Short-time-scale threshold voltage shifts in organic field-effect transistors caused by dipoles on insulator surface

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Abstract

We previously reported that dipoles on the surface of the gate insulator layer in organic transistors cause time decay of the drain current on time scales of less than 0.1 s from the application of the gate voltage. In this study, we investigated the relationship between the time decay and magnitude of the gate voltage. We found that this time decay can be attributed to threshold voltage shifts unaccompanied by mobility changes. When the insulator surface has dipoles that can move somewhat, the threshold voltage shift has two components: one with a time scale of approximately 0.1 s and the other with a time scale of tens of minutes.

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1. Introduction

Organic field-effect transistors (OFETs) have attracted considerable attention due to their application as driving devices in displays [1–4], radio frequency identification tags [5–8], and large-area sensors [9, 10]. One of the most important issues with regard to the stability of OFETs is bias stress instability, that is, the variation in drain current ($I_D$) when a gate voltage is applied for extended periods [11–15]. We previously reported that the bias stress instability of OFETs has two components [16]: One stems from dipoles on the surface of the insulator, which, if they can move slightly, produce a time decay in $I_D$ when a gate voltage is applied [16]. The other is the well-known threshold voltage shift caused by gate bias stress. The application of a negative gate bias causes a negative shift in...
the threshold voltage ($V_t$) and a decrease in $I_D$ [11–15]. These two instabilities have different time scales: The decrease in $I_D$ caused by dipoles on the insulator’s surface occurs on a fast time scale of less than approximately 0.1 s after the application of a gate voltage. On the other hand, the well-known $V_t$ shift caused by gate bias stress occurs over several hours. For stable OFET operation, it is necessary to suppress both components. The $V_t$ shift (long time scale) has been well studied and some groups have succeeded in fabricating an OFET with no significant $V_t$ shift [17]. However, the decrease in $I_D$ (short time scale) is not sufficiently understood.

Transient current measurement is a useful method for analysis of the dynamic characteristics and operation mechanism of OFETs. In this study, we investigated the transient drain current under different gate voltages for OFETs with dipoles on the insulator’s surface. On the basis of this measurement, we calculated the time-variation of mobility and threshold voltage. As a result, the time decay of $I_D$ due to the dipoles could be attributed to time-variation of the threshold voltage unaccompanied by mobility change. This result indicates that when the insulator surface has dipoles that can be slightly displaced, gate bias stress causes a change in $V_t$ over short time scales and a $V_t$ shift over long time scales.

2. Experimental

To investigate the time decay of $I_D$ of the OFET with dipoles on the insulator’s surface, we fabricated top-contact OFETs with a monolayer of 3-chloropropyltrichlorosilane (Cl-monolayer) on SiO$_2$ layers (Fig. 1). The Cl-monolayer was fabricated by immersing the SiO$_2$ substrates in solutions of 3-chloropropyltrichlorosilane in anhydrous toluene (3 mM) for 3 h. The pentacene layer and gold source and drain electrodes were fabricated by vacuum deposition at deposition rates of 0.1 and 0.05 nm/s, respectively. The channel length and width for all the devices were 20 and 1000 μm, respectively.

We measured the time decay of $I_D$ resulting from the application of a step gate voltage ($V_G$) under the application of a $-30$ V drain voltage ($V_D$) [Fig. 1 (b)]. $V_G$ was supplied by a pulse generator (NF Corporation, model 1915) and a voltage amplifier (NF Corporation, HSA4011). The time decay of $I_D$ was measured using an oscilloscope (Tektronix, TDS20). This measurement was carried out in a glove box under nitrogen atmosphere to eliminate the influence of oxygen and water.

Figure 1 (a) Structure of organic field-effect transistor used in this study. Chemical structure of the self-assembled monolayer is also shown. (b) Timing of application of source-drain voltage and gate voltage. Continuous source-drain voltage of $-30$ V and step gate voltage were applied to the devices.
3. Results and discussions

Figure 2 (a) and (b) show transfer curves ($I_D^{0.5}$ vs. $V_G$) of the OFET with a Cl-monolayer and an $I_D$ time decay caused by the application of different gate voltages, respectively. The decay of $I_D$ had completed in less than 0.1 s. We previously reported that the time decay of $I_D$ exhibited a recovery and returned to initial $I_D$ when the gate voltage was turned off for several hundred milliseconds [16]. Measurements of each curve in Fig. 2 (b) were separated by more than 5 s, so as to allow the (lowered) $I_D$ to recover and eliminate the influence of prior measurement.

Figure 2 (a) Transfer characteristics of OFET with Cl-monolayer. (b) Time decay of drain current for OFET with Cl-monolayer. The drain current response from step gate voltages of $-14$, $-16$, $-18$, and $-20$ V was measured under the application of a continuous source-drain voltage of $-30$ V. The zero points on the horizontal axis correspond to the times at which the gate voltage was turned on.

Figure 3 Mobility (a) and threshold voltage (b) as a function of time.
We can plot the transfer curves \((I_D^{0.5} \text{ vs. } V_G)\) at various times using Fig. 2 (b). We extracted the time-variation of mobility and threshold voltage from the gradient and intercept of the transfer curves at various times. Figure 3 shows mobility and threshold voltage as a function of time. The mobility remained at an almost constant value over time. On the other hand, threshold voltage shifted downward with time. Thus, a decrease in \(I_D\), caused by dipoles on the surface of the Cl-monolayer, was attributed to a negative shift in the threshold voltage.

It is well known that gate bias stress (GBS) causes \(V_t\) shift over long time scales (on the order of several ten minutes). From the measurements of the surface potential of OFETs by Kelvin probe microscopy, the origin of the long-time-scale \(V_t\) shift was attributed to the trapping of positive charges with immobile states \[18\]. The trapping of holes, caused by GBS, originates from roughness and long chemical species on the insulator’s surface \[13, 14\]. The long-time-scale \(V_t\) shift is observed even when the insulator surface does not have dipoles \[14\]. This indicates that the origin of the long-time-scale \(V_t\) shift is different from the origin of the time decay of \(I_D\) caused by surface dipoles. Thus, when the insulator surface of the OFET has dipoles that can be slightly displaced, the OFETs show two components in threshold voltage shift, one with a time scale of less than 0.1 s and the other of tens of minutes.

4. Conclusion

In conclusion, the OFET with a Cl-monolayer showed a time decay of \(I_D\) on a time scale of less than 0.1 s. The time decay of \(I_D\) is attributed to threshold voltage shift without mobility change. When the insulator surface of OFETs has dipoles that can be slightly displaced, the threshold voltage shift of an OFET caused by gate bias stress has two components. One component has a time scale of less than 0.1 s and the other component has a time scale of tens of minutes.

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