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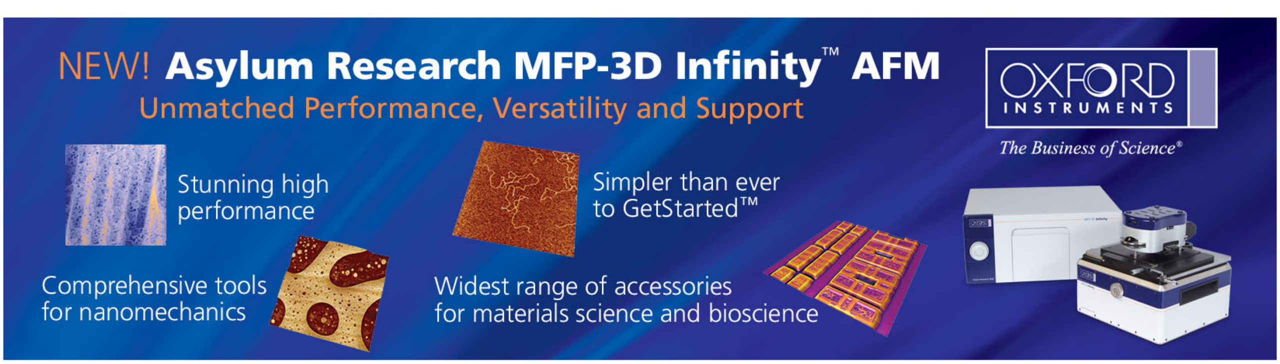

Enhancement-mode polymer space-charge-limited transistor with low switching swing of 96 mV/decade

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In this letter, an enhancement-mode polymer space-charge-limited transistor was realized with a low switching swing of 96 mV/decade, a low operation voltage of 1.5 V, and a high on/off current ratio of 10^4. By investigating the influence of the device's geometric parameters on the transistor characteristics, a low switching swing was obtained by positioning the base electrode at the middle of the channel length and reducing the opening diameter. Simulations of the potential distribution at the central vertical channel verified that the base electrode has the best control over the magnitude of potential barrier, resulting in a low switching swing. © *2011 American Institute of Physics*. [doi:10.1063/1.3586255]

Research on solution-processed organic transistors has increased because organic transistors can be fabricated on a flexible substrate, serving as the key components of low-cost and large-area electronic devices.[1,2] Operation voltage, on/off current ratio, and subthreshold swing are the three important parameters commonly used to evaluate an organic field-effect transistor (OFET). Although conventional OFETs usually show high on/off current ratios, most of them still require a large operation voltage because of the long channel length and the low carrier mobility in organic materials. The subthreshold swing, which describes the ease of switching the transistor using the gate bias is usually high for OFETs. The degraded subthreshold swing, which mainly results from interface and bulk traps,[3] limits the operation frequency and the output current at a low operation voltage. Organic vertical transistors have recently attracted significant attention because of their low operation voltages.[4–12] The organic static induction transistor (SIT) is a well-known vertical transistor, which can achieve a high on/off current ratio of 10^3 at low operation voltage of 3 V.[7] The SIT also delivers a high output current density of about 50 mA/cm^2.[6] Another vertical transistor is the polymer space-charged-limited transistor (SCLT), which is a three-terminal device that functions in a similar way to the vacuum tube triode.[9–12] The device structure is shown in Fig. 1(a). The carrier holes are injected into the semiconducting polymer by an emitter, passing through the openings on the base, and finally being collected by the collector. The on and off states of the SCLT are controlled by the magnitude of the potential barrier constructed between the emitter and the collector at the vertical channel.[11] Both the geometric structure of the device and the voltages applied to the base and the collector are crucial for potential barrier control. Because the SCLTs and OFETs operate according to different operation principles, the term switching swing is used here for SCLTs, similar to the way subthreshold swing is used for OFETs. It has been demonstrated that 1.5 V is large enough to operate a SCLT with a high on/off current ratio of 10^5 and a low switching swing of 300 mV/decade.[11] However, the parameters that seriously influence the switching swings were never systematically studied for any vertical transistor. In addition, the normally on characteristics of these vertical transistors were frequently observed. A nonzero voltage was required to turn off the transistor, which made power consumption inevitable. A normally off vertical transistor therefore needs to be realized as a power-saving device.

In this letter, an enhancement-mode SCLT with a normally off operation is realized. A switching swing as low as

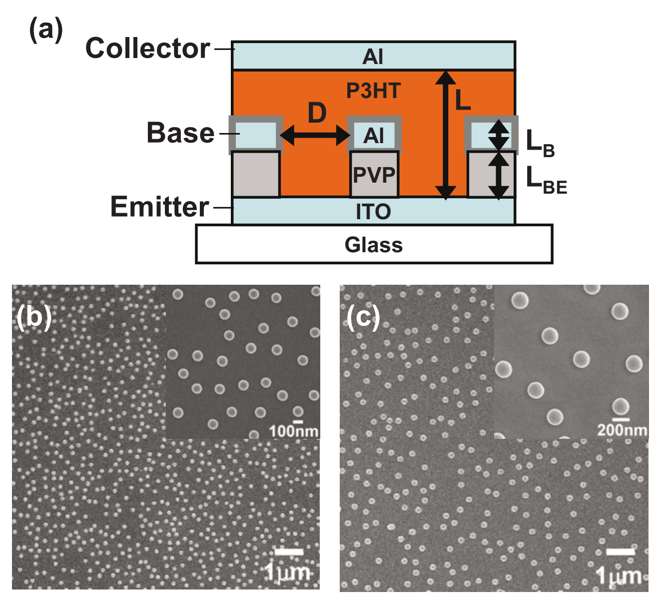

FIG. 1. (Color online) (a) Schematic device structure of SCLT. The opening diameter is denoted by D, the channel length is denoted by L, and the base to emitter distance is denoted by L_{BE}. The scanning electron microscope images of (b) 100 nm and (c) 200 nm PS spheres on poly(4-vinyl phenol) are also shown. The insets show enlarged images.

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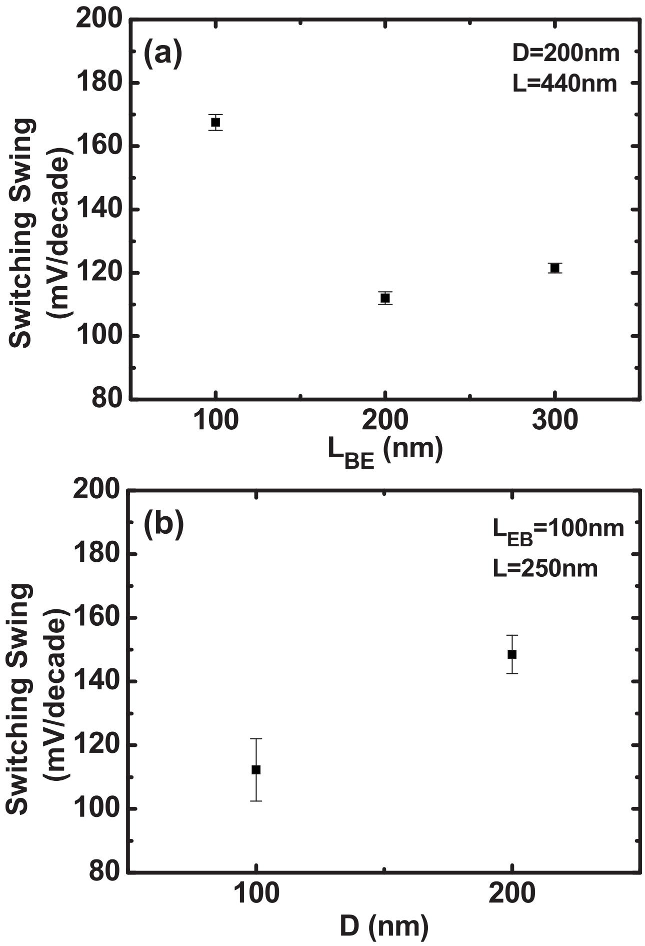

FIG. 2. (a) The switching swings of the SCLTs with various L_{BE} while keeping L and D fixed at 440 nm and 200 nm, respectively. (b) The switching swings of the SCLTs for various values of D while keeping L and L_{BE} fixed at 250 nm and 100 nm, respectively.

96 mV/decade is demonstrated by enhancing the base control on the magnitude of the potential barrier. Simulations of the potential distribution at the central vertical channel provide a reasonable explanation and verify the experimental results. This switching swing is the lowest of various vertical transistors and is close to the theoretical limit of $\ln 10 \times kT/q = 60$ mV/decade in a silicon metal-oxide-semiconductor field-effect transistor at room temperature.[13] The realization of a normally off vertical transistor with a low operation voltage, low switching swing, and high on/off current ratio makes a high-speed and low-voltage operation circuit possible.

Various devices were fabricated with different geometric parameters, including opening diameter (D), channel length (L), and base to emitter distance (L_{BE}), to investigate the influence of the device' s geometric parameters on the transistor's characteristics. Devices were prepared on indium tin oxide glass substrates treated by 150 W oxygen plasma (RF) for 30 min. A layer of cross-linkable poly(4-vinyl phenol) (PVP) was spin coated and annealed at 200 °C for 60 min. Methylated poly(melamineco-formaldehyde) (Aldrich, $M_W = 511$) was used as a cross-linking agent. A layer of 20 nm poly(3-hexylthiophene) (P3HT) was then coated on the PVP and annealed at 200 °C for 10 min. Xylene was used to spin rinse the P3HT to remove the soluble part and the P3HT left on the PVP was estimated to be 15 nm thick. The substrate

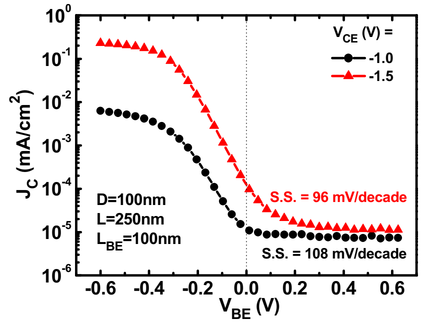

FIG. 3. (Color online) Transfer characteristics of SCLT with D=100 nm, L=250 nm, and L_{BE} of 100 nm.

was then submerged into dilute ethanol solution [0.4% polystyrene (PS) spheres] of 100 or 200 nm diameter negatively charged PS spheres (Fluka) for 1 min to adsorb the PS spheres on the thin P3HT surface as the shadow mask. The substrate was transferred to a beaker of boiling isopropanol solution for 10 s and immediately blow dried. After depositing 40 nm of Al as the metal base electrode ($L_B = 40$ nm), the PS spheres were removed by adhesive tape (Scotch, 3M) and the polymer at the sites without Al coverage was removed by 150 W O_2 plasma (RF). Various thickness of P3HT was spin coated onto the substrate from the chlorobenzene solution and Al was then deposited to complete the SCLT with an active area of 1 mm^2. L_{BE} was controlled by the thickness of PVP layer and D was controlled by the diameter of the PS spheres. L was determined by the thickness of the P3HT layer prepared with the same recipe on another glass substrate.

A reliable comparison between the various SCLTs could only be obtained while the geometric parameters were well controlled. L and L_{BE} can be easily controlled by controlling the thicknesses of the P3HT and the PVP layers, respectively. However, randomly occurring aggregates of PS spheres result in irregular and large openings on the base electrode.[12] Therefore, as a first step, aggregates of PS spheres were prevented by modifying our previous fabrication processes.[12] Reducing the concentration of the PS sphere ethanol solution and the substrate submerging time helped to prevent the formation of aggregates as shown in Figs. 1(b) and 1(c). The opening diameter D is now well controlled and the transistor characteristics are suitable for comparison.

The subthreshold region of a OFET shows how the device is turned on and off and the subthreshold swing represents the switching speed. Here, similar to the formula $[\delta(\log I_{DS})/\delta(V_{GS})]^{-1}$ conventionally used for extracting the subthreshold swing in the OFET, the formula $[\delta(\log J_C)/\delta(V_{BE})]^{-1}$ is adopted to obtain the switching swings of the SCLTs from the transfer characteristics while the collector-to-emitter voltage (V_{CE}) is fixed at -1.5 V. J_C, and V_{BE} are the output current density and the base-to-emitter voltage of the SCLT while I_{DS} and V_{GS} are the drain current and the gate bias of the OFET. The formula $[\delta(\log J_C)/\delta(V_{BE})]^{-1}$ describes the control ability of V_{BE} with respect to J_C. The switching swings of various SCLTs with different D, L, and L_{BE} are shown in Fig. 2. At least two devices, with an on/off current ratio of 10^4, were used to obtain the average switching swing. Figure 2(a) shows the switching swings of the SCLTs with various L_{BE} while keeping L and D fixed at 440 nm and 200 nm, respectively. The

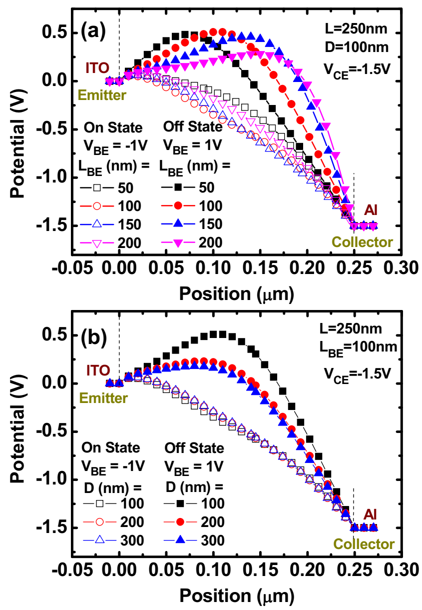

FIG. 4. (Color online) The potential distribution profiles at the central vertical channel of the SCLT for (a) various values of L_{BE} and (b) various values of D.

lowest switching swing was achieved for the device with an L_{BE} of 200 nm. This means that the base electrode has the best control over the output current when it is positioned at the middle of the current channel. For another set of devices with L=250 nm and D=100 nm, the lowest switching swing was also obtained when the base electrode was positioned at the middle of the current channel. Figure 2(b) shows the switching swings of the SCLTs with various D while keeping L and L_{BE} fixed at 250 nm and 100 nm, respectively. A lower switching swing is obtained while reducing the opening diameter D. Both positioning the base electrode at the middle of the current channel and reducing the opening diameter are essential to obtain a low switching swing. As shown in Fig. 3, a low switching swing of 96 mV/decade is achieved for the device with D=100 nm, L=250 nm, and L_{BE}=100 nm. This device shows a normally off operation with a low operation voltage, low switching swing, and high on/off current ratio, which makes it possible to be used in a power-saving and high-speed device.

The change in the switching swing with different geometric structures of the device can be explained by the variation in the potential distribution at the central vertical channel. Simulations based on the device structure shown in Fig. 1(a) are carried out with SILVACO TCAD ATLAS software. Simulation parameters are shown in Ref. 14. Figure 4(a) shows the potential distribution profiles at the central vertical channel of the devices with different L_{BE}. The V_{CE} is fixed at −1.5 V. When V_{BE}=1 V, V_{BE}, and V_{CE} constitute a potential barrier and the device is turned off. The device with an L_{BE} of 100 nm shows the highest potential barrier. As the device is turned on by V_{BE}=−1 V, the lowest potential is also obtained in the device with an L_{BE} of 100 nm. The potential can be modulated to the largest extent in the device with an L_{BE} of 100 nm. This means that when the base electrode is positioned at the middle of the channel length, the base electrode has the best control over the output current. The device with a smaller D is also able to control the potential to a larger extent as shown in Fig. 4(b). The change in simulated potential barrier gives a reasonable explanation of the change in switching swing shown in Fig. 2.

In conclusion, an enhancement-mode vertical transistor is realized with a switching swing as low as 96 mV/decade. Such a low switching swing is obtained by placing the base electrode at the middle of the channel length and reducing the opening diameter. Simulations of the potential distribution confirm the experimental results. The demonstration of a device with a low switching swing, low operation voltage, and high on/off current ratio, illustrates a possible application for high-speed and power-saving logic circuits.

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[14]The SCLT characteristics simulation is made based on the device structure shown in Fig. 1(a). Insulator surrounds the grid is used to make the model more realistic. The highest occupied molecular orbital and lowest unoccupied molecular orbital levels of P3HT are 5.0 and 3.0 eV. The work function of emitter and collector are 5.0 and 4.0 eV. The hole mobility and electron mobility are 10^{-4} and 10^{-6} cm^2/V s.