Behavior of charges in the active zone of composite OFET under the source-drain electric field

P A Dement’ev¹, P A Alekseev¹, M S Dunaevskii¹,² and A N Aleshin¹,³

¹ Ioffe Physical-Technical Institute, Russian Academy of Sciences, Politekhnicheskaya ul. 26, St. Petersburg, 194021 Russia
² National Research University of Information Technologies, Mechanics and Optics (ITMO), St. Petersburg 197101, Russia
³ St. Petersburg Electrotechnical University “LETI”, ul. Professora Popova 5, St. Petersburg, 197376 Russia

e-mail: demenp@yandex.ru

Abstract. Charge accumulation and relaxation processes in the OFET active zone are studied. It is found that positive and negative charges injection from metal electrodes under drift field occurs. Characteristic time of these processes is found to be about 30 sec. Behaviour of charges under the combination of source-drain and gate potentials is also investigated.

1. Introduction
One of the main challenges of diagnostics of organic electronics devices is the visualization of electrophysical processes in their active zone under working conditions. It could provide more detailed understanding in physics of memory, “bias-stress” and other known effects in organic field-effect transistors (OFET). The most useful method for solving this problem is the scanning Kelvin-probe microscopy (KPM). It has been already used for characterization of semiconductor laser diodes and other structures under working conditions [1]. The KPM key difference from the traditional testing techniques is the possibility of electric charge and potential measurements with high spatial resolution.

In our work KPM was used to investigate the charge accumulation and dissipation processes in OFET with active zone composed of poly(9-epoxypropylecarbazole) (PEPK) polymer and Au nanoparticles with the diameter 50-70 nm. We studied the influence of the drift and gate electric fields on these processes.

2. Objects and methods
The composite for active zone was made from PEPK and “SigmaAldrich” Au nanoparticles. Both PEPK and Au nanoparticles were dissolved in chloroform. The obtained solutions were mixed and, after the ultrasound treatment during 8–10 min (f ~ 22 kHz), were applied onto silicon substrates (Si with a ~200nm SiO₂ layer) with prepared Au (source) and Al (drain) electrodes (Figure 1).

KPM measurements were performed on NTEGRA-Aura microscope produced by NT-MDT company (Moscow, Russia) in ambient conditions. Standard DCP11 conducting probes (NT-MDT) were used.
3. Experimental

3.1. Charge injection by source-drain electric field.

Typical experimental procedure was the following. For the observation of negative and positive charges accumulation in OFET active zone by KPM a +2V bias voltage was applied for 2 minutes to Au-electrode (Al electrode was grounded). After the stabilization of electrical potential redistribution process the voltage was turned off that caused the dissipation of accumulated charges. Figure 2 illustrates these two stages of experiment. To eliminate the influence of topography and composite inhomogeneities to the resulting potential distribution the initial unperturbed potential distribution was mathematically subtracted from the whole picture. The initial potential distribution can be seen in region I of figure 2.

Region II in figure 2 illustrates the change of the potential distribution in the OFET active zone under an external bias of +2V. It can be seen, that at the beginning the main part of the applied voltage falls on the barriers near the borders composite - metal electrodes. Then the potential barriers are reduced with time due to the charge accumulation process. Indeed, after grounding of both electrodes one can see the accumulated positive and negative charges near the former barriers (Region III). Then the accumulated charges dissipate with characteristic time of several minutes. Detailed potential
distribution profiles for accumulation and dissipation processes are shown in figure 3 and figure 4 respectively. Potential profiles were measured every 2.5 sec, but only several of them are shown on figures.

The most significant change in the potential drop profile is observed in areas near point A and C on figure 3(a). Its value reaches 0.5 V for negative charges and 0.3 V for positive. It should be noted that the accumulation process is due to the charge injection from the metal electrode instead of the polarization of the composite. This is evidenced by the fact that the negative charges accumulation was observed near the ground electrode and positive charges near the positive electrode. The potential in the areas of strongest accumulation is changed with time by exponential law \( \sim 1 - e^{-t/\tau} \) with a characteristic saturation time of about 30 seconds.

![Figure 3. Accumulation of charges under drift field: (a) change in potential distribution: 1 – initial potential; 2-4 – potential distribution in every 25 seconds after applying drift field; (b) time dependence of the potential in several points: A – 1.2 \( \mu \)m from Au electrode, B – in the middle of active zone, C – 1.5 \( \mu \)m from Al electrode.](image)

The relaxation (dissipation) of accumulated charges begins when the external field is switched off. This process is illustrated in region III of figure 2. One can see that not only a reduction of charge-related potentials takes place but also a spatial redistribution (see figure 4).

![Figure 4. Dissipation of accumulated charges: (a) change in potential distribution, time between curves is about 40 seconds; (b) time dependence of the potential in maxima of charge spots; (c) time dependence of the position of charge spot maxima.](image)
The potential distribution and the time dependence of the size and position of the charge spots maximum are shown in figure 4. It is seen that while the value of the potential at the center of the charge spots decreases exponentially, the spatial position of maximum changes linearly (with velocity $v \sim 1\ \text{mkm/min}$). The spatial movement of charge spots cannot be explained by the drift mechanism. The estimated mobility of charges is abnormally low $\mu \approx 10^{-9}\ \text{cm}^2/\text{V} \cdot \text{s}$, which is several orders of magnitude lower than the expected value of mobility $\mu \approx 4 \cdot 10^{-2}\ \text{cm}^2/\text{V} \cdot \text{s}$ obtained for the same samples by conventional methods [2]. This suggests that the change in position of the charge spots maxima is related with the different charge dissipation rates at the near electrodes area and at the center of the active zone.

3.2. Charge injection by source-drain and gate electric fields.

Since the OFET working conditions are controlled by gate electrode voltage, the effect of charge accumulation/dissipation under the simultaneous applying of gate and source-drain voltages [3] was studied. The combined measurements were carried out as follows: at first the source-drain voltage was applied for a time sufficient for full charge storage near the contact region, and then the gate voltage of -10 V was applied for 5 minutes as in ref [3]. The potential drop profiles during the accumulation are shown in figure 5a.

**Figure 5.** Charge accumulation under simultaneous applying of gate and source-drain voltages: (a) change in potential distribution during accumulation process. Time between profiles is about 60 sec. Dotted line shows the equilibrium profile with grounded gate electrode; (b) difference profiles after subtraction; (c) comparison of time dependence of the potential in the minimum of potential distribution with and without drift field during accumulation process; (d) comparison of time dependence of the potential in the maximum of potential distribution with and without drift field during relaxation process.
Mathematical subtraction of the equilibrium profile of the potential at the gate grounded structure (shown by dotted line) was made to simplify the interpretation of the data. This resulted in the difference profiles shown in figure 5b. The figures show that initially the gate voltage leads to a shift in the voltage distribution profile by -0.8 V, but with time, this shift is reduced due to the screening of gate potential by charges, accumulated in the polymer. When turning off the gate voltage, the charges are dissipating (not shown here).

Amplitudes of potential drop (figure 5b) due to the accumulation/dissipation processes versus time are plotted on figure 5c and figure 5d respectively. For comparison the corresponding data for the only gate voltage case (without applying source-drain voltage) also plotted on figure 5 by red dots. The detected surface potential of the OFET active zone at first after applying the gate voltage coincides for the both cases. On the other hand, in the presence of the applied source-drain voltage (see figure 5c) the accumulation of charges and, respectively, screening of the gate voltage is faster by about 20%. The situation is similar at the beginning of the accumulated charges dissipation – immediately after turning off the gate voltage (see figure 5d), value of the charge in the center of the active zone coincides with that measured in the absence of the applied source-drain field. The relaxation process goes 3–4 times faster with the presence of the applied source-drain drift field. The acceleration of these processes could be associated with an increase in the electric field acting on the charge carriers in the composite layer.

4. Conclusion

Thus, the effect of positive and negative charges injection from metal electrodes into the active zone of OFET was found. By Kelvin probe microscopy technique it was performed a detailed study of the time evolution of the injected charges under complex configuration of electrically biased contacts. It was shown that characteristic time of accumulation and dissipation processes is tens of seconds. Nature of such long characteristic time is still unclear. Nevertheless, in other works on composite OFET [4] characteristic times are even longer.

Injection and accumulation of charges in the active region is an important process that has a significant impact on the current-voltage characteristics of OFET and the account of this effect is required in the design of device structures of organic electronics.

References

[1] Ankudinov A V, Evtikhiev V P, Ladutenko K S, Titkov A N, Laiho R 2006 Semiconductors 40 (8) 982–989
[2] Aleshin A N, Fedichkin F S, and Gusakov P E 2011 Phys. Solid State 53 (11) 2370–2374
[3] Dement’ev P A, Dunaevskii M S, Aleshin A N, Titkov A N and Makarenko I V 2014 Phys. Solid State 56 (5) 1054–1057
[4] Lee K, Weis M, Taguchi D, Manaka T, Iwamoto M 2012 Chem. Phys. Lett. 551 105-110