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Low voltage active pressure sensor based on polymer space-charge-limited transistor

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Low voltage active pressure sensor is realized by vertically stacking a pressure sensitive rubber on a polymer space-charge-limited transistor. The sensor can be turned on and off by modulating the metal-grid base voltage within the range of 3 V. The output current is irrelevant to the pressure as the sensor is off. As the sensor is turned on, the output current values can be used to monitor the pressure. Reversible pressure sensing characteristics is observed below the pressure of 7.11 psi. The response time of the sensor to the pressure is as short as 22 ms. [doi:10.1063/1.3266847]

There is now a rising demand from diversified areas for an array of semiconductor devices distributed over a large area on potentially nonplanar surfaces. The general concept of flexible and large-area electronics consists of a flexible substrate, a driving transistor array, and a sensor array.[1] The transistor array controls the active matrix switching while the sensor array monitors the information outside or inside of the surface of human body, robot, moving machine, or other organisms. The information can be either outside the surface as in the cases of proximity,[2] pressure,[3] and temperature[4] or inside the surface as in the case of chemical species inside an organism. Various form of information could be converted into electronic signals for convenient data processing. Organic electronics, especially made by conjugated polymer semiconductors, appear to be the most promising technology to meet the strict demands of large-area sensor array.[5] Pressure sensors based on organic electronics which may give robot hands tactile sensitivity like human hands have attracted considerable attention. Previous works have demonstrated a pressure sensor array for artificial skin application by integrating pressure sensitive rubber with organic field-effect transistor (OFET).[6,7] However, owing to the long channel length between source and drain electrodes, low mobility, and air sensitive nature of organic material, the OFET utilized in previous works possess drawbacks such as high operation voltage, low operation frequency, and low output current. Besides, via hole fabricated by laser drilling is needed to make electrical connection between pressure sensitive rubber and OFET. These drawbacks seriously limited the performance of OFET to be utilized as component of transistor array or mobile device. A transistor free from these drawbacks is therefore crucial for the development of macroelectronics.

Organic vertical metal-base transistors[8–16] have been developed to overcome the limits of conventional horizontal OFET. The channel length of vertical metal-base transistor is determined by the thickness of the organic semiconductor layer. The output current is modulated by the voltage of a base electrode embedded in the organic layer. One of these vertical metal-base transistors, namely the space-charge-limited transistor (SCLT), shows promising performance.[14,15] The SCLT is a vertical transistor with a grid electrode inserted between emitter and collector to control the vertical current flow. The device structure of the SCLT is shown in Fig. 1(a). The grid contains random submicron openings formed by a nonlithographic method. The carriers are injected from the emitter into the semiconductor, passing through the openings on the metal grid and finally arriving at the collector. The voltages of grid and collector control the potential distribution between emitter and collector as shown

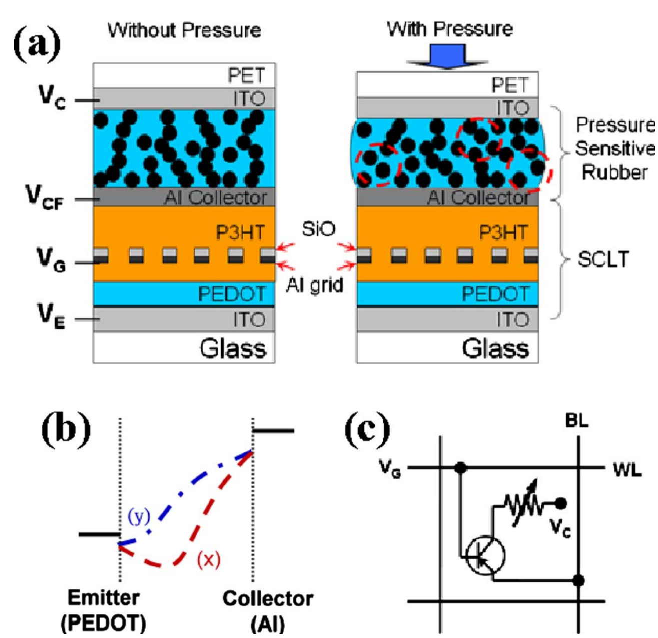

FIG. 1. (Color online) (a) The schematic device structure. The left part shows the device structure without pressure applied. The right part shows the device structure under pressure. Different graphite particles distributions in PDMS are also shown. The conductive paths break at the place indicated by red dashed circles. (b) The potential profile along the emitter—collector path through the opening when V_C is fixed at a negative value. Curve (x) is a potential profile with energy barrier for hole. Curve (y) is a potential profile without energy barrier for hole for a positive enough grid potential V_G. (c) Circuit diagram of one active pressure sensor.

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in Fig. 1(b). When high barrier forms between emitter and collector [curve (x)], few carriers can arrive at the collector and this corresponds to the off state of the transistor. While low or no barrier forms [curve (y)], lots of carriers can arrive at the collector and this corresponds to the on state of the transistor.

In this letter, one pixel active pressure sensor operated with low voltage is demonstrated by vertically integrating SCLT with the pressure sensitive rubber as shown in Fig. 1(a). Circuit diagram of one active pressure sensor of an active matrix pressure sensor is shown in Fig. 1(c). The SCLT is represented by the symbol of bipolar junction transistor. The pressure sensitive rubber is a composite containing poly(dimethylsiloxane) (PDMS) and graphite particles, and it functions as a variable resistor. Integration between SCLT and pressure sensitive rubber is easy since both of them are in sandwich structures. Drilling process needed in previous work is avoided.[6,7] The resistance of the pressure sensitive rubber changes when subjecting to a pressure and can be read out by the SCLT for pressure monitoring. The operation voltage of the integrated pressure sensor is as low as 4 V and the output current density is around 5 mA/cm^2. Furthermore, the response time of the pressure sensitive rubber to the pressure is as short as 22 ms. Such a fast response time makes the device suitable for serving as a component of active matrix pressure sensor array.

Since graphite particle is more incompressible compared with rubber, the response of the pressure sensitive rubber to the pressure mainly results from the deformation of the PDMS.[17] As the pressure is applied on the pressure sensitive rubber, the distribution of graphite particles in the PDMS changes as PDMS deforms. In this work, graphite particles are blended with PDMS in proper weight ratio to make graphite particles already constitute conductive paths in the rubber as shown in the left part of Fig. 1(a). The application of external pressure extrudes graphite particles out of the conductive paths and increases the resistance of the pressure sensitive rubber as indicated in the red dashed circles in the right part of Fig. 1(a). Without pressure, the pressure sensitive rubber shows the resistance comparable to the on state resistance of SCLT in the order of 10^4 ohm. While pressure is applied on the pressure sensitive rubber, the pressure-dependent resistance falls in the range from on state resistance of SCLT to the off state resistance of SCLT.

The pressure sensor is fabricated by integrating the SCLT with the pressure sensitive rubber. After cleaning the substrate, a layer of 400 Å poly(3,4-ethylenedioxythiophene) doped with polystyrene sulfonated acid (PEDOT:PSS) is spin coated on ITO and annealed at 200 °C for 10 min. After poly(3-hexylthiophene) (P3HT) is spin coated and annealed at 200 °C for 10 min, the P3HT film is spin rinsed with xylene. The 2000 Å polystyrene spheres are absorbed on the P3HT surface as evaporation mask by submerging the substrate in a polystyrene spheres ethanol solution for 40 s. The substrate is then dipped in a boiling isopropanol solution for 10 s and blown dry in a nitrogen flow. After depositing 150 Å Al and 500 Å SiO as grid electrode and insulating layer, the spheres are removed by an adhesive tape. Another layer of 800 Å P3HT is then spin coated from xylene, following the deposition of 400 Å Al collector to complete the fabrication procedures of the transistor. The transistor active area is 1 mm^2. The pressure sensitive rubber is then prepared on top of the transistor. The pressure sensing rubber is a blend of

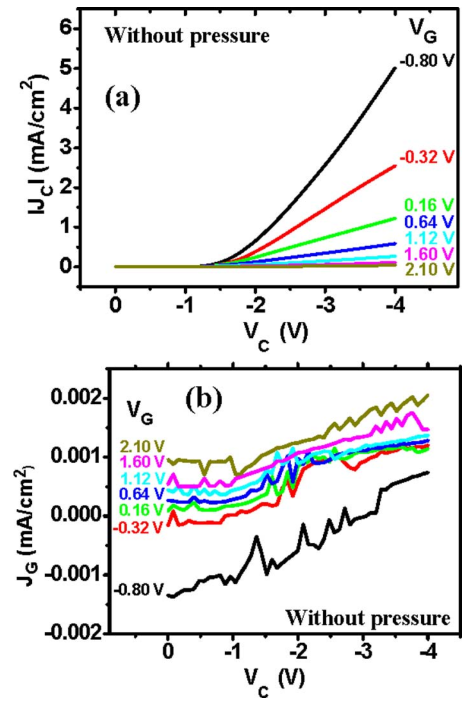

FIG. 2. (Color online) (a) $|J_C|$ and (b) J_G as a function of V_C at various grid voltages of the pressure sensor with 2000 Å opening on Al grid.

PDMS and graphite particle (Sigma Aldrich) in weight ratio of 3.5:1. The diameter of the graphite powder is smaller than 20 μm. The blend is then poured into a mold placed on the sample. The thickness of the pressure sensitive rubber is around 2 mm. After placing a sheet of ITO coated polyethylene terepthalate (PET) flexible substrate on top of the pressure sensing rubber, whole device is annealed at 100 °C for 10 min to cure PDMS and complete the device fabrication procedure.

The electric characteristics of the pressure sensor without applying pressure are shown in Fig. 2. Voltages applied on ITO emitter, Al grid, Al collector, and ITO electrode on PET flexible substrate are represented by V_E, V_G, V_{CF}, and V_C. The PEDOT:PSS covered ITO emitter is commonly grounded and hence V_E is zero. V_{CF} is floating and its value is determined by the voltage drop across the pressure sensitive rubber. While no pressure is applied on the device, the resistance of the pressure sensitive rubber is low and hence V_{CF} is almost equals to the V_C. Figure 2(a) demonstrates an apparent modulation of output current from the ITO electrode on PET ($|J_C|$) by V_G from −0.8 to 2.1 V while no pressure is applied. When V_C is −4 V and V_G is −0.8 V, the transistor output current density is 5.02 mA/cm^2. The on/off ratio 132 is obtained by dividing $J_C(V_G=-0.8\ V)$ by $J_C(V_G=2.1\ V)$ while V_C is −3.12 V. Figure 2(b) shows the leakage current density J_G of Al grid as a function of V_C. J_G keeps low under various biasing voltages. As V_C is −4 V, the current gain $|J_C|/J_G$ is 6756.

While different pressure is applied on the device, different amount of conductive paths break which result in different resistance value. Figure 3(a) shows the response of $|J_C|$ under various pressures. The pressure is created by placing weight on the device. When V_G is −0.8 V, the transistor is in the on state, $|J_C|$ is decreased by applying 2.84 psi on the device. $|J_C|$ keeps at the same value until the pressure is changed. While increasing the pressure, $|J_C|$ decreases once

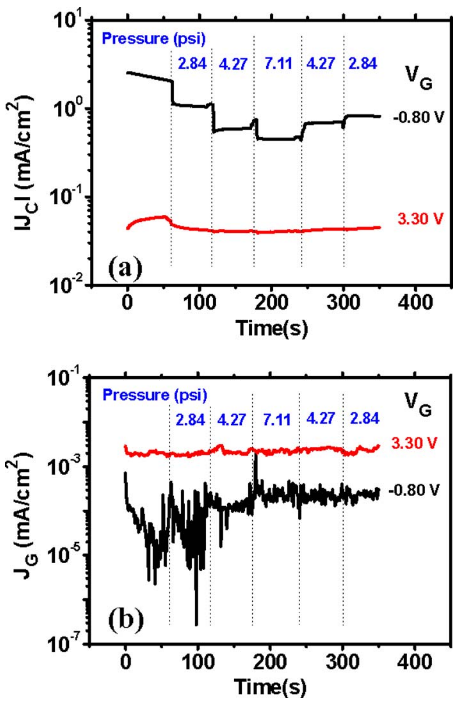

FIG. 3. (Color online) The response of (a) $|J_C|$ and (b) J_G under various pressure. V_G is -0.8 and 3.3 V. V_C is biased at -4 V.

again. As the pressure is decreased from 7.11 to 4.27 psi, $|J_C|$ recovers almost to its original value under the pressure of 4.27 psi. On the other hand, when V_G is 3.3 V, the transistor is in the off state, $|J_C|$ keeps at the same value without changing with pressure. At this time, the resistance of the SCLT is larger than the pressure sensitive rubber. The voltage difference on the pressure sensitive rubber is small and the response on pressure cannot be resolved from $|J_C|$. Figure 3(b) shows that J_G also keeps at the same value under various pressure. These results suggest that the integration between SCLT and pressure sensitive rubber is an excellent candidate for pressure sensor.

Furthermore, the response time of the pressure sensitive rubber is also investigated. The response time is recorded with the circuit as shown in the inset of Fig. 4. The pressure sensitive rubber is connected in series with a 10 kΩ resistor

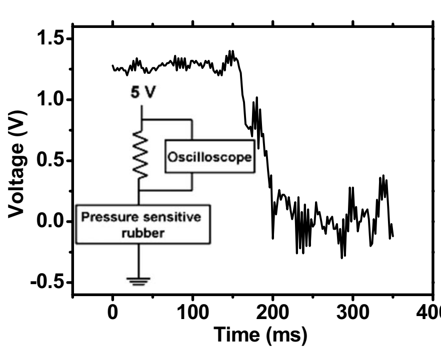

FIG. 4. The response of the pressure sensitive rubber. The inset shows the measuring circuit.

in order to probe the variation in the resistance of the pressure sensitive rubber. The response time is defined as the time required for the voltage drop across the resistor decreases to half of its original value. Before applying pressure, the voltage drop across the resistor is about 1.25 V. When we touch the pressure sensitive rubber carefully by hand, the voltage drops to the value almost zero within 50 ms. This changing from low to high resistance is matching to the result shown in Fig. 3. It takes about 22 ms for the voltage across the resistor drops to 0.625 V. The actual response time of the pressure sensitive rubber may be faster than 22 ms since the deformation of the soft tissue on hand also takes place. Such a short response time is suitable for a high sensitive pressure sensor.

In summary, the pressure sensitive rubber is vertically integrated with SCLT to demonstrate one pixel active pressure sensor. The operation voltage of this pressure sensor is as low as 4 V, and the response time is as short as 22 ms. Since the pressure sensitive rubber is also in the sandwich structure, the integration between SCLT and pressure sensitive rubber is easy. The integration is also applicable for any other devices with sandwich structure such as photodiode and light-emitting diode. Such device concept has the potential advantages of easy large-area solution process, low voltage, and being lithography-free.

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