Temporal Phenomena in Organic Field-Effect Transistors through Kelvin-Probe Force Microscopy

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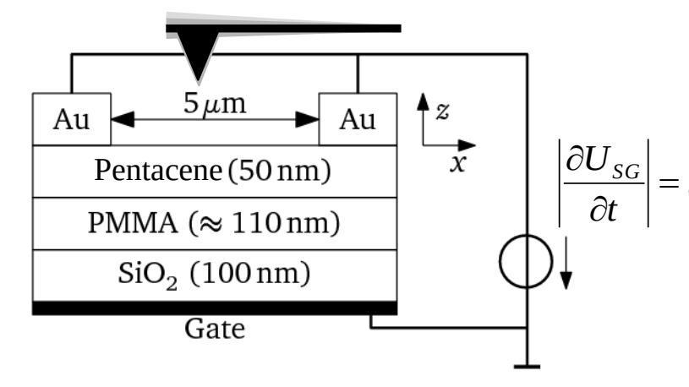
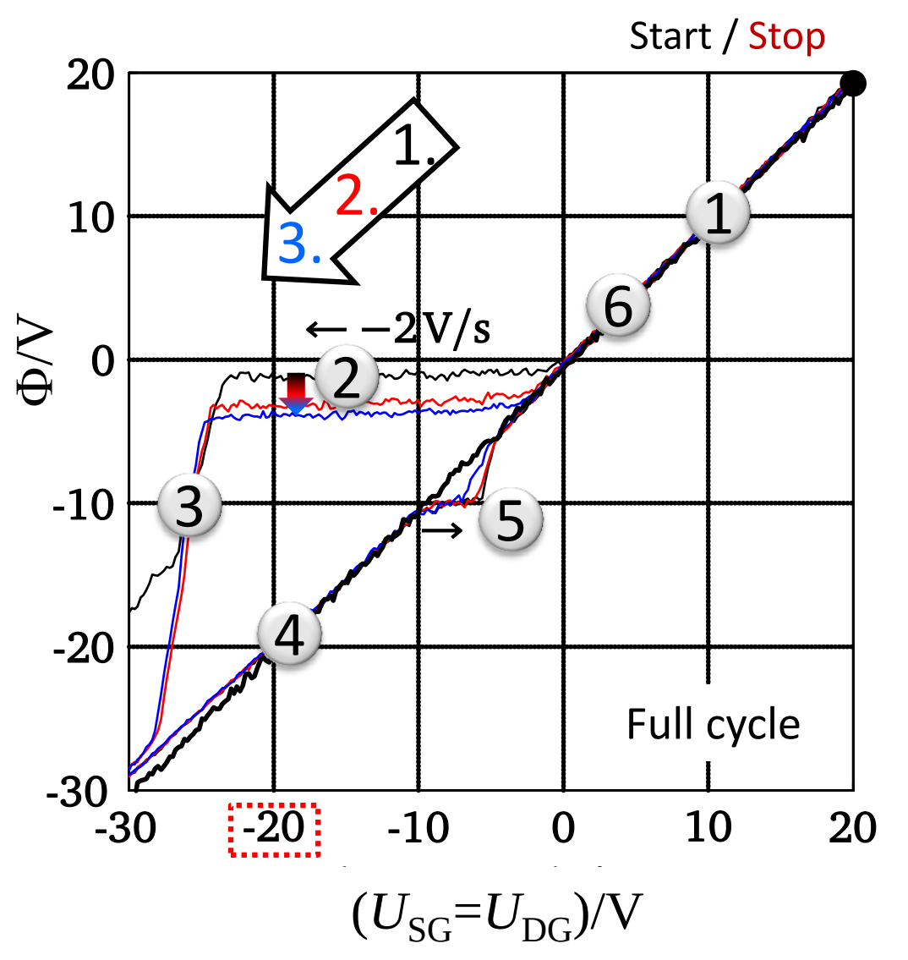
The stability of organic field-effect transistors (OFETs) is not only an issue for future applications but needs to be considered for a proper device characterization. Here, the charging and discharging of pentacene based OFETs are investigated with time dependent Kelvin-Probe Force Microscopy (KPFM) measurements performed in the vicinity of the charge reversal points [1,2]. On the one hand, these measurements allow for the analysis of the often observed device hysteresis. On the other hand, at certain conditions, the measurements can be used to perform transient experiments for the determination of the charge-carrier mobility valid during the charging of the device.

Device Instability

The device stability of pentacene based OFETs are investigated by KPFM in the spectroscopic mode. The investigated device allows for an ambipolar carrier transport in the channel. Unipolarity is defined via the Source and Drain contacts.

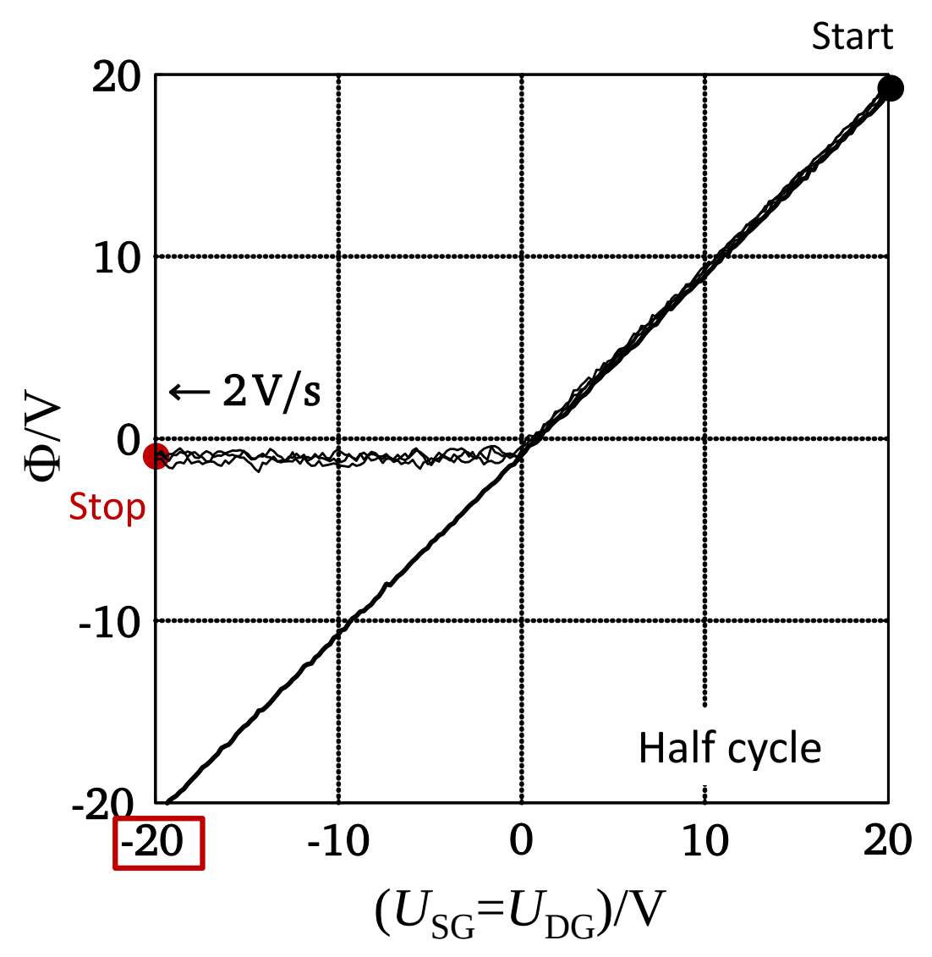
Charge reversal of an **p-type OFET**

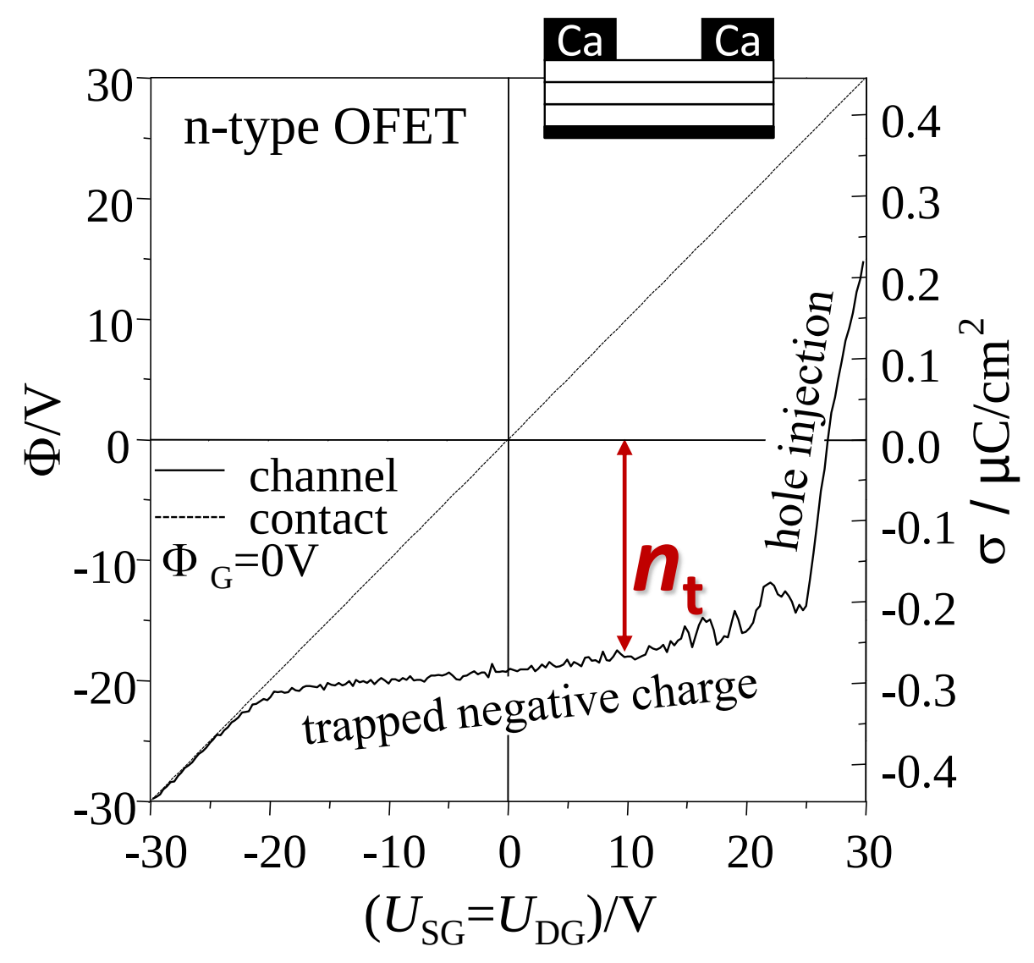




1. Hole accumulation
2. Full depletion
3. Electron injection
4. Electron accumulation
5. Charge reversal
6. Hole accumulation

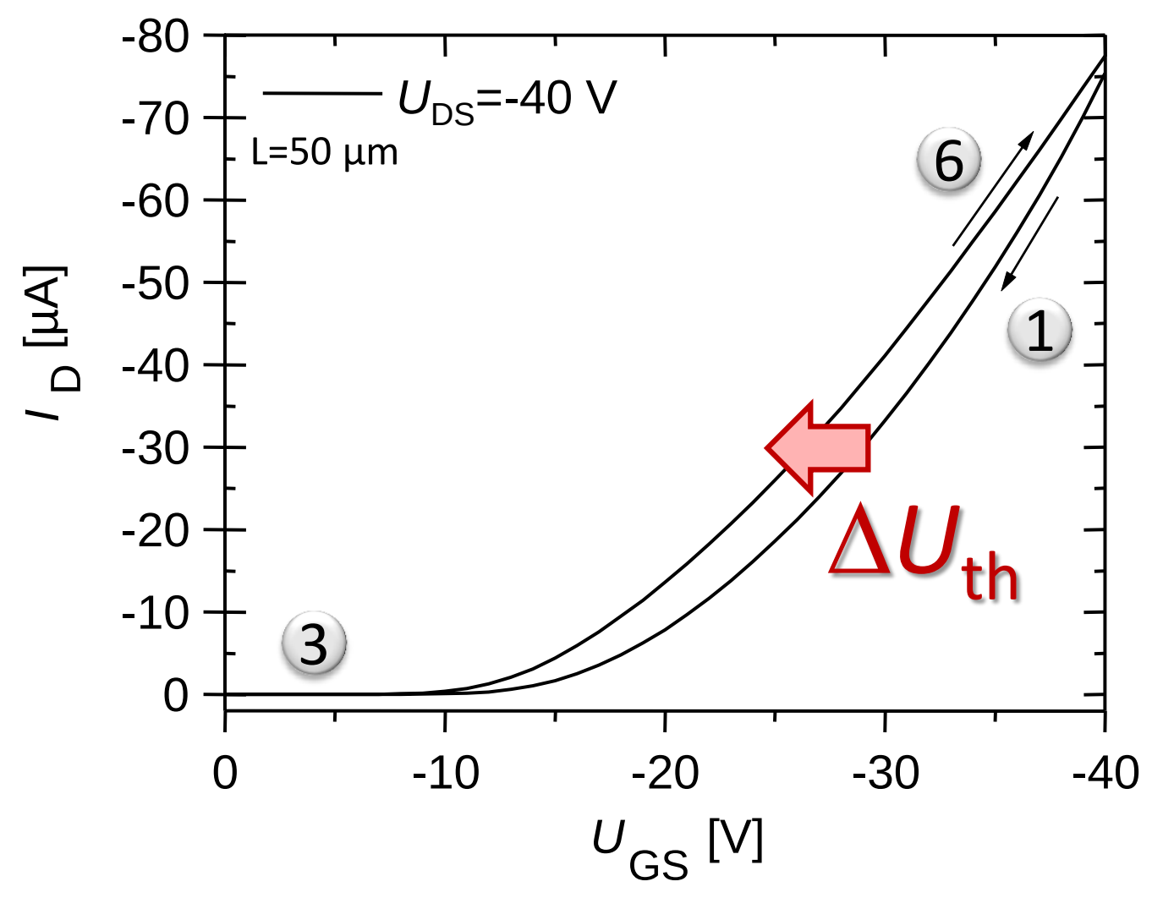
The electron injection causes a device instability



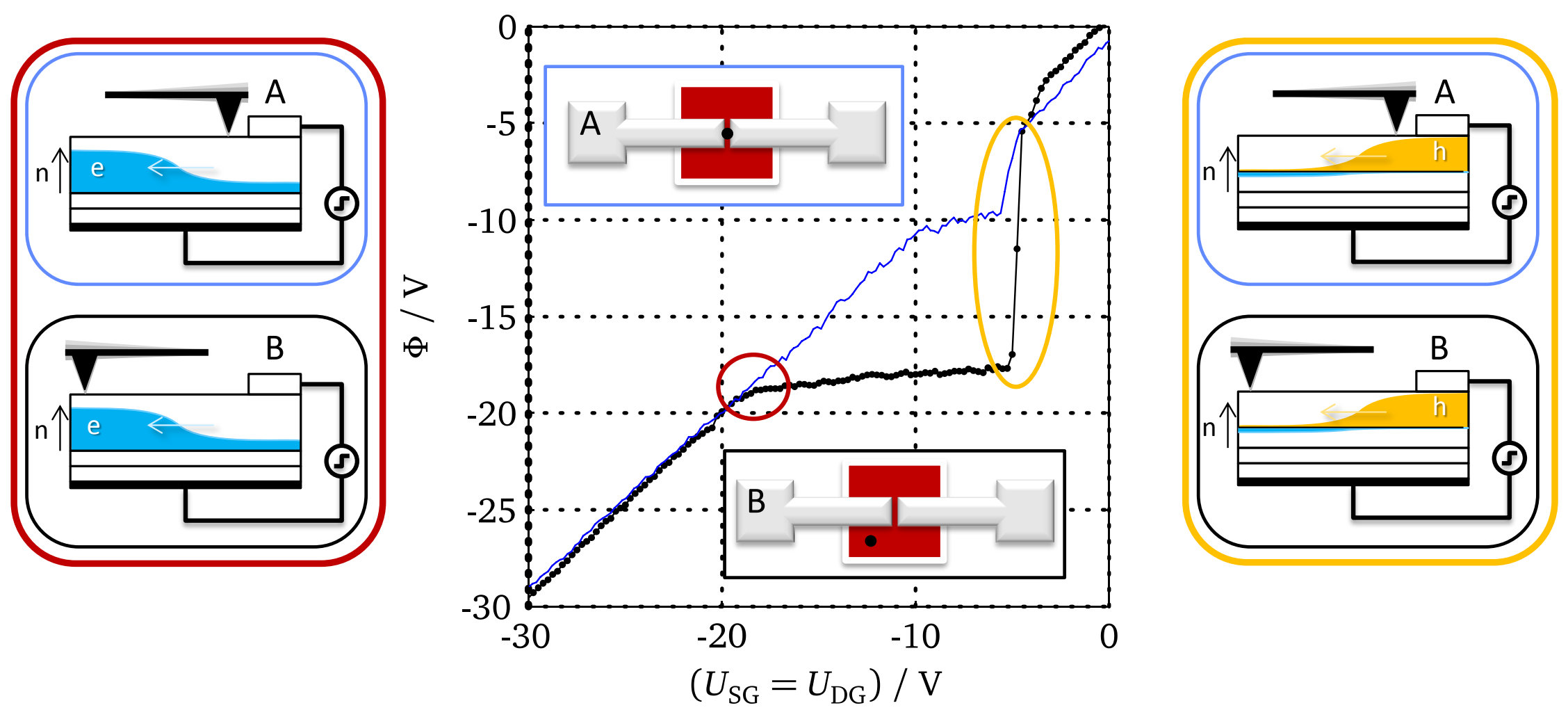


In **n-type OFETs** the electron trapping capability of the channel becomes apparent

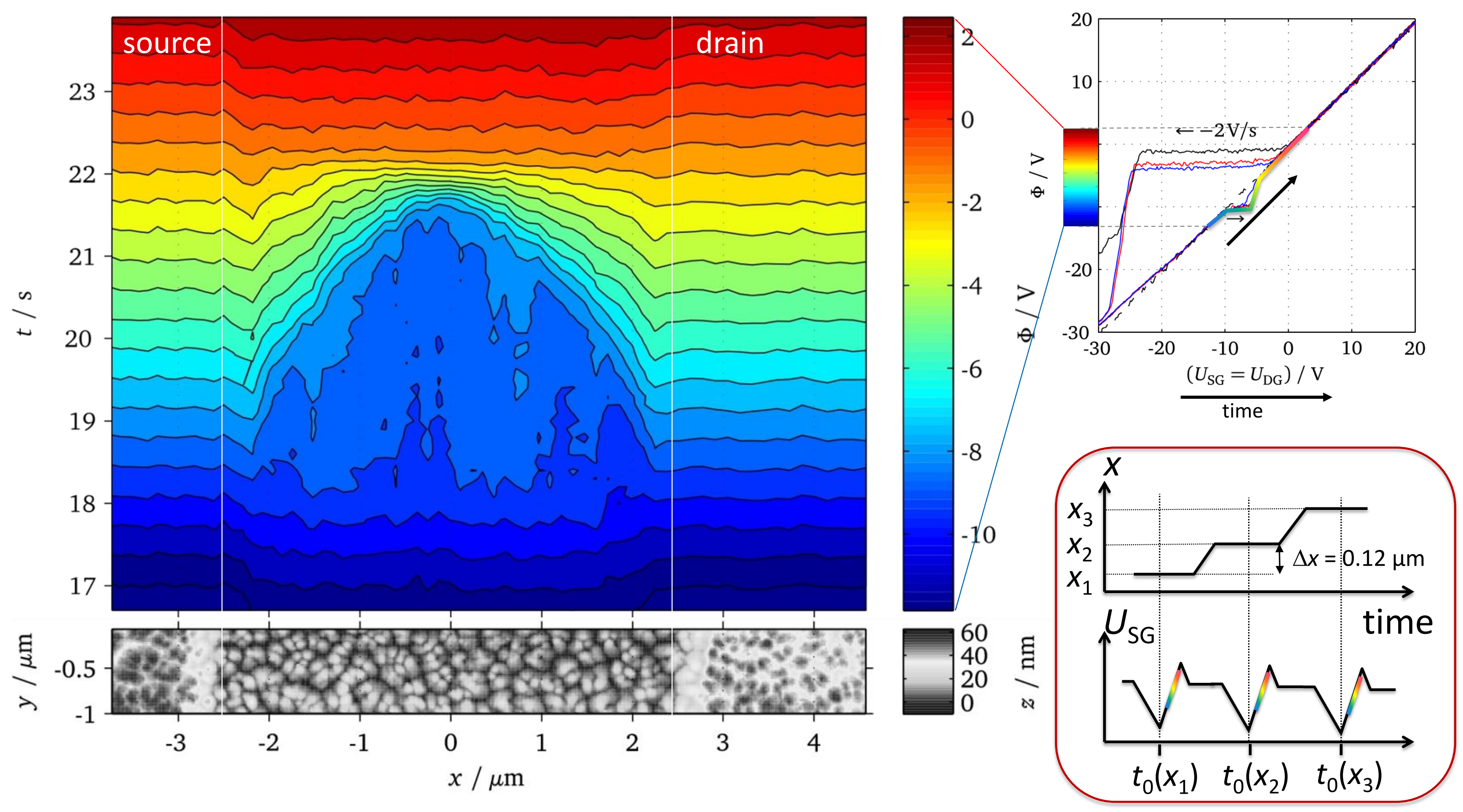
The electron injection in the depletion mode of the p-type transistor results in a negatively charged channel. A positive threshold-voltage shift is observed.



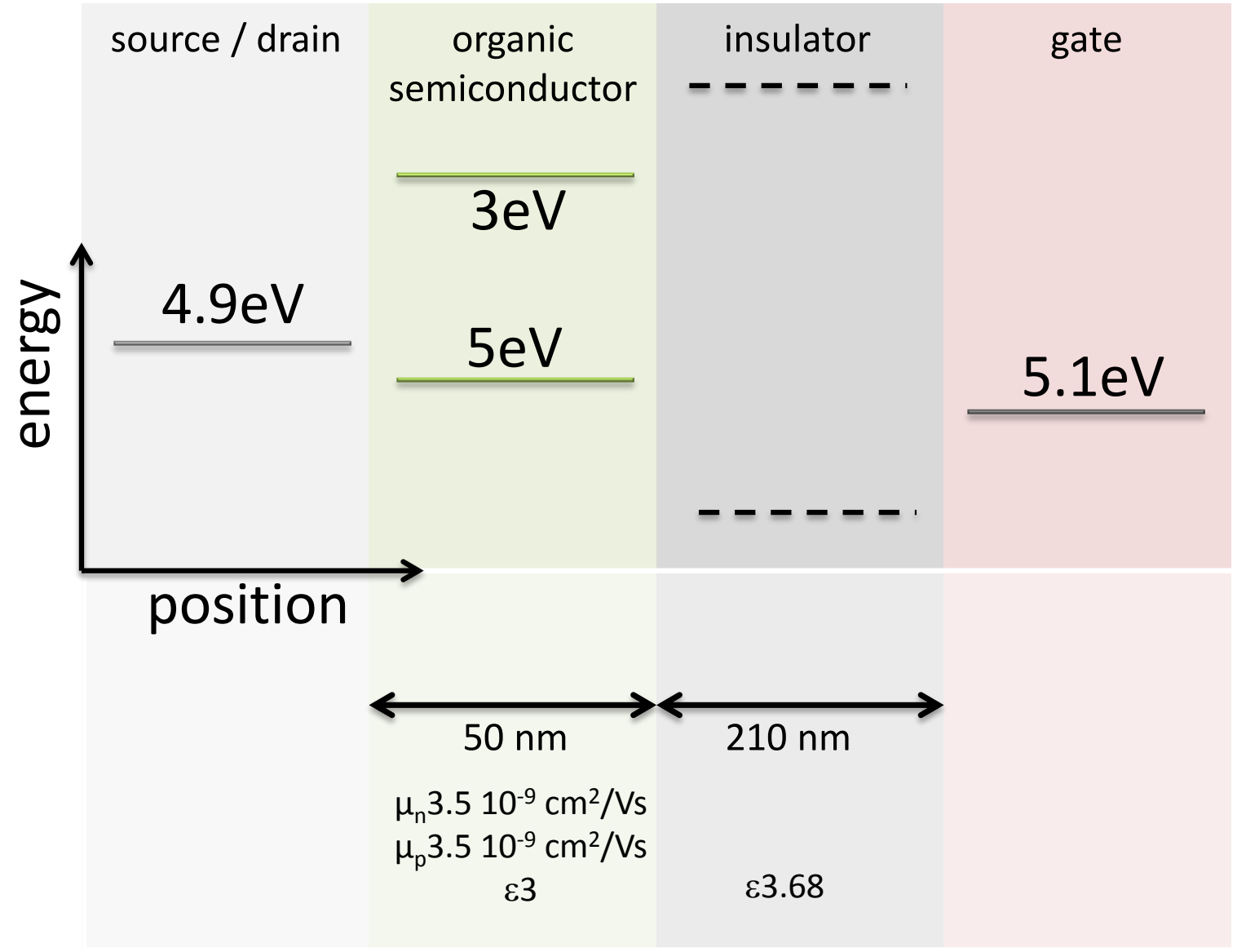
Transient Kelvin-Probe Force Microscopy

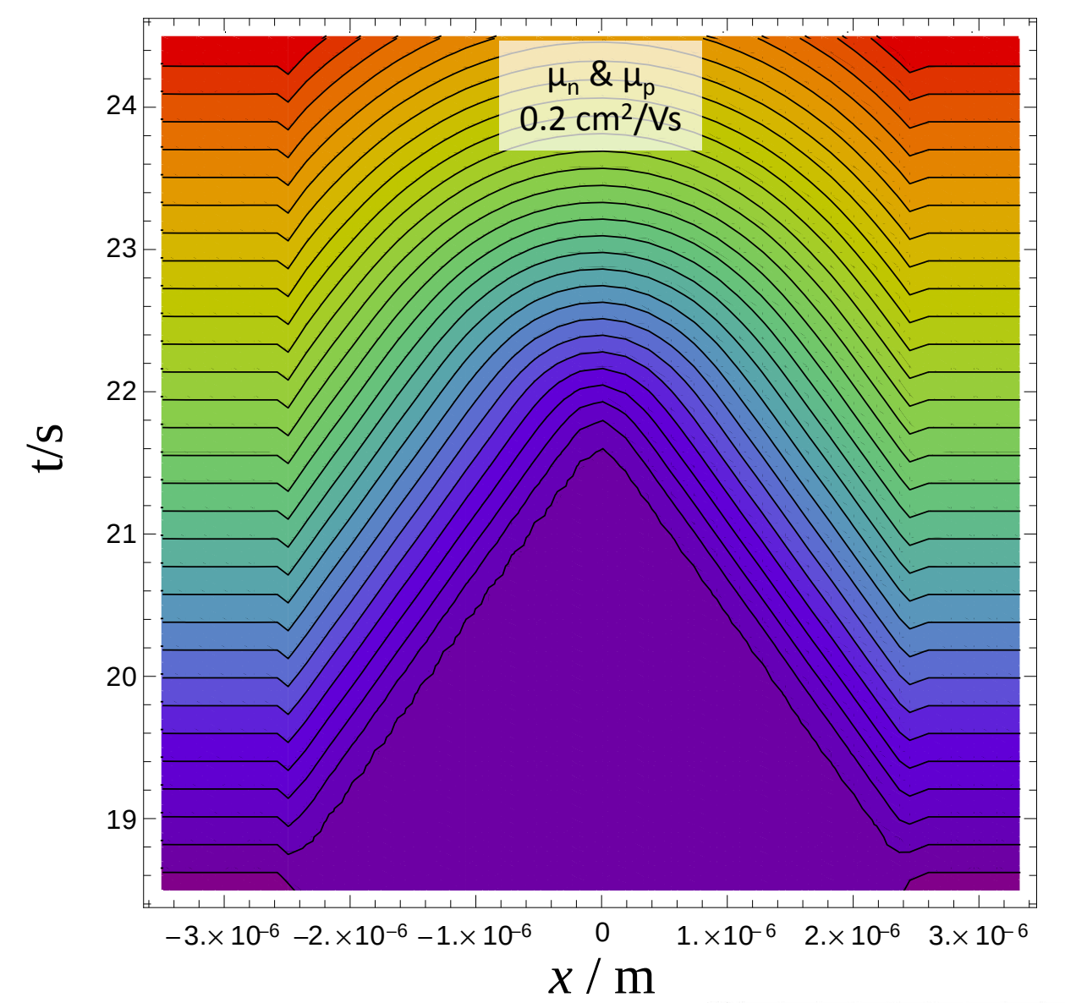


The charge reversal point from electron to hole accumulation is transient determined. Since after multiple repetitions of the bias sweep the surface-potential evolution becomes invariant, a mapping of ϕ in time and space becomes possible.

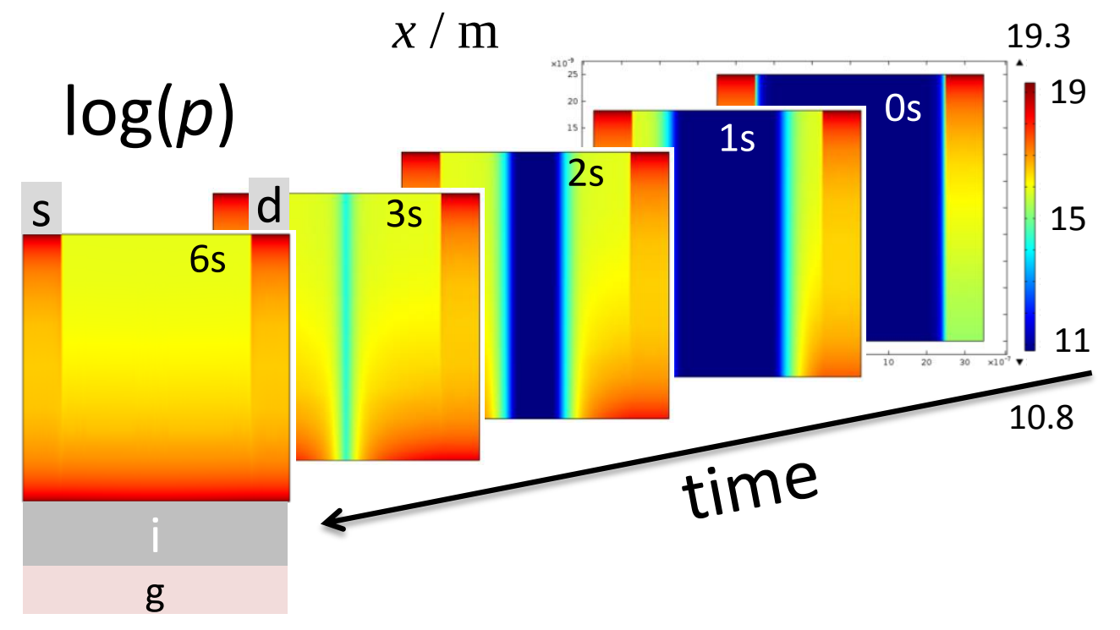


2D FEM Device Model





The temporal response of the top-contact, bottom-gate OFET under a voltage ramp between source/drain and gate was modeled with 2D FEM assuming drift / diffusion equations, Langevin recombination, classical Einstein relation and Schottky contacts.



Low density hole mobility

Using the transmission-line model, the low carrier-density mobility can be estimated. To merge the two carrier fronts coming from the source and the drain, the time τ is required.

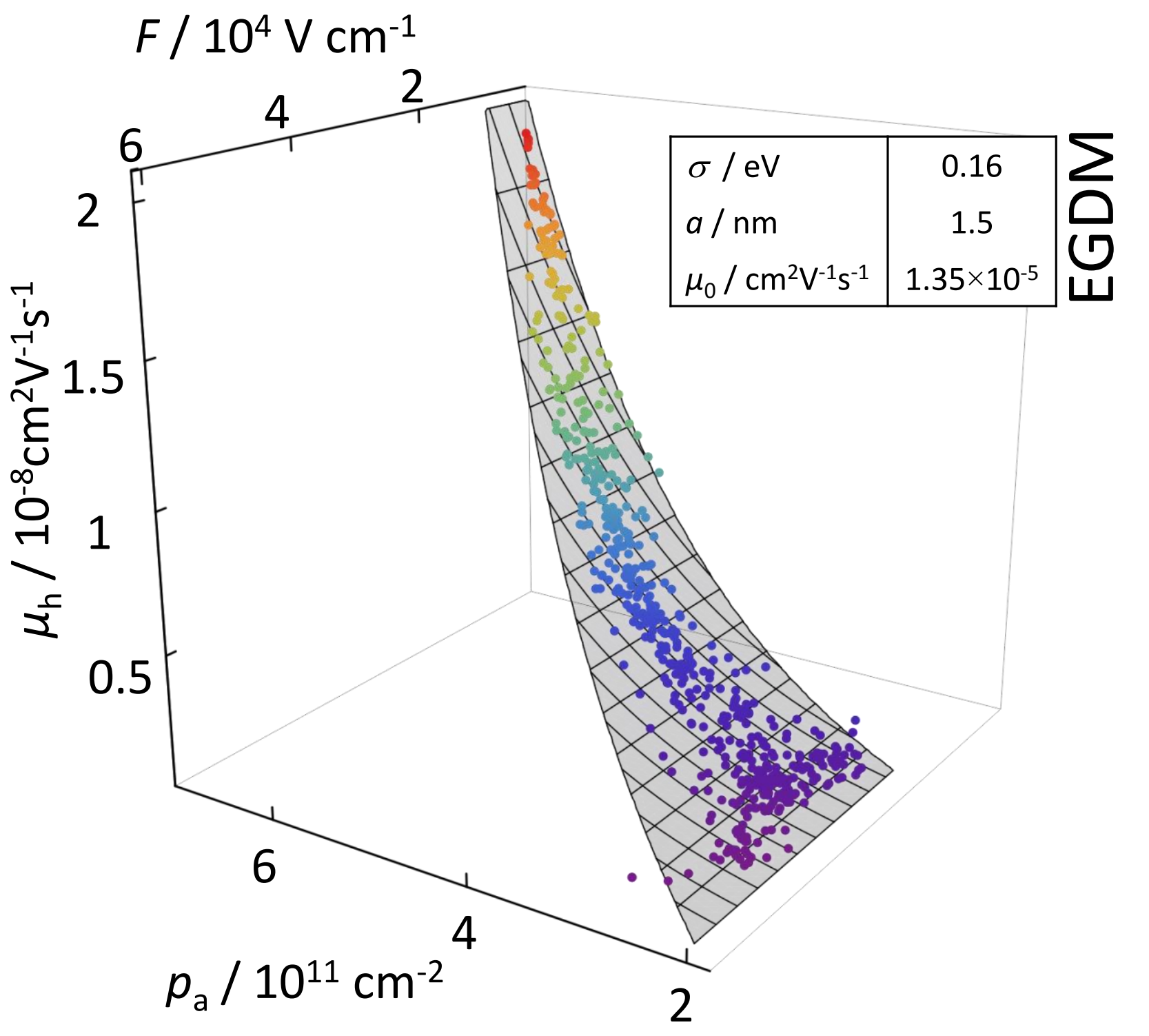
$$\tau = \frac{L}{\sqrt{4\beta\mu}}$$

μ_h
3.5×10^{-9} cm²V⁻¹s⁻¹

The carrier density and field dependent mobility can be determined with transient KPFM by using:

$$F(x,t) = -\partial_x \phi(x,t)$$
$$p_a(x,t) = {}^{C_0}\!/\!_q\left(\phi(x,t) - \phi_0(x)\right)$$
$$I(x,t) = WC_0\int_0^x \partial_t \phi(y,t)\partial y$$

$$\boxed{I(x,t) = W\cdot q\cdot\mu\cdot p_a(x,t)\cdot F(x,t)}$$



σ / eV	0.16
a / nm	1.5
μ_0 / cm²V⁻¹s⁻¹	1.35×10⁻⁵

The result was fitted by the Extended Gaussian Disorder Model [3].

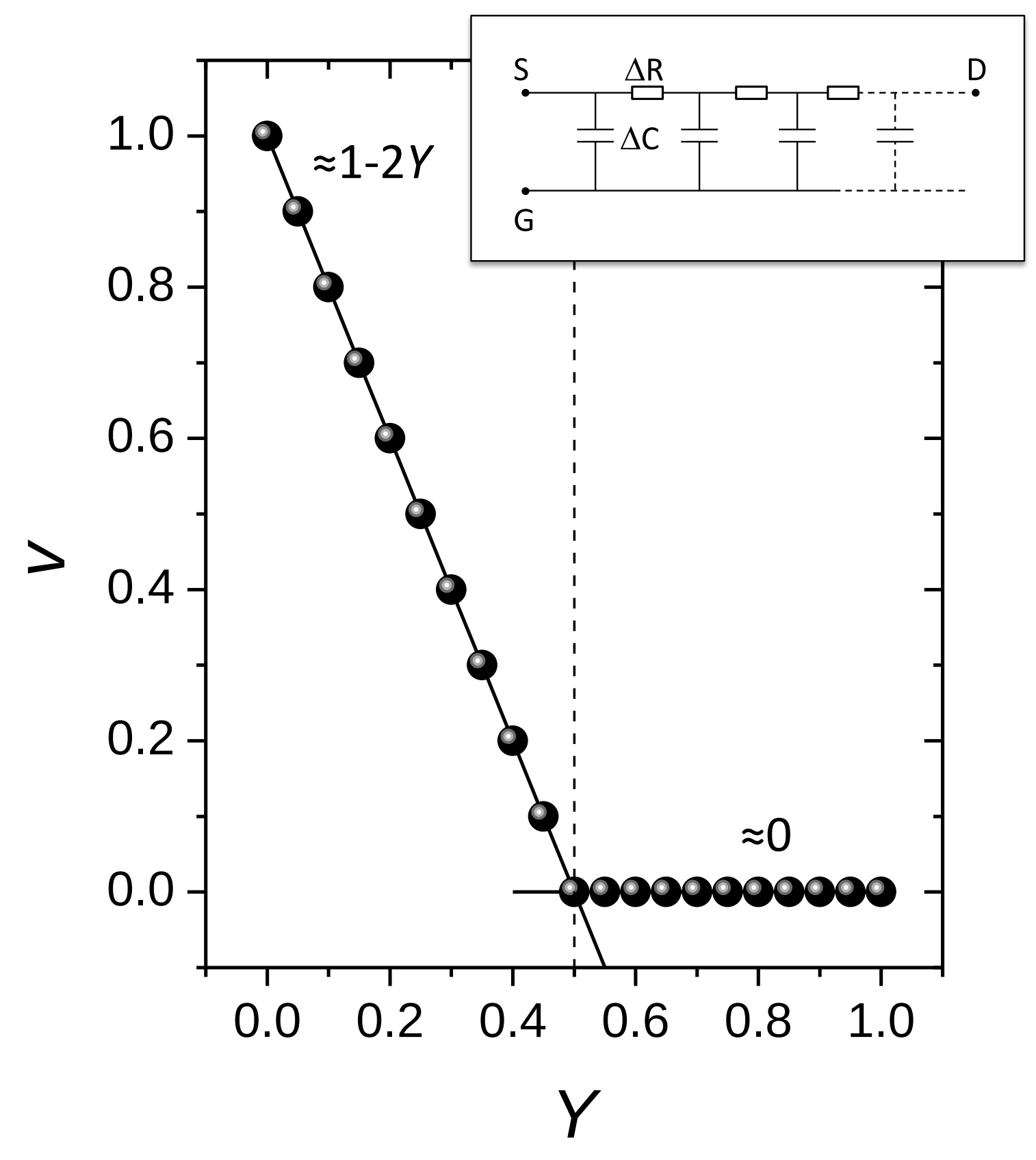
The charging can be understood using the transmission-line equations leading to:

$$\frac{\partial\phi(x,t)}{\partial t} = \frac{\mu}{2}\cdot\frac{\partial^2\phi(x,t)^2}{\partial x^2}$$

$$\phi(x,t) = \beta\cdot t\cdot v(x,t) \quad \text{and} \quad Y = (x + L/2)/\left(2\sqrt{\beta\mu}\cdot t\right)$$

$$4v(Y) = 4Y\frac{\partial v(Y)}{\partial Y} + v(Y)\frac{\partial^2 v(Y)}{\partial Y^2} + \left(\frac{\partial v(Y)}{\partial Y}\right)^2$$

$$\phi(x,t) = \beta\cdot t - \sqrt{\frac{\beta}{\mu}}\left(x + \frac{L}{2}\right) \quad \text{for} \quad x + \frac{L}{2} < (\beta\mu)^{1/2}t$$
$$\phi(x,t) = 0 \quad \text{for} \quad x + \frac{L}{2} \geq (\beta\mu)^{1/2}t$$



Conclusions

For p-type pentacene devices, the remanent charging of the transistor channel with electrons in the hole-depletion mode induces a substantial device instability. Yet, after several iterations the temporal evolution of the surface potential becomes steady allowing for the mapping of the surface potential evolution during the charge reversal. The response is modeled on basis of 2D FEM-simulations and transmission-line equations. By transient KPFM the subthreshold hole mobility - dependent on the electric-field and carrier-density - becomes accessible.

References

[1] C. Siol, C. Melzer, H. von Seggern, Appl. Phys. Lett., **93**, 13 (2008), 133303
[2] C. Melzer, C. Siol, H. von Seggern, Adv. Mater., **25**, 31 (2013), 4315
[3] W. F. Pasveer, J. Cottaar, C. Tanase, R. Coehoorn, P. A. Bobbert, P. W. M. Blom, D. M. de Leeuw, M. A. J. Michels, Phys. Rev. Lett., **94**, 20 (2005), 206601