a transistor is obtained.

We have made organic field-effect transistors with poly-(triarylamine) (PTAA). This organic semiconductor was obtained from Merck, UK, and yields reproducible *p*-type transistors with a mobility of about $10^{-3}-10^{-2}$ cm^2/V s.[9] The chemical structure is depicted in the inset of Fig. 1(a). The transistors were fabricated using heavily doped *p*-type Si wafers as the common gate electrode with a 200 nm thermally oxidized SiO_2 layer as the gate dielectric. Gold source and drain electrodes were defined by photolithography with a channel width and length of 2500 and 10 μm, respectively. A 10 nm titanium layer was used for adhesion. The SiO_2 layer was passivated with hexamethyldisilazane prior to semiconductor deposition. PTAA films were spin coated from toluene, resulting in a layer thickness of approximately 80 nm.

Scanning Kelvin probe microscopy measurements were performed with a Veeco Dimension 3100 atomic force microscope (AFM) operated at ambient temperature in a dry nitrogen environment. First the height profile was recorded in tapping mode. Then the potential profiles were measured in a noncontact lift mode at a distance of 50 nm from the surface. An internal voltage source of the AFM, coupled to a voltage amplifier (HP 6826A), was used to apply the biases on the electrodes. A current meter (Keithley 6485) was used to measure simultaneously the source-drain current down to 10^{-9} A.

The surface potential was probed with a spatial resolution of approximately 10^2 nm.[8] The absolute values for the measured potentials depend on the capacitive coupling between the AFM probe and the investigated device, which leads to a small offset at the reference source and drain contacts. A simple scaling is done to correct for the deviation of the applied bias and the observed surface potential difference between the source and drain electrodes.[8]

We first investigated the drain current as a function of the applied gate bias V_g. The drain bias V_d was −9 V, the source electrode grounded. Figure 1(a) (black circles) shows

[a)]FAX: +31 40 2746505; electronic mail: s.g.j.mathijssen@tue.nl

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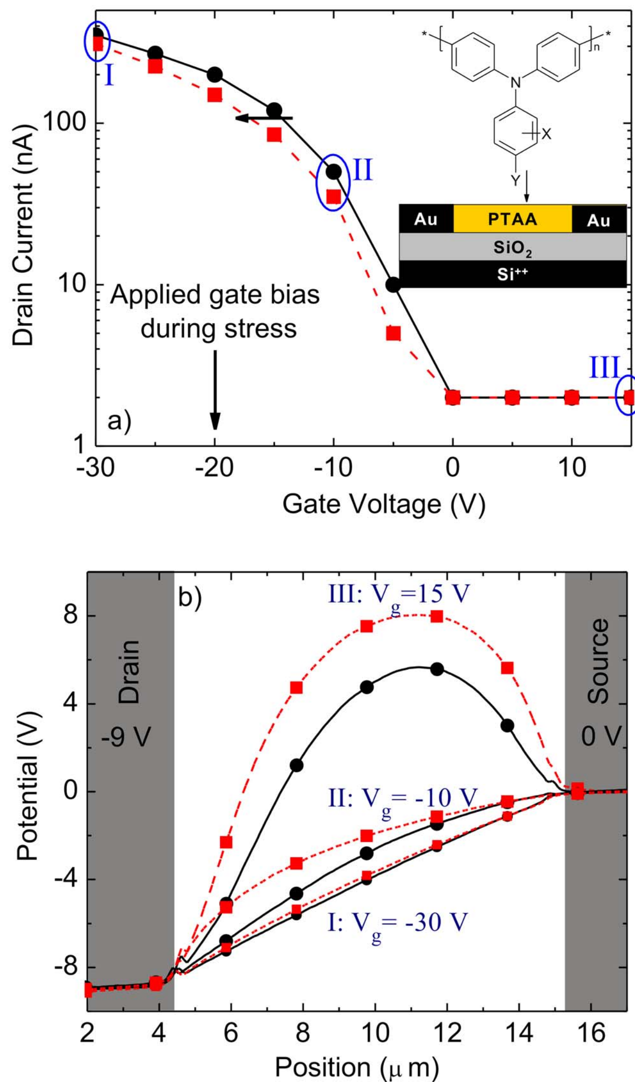

FIG. 1. (Color online) (a) Drain current of a PTAA transistor as a function of gate bias. The drain voltage was −9 V. The source was grounded. The line with black circles represent the transfer curve of a pristine OFET and the one with red squares the drain current after exposure to a gate bias stress of −20 V for 0.5 h. The inset shows the schematic cross section of the transistor and the chemical structure of poly-(triarylamine). (b) Potential profiles corresponding to the transfer curves shown in (a), indicated with I, II, and III for gate biases of −30, −10, and 15 V, respectively. In this graph, the drawn lines with circles and dashed lines with squares represent the potential profiles of the pristine and stressed OFET, respectively.

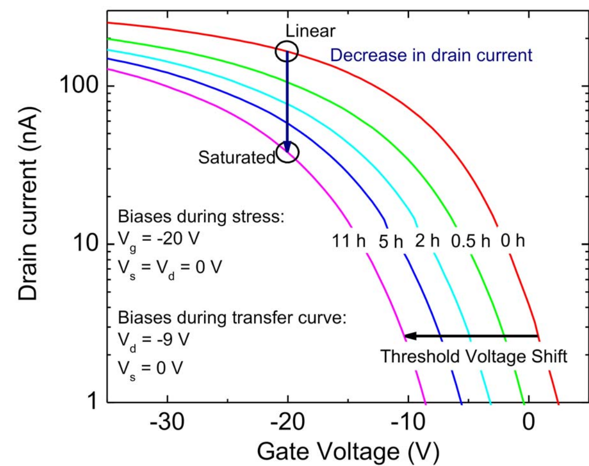

FIG. 2. (Color online) Transfer curves of poly(triarylamine) transistors as a function of stress time. The drain voltage was −9 V. The gate bias during stress was −20 V. The curves shown are taken after 0, 0.5, 2, 5, and 11 h of gate bias stress.

the transfer curve, the drain current as a function of the applied gate bias, of a pristine device. For negative gate biases, a hole-accumulation layer is formed at the insulator-semiconductor interface and current between source and drain is flowing. For positive V_g the transistor is switched off.

Simultaneously with the current we have measured the surface potential. The obtained potential profiles (solid lines with black circles) are depicted in Fig. 1(b) for gate biases of −30, −10, and 15 V. We do not observe an additional contact resistance, which we conclude from the absence of a voltage drop at the source and drain contact.[8] Qualitatively, the potential profiles in accumulation can be explained as follows. In the linear regime when the drain bias (V_d) is much smaller than the gate bias minus the threshold voltage (V_{th}), the charge density is only determined by the applied gate bias and the charge distribution is uniform throughout the channel.[10] Therefore the lateral field due to the small drain bias is constant and the potential profile is a straight line. When the drain bias cannot be neglected, the charge carrier density distribution becomes nonuniform with a decreasing density from source to drain. Since the conductance decreases with decreasing charge carrier density, the continuity of the current density demands that the lateral electric field decreases monotonically from drain to source. Therefore the potential profile is superlinear from drain to source. Hence, increasing the gate bias leads to a transition from the linear to the saturated regime, and the potential profile in the channel gets convex. This development in shape is clearly visible in the potential profiles of Fig. 1(b). When we increase the applied gate bias beyond the threshold voltage, the transistor channel is depleted and a potential barrier appears. This barrier prohibits the positive charge carriers to move from the source to the drain electrode and hence the transistor is switched off, in agreement with the simultaneously measured negligible drain current at positive gate bias.

Under an applied gate bias for a prolonged period of time, we observe a shift of the threshold voltage. As an example, transfer curves are presented in Fig. 2. The applied gate bias during stress was −20 V. The transfer curves were measured at a drain bias of −9 V by sweeping the gate bias from 5 to −35 V. The transfer curves shift with stress time in the direction of the applied gate bias; in Fig. 2 to the left. Five transfer curves are shown, taken after 0, 0.5, 2, 5, and 11 hours, respectively. A shift in threshold voltage indicated by the horizontal arrow corresponds directly with a decrease in current pointed out by the vertical arrow at −20 V. This threshold voltage shift implies a shift from the linear to the saturated regime and, according to the discussion above, an increase in the curvature of the potential profiles is anticipated.

To investigate the influence of gate bias stress on the potential profile we applied a continuous bias of −20 V to the gate and −9 V to the drain. The source electrode was grounded. For 15 h, we have measured the potential profiles between the source and drain electrodes. In Fig. 3 we show seven profiles, with a time interval of 2.5 h in between them. A continuous increase of the curvature of the potential is

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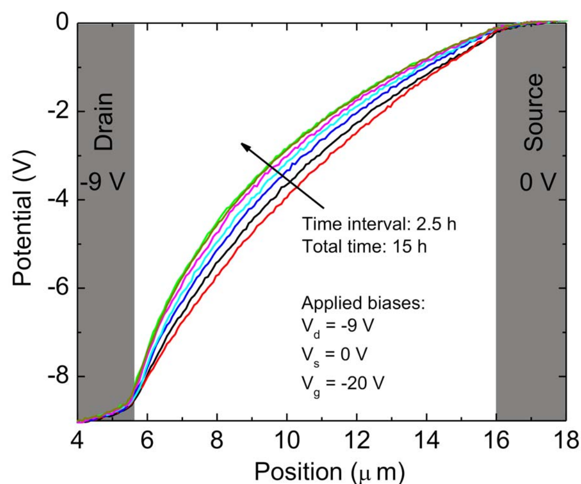

FIG. 3. (Color online) Potential profiles as a function of time taken with continuous biases of −9 and −20 V to drain and gate, respectively. The seven potential profiles were measured for 15 h with a time interval of 2.5 h.

observed. Hence, we demonstrate a direct relation between threshold voltage shift, decreasing current, and change of the potential profile in the channel of the transistor.

The discussion above strongly suggests that the principal behavior of the change of the potential during gate bias stress is the same in all operating regimes: the potential profile gets more convex. To further substantiate this, we have measured the potential profiles as a function of applied gate bias of an OFET before and after 0.5 h of gate bias stress of −20 V. The threshold voltage shifts approximately 4 V in the direction of the applied gate bias, as shown by the dashed line with squares in Fig. 1(a). The simultaneously measured potential profiles are shown in Fig. 1(b), for gate biases of −30, −10, and 15 V indicated with I, II, and III, respectively. The drawn lines with circles and the dashed lines with squares represent the potential profiles of the pristine and stressed OFETs, respectively. In the linear regime (I) the change in potential profile is negligible. However, in the saturated regime (II) and in depleted regime (III), we observe substantial changes in the potential profile. The increased curvature of the potential profiles in Fig. 1(b) indicates that additional charges are present in the transistor that influence the electric field. The sign of these charges can be understood from the increased potential in depletion as measured after stress [i.e., curve III in Fig. 1(b)]. The additional carriers contribute with the same sign to the measured potential as the positive gate. Hence these carriers must be positive as well. Together with the decrease in source-drain current in Fig. 1(a), we conclude that these positive charges should be immobile. This also explains that the largest changes occur near the drain electrode: the impact of a sheet of immobile charge on the potential profile is largest where the density of mobile carriers is smallest. We therefore conclude that the threshold voltage shift is most likely due to accumulated immobile positive charges that contribute to the potential profile, but do not contribute to the current.

In summary, we have shown a direct correlation between the current and potential profiles between the source and drain electrodes in all operating regimes of a transistor. In the saturated regime, the potential profiles are convex, while in the linear regime, the potential profiles are straight. When the transistor is biased in depletion, a potential barrier in the channel is formed that prohibits the charge carriers to move from the source to the drain electrode. During electrical gate bias stress, we observe a decrease in current, which is directly correlated with the increase of the curvature of the potential profile. The difference of the potential profiles before and after stress is negligible in the linear regime. Changes are mainly visible when the transistor is operated in depletion and saturation, especially near the drain contact. The changes of the potential profile are attributed to positive immobile charges.

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