University of Groningen

Conductance switching in organic ferroelectric field-effect transistors

Asadi, Kamal; Blom, Paul W. M.; de Leeuw, Dago M.

Published in:
Applied Physics Letters

DOI:
[10.1063/1.3621857](https://doi.org/10.1063/1.3621857)

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2011

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Asadi, K., Blom, P. W. M., & de Leeuw, D. M. (2011). Conductance switching in organic ferroelectric field-effect transistors. *Applied Physics Letters*, 99(5), 053306-1-053306-3. [053306].
<https://doi.org/10.1063/1.3621857>

Copyright

Other than for strictly personal use, it is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license (like Creative Commons).

The publication may also be distributed here under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license. More information can be found on the University of Groningen website: <https://www.rug.nl/library/open-access/self-archiving-pure/taverne-amendment>.

Take-down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from the University of Groningen/UMCG research database (Pure): <http://www.rug.nl/research/portal>. For technical reasons the number of authors shown on this cover page is limited to 10 maximum.

Conductance switching in organic ferroelectric field-effect transistors

Kamal Asadi,^{1,2,a)} Paul W. M. Blom,^{1,3} and Dago M. de Leeuw^{1,2}

¹*Zernike Institute for Advanced Materials, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands*

²*Philips Research Laboratories, High Tech Campus 4, NL-5656 AE Eindhoven, The Netherlands*

³*Holst Centre, High Tech Campus 31, NL-5605 KN Eindhoven, The Netherlands*

(Received 18 March 2011; accepted 2 July 2011; published online 4 August 2011)

Staggered bottom-contact top-gate organic ferroelectric field-effect transistors are fabricated with poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) as ferroelectric gate and poly[bis(4-phenyl)(2,4,6-trimethylphenyl)amine] as semiconductor. Polarization reversal of the ferroelectric gate is monitored by displacement transients in the gate current. By varying both the source and drain biases and by using fully and partially polarized transistors, we show that conductance switching only requires polarization of P(VDF-TrFE) at the source electrode. Polarization at the drain is irrelevant and does not impede charge extraction. © 2011 American Institute of Physics. [doi:10.1063/1.3621857]

Flexible and organic electronics has emerged as a promising technology for low-cost, large area microelectronic applications RFID tags and smart labels. These applications require non-volatile memory, a memory that does not lose its data when the power is turned off and that can be programmed, erased, and read electrically. Many concepts have been investigated.¹ A promising memory element is an organic field-effect transistor (FeFET) with a ferroelectric gate dielectric.² The memory functionality is obtained by the bistable polarization of the ferroelectric, which remnantly modulates the charge carrier density in the semiconductor channel. Depending on the polarization direction the FeFET is programmed into high conductive on-state “1” and low conductive off-state “0.” The conductance can be probed any time with a low drain bias that does not disturb the polarization.

Solution-processed organic FeFETs have been demonstrated based on the random copolymer of poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) as ferroelectric combined with various organic semiconducting polymers.^{3,4} Relatively short switching time, long data retention time, and high programming cycle endurance have strengthened the viability of the organic FeFET for non-volatile data storage.³

Common perception is that full polarization of the ferroelectric gate is required for FeFET operation. Typically a small source-drain bias is applied while the ferroelectric is poled by applying a gate bias that exceeds the coercive field which for P(VDF-TrFE) is 50 MV/m. This corresponds for a layer thickness of 1 μm to a gate bias of ± 50 V. The switching bias can be reduced by decreasing the layer thickness.^{5–7} Here, we investigate switching of ferroelectric P(VDF-TrFE) transistors, especially the influence of the source-gate and drain-gate bias on the electrical transport. We show that conductance switching of only the source is sufficient for full transistor operation. Consequences for driving schemes of memory arrays are briefly discussed.

Bottom contact top gate transistors were fabricated on thermally oxidized Si monitor wafers. Source drain electrodes were defined by standard photolithography in 150 nm of Au on a 2 nm Ti adhesion layer. The semiconductor poly[bis(4-phenyl)

(2,4,6-trimethylphenyl)amine] (PTAA) (Aldrich) was dissolved in toluene, 3–5 mg/ml, filtered through 0.2 μm PTFE filters and spin coated at 3000 rpm. Subsequently the random copolymer P(VDF-TrFE) (65%–35%, Solvay, Belgium) layer was spin coated at 1000 rpm from methylethylketone (MEK) with a concentration of 100 mg/ml. We note that MEK is an orthogonal solvent for PTAA. The stack was annealed in a vacuum oven (10^{-1} mbar) at 140 °C to enhance the crystallinity of P(VDF-TrFE).⁸ To form the staggered top gate of the FeFETs, a 70 nm Ag layer was evaporated via a shadow mask. The film thicknesses measured with Dektak profilometer were 30 nm and 1000–1500 nm for PTAA and P(VDF-TrFE), respectively. Electrical measurements were conducted in a probe station with a base pressure of 10^{-5} mbar.

Typical bistable transfer characteristics are presented in Fig. 1. The source electrode was grounded, and the gate bias was swept from +110 to –110 V and back. The drain bias in Figs. 1(a)–1(d) was varied from –2, –10, –20 to –30 V, respectively. The source drain current is presented in blue and the gate current in red.

Fig. 1(a) we scan the gate bias from +110 to –110 V. We start in the off-state with a depolarized ferroelectric. PTAA is a *p*-type semiconductor; hence, upon application of negative gate bias holes are accumulated. The current therefore increases with increasing negative bias. The mobility amounts to 10^{-3} cm^2/Vs , in good agreement with literature data.⁹ At about –65 V gate bias the coercive field is reached. The ferroelectric then polarizes, and the displacement current shows up as a peak in the gate current. The negative polarization is compensated by accumulated holes in the channel; hence, the current shows a sudden increase about an order of magnitude and the transistor is in the on-state. Upon sweeping back the gate bias, the ferroelectric remains polarized and the current hardly changes. When the gate bias reaches the coercive field at +65 V, the ferroelectric polarization is reversed as can be seen as a displacement current peak in the gate current. The polarization is now positive. The *p*-type semiconductor PTAA cannot deliver the charge compensating electrons. Hence, the channel is fully depleted of charge carriers, and the current is low. Due to lack of compensation charges, the ferroelectric depolarizes after field removal.¹⁰

^{a)}Electronic mail: kamal.asadi@philips.com.

FIG. 1. (Color online) Transfer characteristics and gate leakage currents of organic FeFETs under different drain bias conditions while source electrode is grounded. The film thicknesses were 30 nm and 1300–1400 nm for the semiconductor PTAA and the ferroelectric P(VDF-TrFE). Channel length and width are 5 and 10 000 μm . The dotted lines show polarization reversal at the source (V_{gs}).

The transistor is now back in the original off-state, and the next gate sweep shows exactly the same transfer curve. We note that PTAA was used as received without further purification. Thus appearance of positive turn-on voltages of $\sim +25$ V and “hump” in the transfer characteristics could originate from presence of doping in PTAA.¹¹

To investigate the effect of the drain voltage, we increased the drain bias to -10 , -20 , and -30 V, kept the source electrode grounded, and swept the gate voltage. Fig. 1 shows that the transfer curves do not depend on the drain bias, apart from the fact that the drain current in the on-state

FIG. 2. (Color online) Transfer characteristics and gate leakage currents of organic FeFETs under different source bias conditions while the drain electrode is grounded. The film thicknesses were 30 nm and 1300–1400 nm for the semiconductor PTAA and the ferroelectric P(VDF-TrFE). Channel length and width are 5 and 10 000 μm . The dotted lines show polarization reversal at the drain electrode (V_{gd}).

increases due to a larger source-drain field. The behavior of the gate current, however, changes. The single peak in Fig. 1(a) splits into two peaks in Figs. 1(b)–1(d). One peak remains fixed at the ± 65 V, and other peak shifts by an amount that exactly corresponds to the source-drain voltage difference. The transient peaks are due to displacement current upon polarization reversal of the P(VDF-TrFE) ferroelectric. The polarization switches when the voltage difference between source, or drain, and gate electrode is ± 65 V. Hence, the constant gate current transients at ± 65 V correspond to switching

FIG. 3. (Color online) Retention time measurements of a fully polarized and a partially polarized ferroelectric field-effect transistor. The squares show the on-state and off-state current as a function of time for a fully polarized FeFET. The circles represent retention time of a FeFET where the source is polarized and the drain is depolarized. The inset is a schematic presentation of the expected potential profiles inside the channel. The black arrows show partial polarization of P(VDF-TrFE) and the red triangle shows the potential profile. The channel is pinched-off by the ferroelectric polarization.

at the source contact. The second transient in the gate current is observed when the drain gate voltage difference is exactly ± 65 V. Hence, the second transient corresponds to switching at the drain contact. The transfer curves of Fig. 1 show that the source-drain current abruptly changes when the source electrode is switched. The source-drain current does not change when the drain electrode is switched. This implies that the injecting electrode, the source, dominates the conductance modulation. Extraction of injected carriers by the drain does not impede the transport or current modulation.

To substantiate our conclusion that the source is the dominating contact in the operation of the FeFET, we deliberately applied positive bias on the source electrode, keeping the drain grounded. There is a negative voltage difference between drain and source; hence, the source electrode remains source. The transfer curves and gate currents are presented in Figs. 2(a)–2(d) as a function of gate bias. At low source bias of +2 V, the transfer curve and gate currents, Fig. 2(a), are basically the same as when using a small drain bias, Fig. 1(a). When we apply positive gate biases, the transfer curves shift and the gate transients split into two peaks. One gate transient stays fixed at a gate bias of ± 65 V and corresponds to switching of the drain contact. The second transient shifts exactly with the source-drain voltage difference and is due to switching of the source contact. Comparison of the gate currents with the corresponding transfer curves shows that the conductance of the FeFET is modulated when the source switches. The switching occurs at voltages that correspond to the coercive field at the source electrode. Switching of the drain electrode has no influence on the channel conductance. The transfer curves are shifted because they are presented as a function of gate bias instead of gate-source voltage difference. The magnitude of the current increase from Figs. 2(a) through 2(d) is due to the increase in source-drain field.

To unambiguously connect modulation switching in FeFETs to the source contact we compared fully and par-

tially polarized transistors. A transistor was fully polarized in the on-state and in the off-state by applying a programming bias of -70 or $+70$ V on the gate, respectively, with grounded source and drain electrode. Then the gate was grounded, and the on-state and off-state currents were measured with grounded source at a low drain bias of -2 V. The currents are presented as a function of time in Fig. 3. To partially polarize transistor, we applied half the programming bias on the source and half the programming bias on the gate, hence ± 35 V. The drain was grounded. Hence, only the source is polarized; the drain is depolarized.¹⁰ The gate was grounded again, and the on-state and off-state currents were measured as a function of time. Fig. 3 shows that within experimental error the currents in the fully polarized transistor are identical to the partially polarized transistor. The source electrode dominates the current modulation in FeFETs; the drain is irrelevant. Fig. 3 shows that the data retention is similar for both full and half polarization of the ferroelectric gate. We did not measure for long times because it has already been shown that the retention of fully polarized organic FeFETs does not change over a week.³ The experiments show that charge extraction at the drain does not impede charge transport or current modulation. A similar situation exists for regular organic transistors operated in saturation. The drain pinches off the channel at $V_d = V_g$.¹² For charge transport, the depleted part of the semiconductor is ignored as well. A cartoon of the expected field distribution in the transistors is included in Fig. 3. We note that for a fully depleted channel the source-drain current switches on when the gate-source voltage reaches the coercive field. In this case only a very small region next to the source contact would be in full accumulation, the rest of the channel remains depleted. In practice this situation does not occur. Firstly, this argument holds for square polarization loops. For slim loops other parts of the channel that almost reach the coercive field will also start switching. Secondly, the transfer curves show that at the switching point, there is already a considerable current due to accumulated holes by the gate field. Hence, there are enough counter charges to compensate the ferroelectric polarization. The drain transients support these arguments; anytime the drain switches there is no change in source-drain current.

Finally we note that for functional FeFETs the fact that only the source has to be polarized can have consequences for design of memory arrays. The programming bias can be divided between source and gate, and the power consumption might be reduced.

We would like to thank the EU project ONE-P, No. 212311 for financial support.

¹J. C. Scott and L. D. Bozano, *Adv. Mater.* **19**, 1452 (2007).

²R. C. G. Naber *et al.*, *Adv. Mater.* **22**, 933 (2010).

³R. C. G. Naber *et al.*, *Nat. Mater.* **4**, 243 (2005).

⁴R. C. G. Naber *et al.*, *Org. Electron.* **7**, 132 (2006).

⁵R. C. G. Naber *et al.*, *Appl. Phys. Lett.* **87**, 203509 (2005).

⁶R. C. G. Naber *et al.*, *Appl. Phys. Lett.* **85**, 2032 (2004).

⁷J. Hoffman *et al.*, *Adv. Mater.* **22**, 2957 (2010).

⁸T. Furukawa, *Adv. Colloid. Interface* **71**(2), 183 (1997).

⁹J. Veres *et al.*, *Adv. Funct. Mater.* **13**, 199 (2003).

¹⁰R. C. G. Naber *et al.*, *Appl. Phys. Lett.* **90**, 113509 (2007).

¹¹E. J. Meijer *et al.*, *J. Appl. Phys.* **93**, 4831 (2003).

¹²G. Horowitz, *Adv. Mater.* **10**, 365 (1998).