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Tunable organic transistors that use microfluidic source and drain electrodes

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This letter describes a type of transistor that uses conducting fluidic source and drain electrodes of mercury which flow on top of a thin film of the organic semiconductor pentacene. Pumping the mercury through suitably designed microchannels changes the width of the transistor channel and, therefore, the electrical characteristics of the device. Measurements on transistors with a range of channel lengths reveal low contact resistances between mercury and pentacene. Data collected before, during, and after pumping the mercury through the microchannels demonstrate reversible and systematic tuning of the devices. This unusual type of organic transistor has the potential to be useful in plastic microfluidic devices that require active elements for pumps, sensors, or other components. It also represents a noninvasive way to build transistor test structures that incorporate certain classes of chemically and mechanically fragile organic semiconductors. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1609056]

The integration of active electronics directly with molded microfluidic channel arrays represents a promising way to increase the functionality, lower the cost, and reduce the size of microfluidic reactors, separation, and analysis systems. Organic electronic circuits have certain characteristics—intrinsic compatibility with plastics, ease of fabrication and processing, ability to be patterned with the types of soft lithographic methods that are useful for building microfluidic devices,[1–3] etc.—that make them attractive for this purpose. Here we explore one route for directly combining the active elements of plastic circuits (i.e., the transistors themselves) with moving fluids that can be coupled in various ways to the microfluidic elements of the system. We demonstrate, in particular, that microchannels filled with mercury can serve as dynamically tunable source and drain electrodes in transistors that incorporate the *p*-type organic semiconductor pentacene. This letter begins with a description of the layout of these devices and the sequence of steps for their fabrication. Measurements on transistors with channel lengths between 25 and 200 μm demonstrate the good performance of these devices and the low contact and parasitic resistances associated with them. Pumping the mercury back and forth in the channels reversibly adjusts the electrical characteristics of the transistors in a systematic and easily understandable way. Devices with this design could find applications as sensors or elements of drive circuits for pumps in microfluidic systems. In addition, the noninvasive and low resistance microchannel mercury contacts may be useful for basic studies of charge transport in chemically and mechanically fragile classes of organic semiconductors, in a way that is analogous to the recent application of mercury droplets for probing organic molecular-scale diodes.[4]

Figure 1(a) shows a schematic view of a typical device. It consists of a bottom substrate that supports a thin film of an organic semiconductor (pentacene; 25 nm, deposited by thermal evaporation through a shadow mask at 0.02 nm/s) on a gate dielectric (SiO_2; 300 nm, thermally grown) and a gate electrode (highly doped Si wafer). The microfluidic channels are formed by conformal contact of this substrate with an elastomeric element that is built using the techniques of soft lithography. In particular, casting and curing a prepolymer to poly(dimethylsiloxane) (PDMS) (Dow Corning) against a ''master'' structure of patterned negative photoresist (SU-8, Microchem Corp.; thickness ~15 μm) forms a transparent element with relief in the geometry of the resist. For the photolithography, we used printed transparencies for photomasks; the resolution of these masks (~25 μm) determined the smallest features in our devices. As shown in Fig. 1(a), for the microfluidic transistors illustrated here, the relief consists of two square (~2 mm×2 mm) ''reservoirs,'' each of which is connected to a narrow channel. These channels travel from the reservoirs to a region where they are parallel and separated by a small distance. This area, which we refer to as the ''transistor region,'' forms the part of the device that defines the source and drain electrodes. After this transistor region, the channels lead to exits on opposite edges of the

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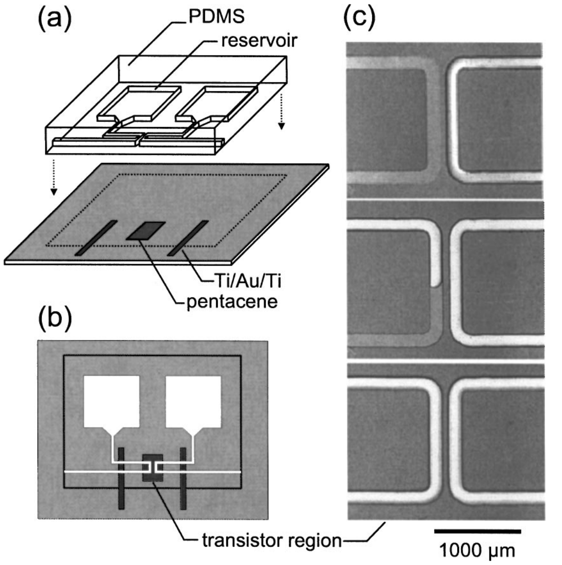

FIG. 1. Part (a) shows a schematic angled view of a PDMS element with relief on its surface (top) and a substrate that supports the semiconductor, gate dielectric, Ti/Au/Ti contact lines, and gate electrode. Part (b) shows a schematic illustration of the assembled device as viewed from the top through the transparent PDMS. Part (c) presents optical micrographs of the transistor region with mercury (white) pumped into the channel on the left hand side to various degrees. The extent that the mercury fills the channels defines the effective transistor channel width.

PDMS element. Depositing small droplets of mercury at the positions of the reservoirs, flipping the PDMS element over (the mercury clings to the surface of the PDMS) and then placing it against the substrate that supports the other components of the device leads to a ‘‘wetting’’ contact that seals the mercury in the reservoirs and forms closed microchannels. When the surfaces of the SiO_2 and the PDMS have been exposed briefly to an oxygen plasma, this contact leads to a strong, permanent bond between these two elements.[5] Experiments described elsewhere show that contact of the PDMS against the top surface of the pentacene film does not change the electrical properties of the accumulation channel that develops at the interface between the dielectric and the semiconductor or other characteristics of the transistors (e.g., the off currents, etc.).[6]

The PDMS element is aligned so that the transistor region overlaps with the rectangular area of the substrate that supports the pentacene. See Fig. 1(b). Applying slight mechanical pressure to the PDMS above the reservoirs (the low modulus of the PDMS allows it to be easily deformed) pumps the mercury into the channels. By adjusting the applied pressure, it is possible to control the distance that the mercury travels through the channels. Pumping the mercury so that it completely fills the channels causes it to flow over the pentacene and to complete a transistor whose source/drain electrodes are defined by the geometry of the PDMS element (i.e., the separation between the channels, and the distance along which they are parallel in the transistor region). In other words, in this configuration, the microchannels define the width (*W*) and length (*L*) of the transistor channel. When the mercury is only partially pumped through the transistor region, then the position of the fluid plug determines the transistor channel width. Figure 1(c) shows optical micrographs collected by viewing the device through the transparent PDMS element in the transistor region, at three stages of pumping the mercury through the channel on the left. The mercury appears bright in these images. The curved corners of the channels facilitate flow.

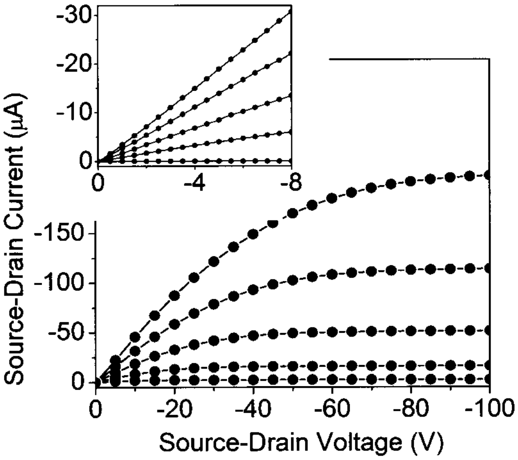

FIG. 2. Current–voltage characteristics of a microfluidic transistor that uses mercury for the source/drain electrodes and pentacene for the semiconductor. The top inset illustrates the response for source/drain voltages that are small compared to the gate voltage. The gate voltages for the inset are (from bottom to top curves): 0, −40, −60, −80, and −100 V. The gate voltages for the main part of this figures are (from bottom to top curves): −20, −40, −60, −80, and −100 V.

The microfluidic channels and the mercury overlap lines of Ti (2.5 nm)/Au (50 nm)/Ti (30 nm) which are formed on the substrate by electron beam evaporation through a shadow mask. These lines extend beyond the edges of the PDMS elements to enable electrical connection with conventional probe tips. See Figs. 1(a) and 1(b). The resistance at the contact between the mercury and the Ti/Au/Ti lines is negligible. The current–voltage characteristics of the devices were determined with a semiconductor parameter analyzer (Agilent 4155). Figure 2 shows the properties of a device that has mercury pumped all the way through the transistor region of the microfluidic channels [i.e., in the geometry of the micrograph at the bottom of Fig. 1(c)]. The *L* and *W* of this device are 110 μm and 2.5 cm, respectively. The inset shows the response at source/drain voltages that are small compared to the gate voltage. The linear behavior is consistent with ohmic contacts between the mercury and the pentacene. The mobilities and threshold voltages computed using the standard expressions[7] in the saturation and linear regimes are, to within uncertainties, the same: 0.18 $\pm 0.02\ \mathrm{cm}^2/\mathrm{V\,s}$ and -18 ± 2 V. We did not observe a systematic dependence of the linear or saturation regime mobilities or threshold voltages on *L*. These results are consistent with negligible effects of contacts for this range of transistor geometries.

Figure 3 shows parasitic resistances computed by analyzing the linear regime behavior of 12 devices with a range of channel lengths between 25 and 200 μm. This set of devices includes pentacene deposited in several different evaporations. The inset shows the overall width-normalized device resistance measured at small source/drain voltages and at different gate voltages; the *y* intercepts determine the parasitic resistances (i.e., the component of the device resistance that remains when the length of the channel is zero).

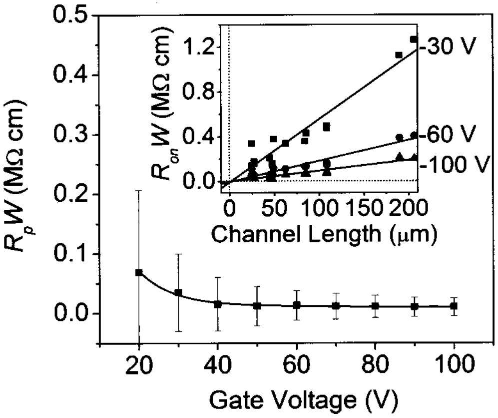

FIG. 3. Parasitic resistances associated with microfluidic transistors, as evaluated from the dependence of the device resistance on transistor channel length (as shown in the inset).

These parasitics (which include the mercury–pentacene contact resistance) are sufficiently small that they are difficult to measure accurately in the devices described here. The transistor channel sheet conductances (S) can be measured from the inverse of the slope of the line fits shown in the inset to Fig. 3. The intrinsic mobility and threshold voltage ($0.14 \pm 0.02\ \mathrm{cm^2/V\,s}$ and -18 ± 2 V, respectively) follow from linear fits to these data according to

$$S = \mu_i C(V_G - V_{T,i}), \tag{1}$$

where μ_i and $V_{T,i}$ are the intrinsic mobility and threshold voltage, respectively, C is the capacitance of the gate dielectric, and V_G is the gate voltage.[8] These intrinsic channel properties are consistent with the saturation and linear regime results. They are also similar to intrinsic values determined from analysis of devices fabricated on the same substrate by evaporating gold electrodes (1 nm/s; 50 nm thick) onto the pentacene through a shadow mask. The parasitic resistances associated with evaporated gold devices[7] are typically higher than those associated with the mercury microchannel electrodes.

Pumping the mercury through the transistor region of the microfluidic system changes the width of the transistor channel. Figure 4 illustrates current–voltage responses of a device pumped to configurations that yield different effective channel widths. For these data, the mercury was pumped to a fixed location in one of the two channels while the current–voltage measurements were made. The other of the two channels was filled completely with mercury for all measurements. The results show a large tuning contrast ($>10^6$), which is limited partly by small leakage currents through the gate dielectric. Measurements performed as the mercury is pumped into and out of overlap with the pentacene in the transistor region yield the same results, to within uncertainties associated with determining the position of the front of the mercury plug. Although we did not perform long term reliability or cycling tests, there was no noticeable degradation in device performance during the several hours of measurements on several different devices before, during and after pumping.

The results presented in this letter demonstrate that (i) pumped microfluidic mercury source/drain electrodes and organic semiconductors provide the basis for a type of tunable transistor that can be integrated directly with plastic microfluidic systems, and (ii) the contact resistances between mercury and the organic semiconductor pentacene are <0.02 MΩ cm at large gate voltages, and the performance of the associated transistors are comparable to or better than those that are built in the conventional way. The fabrication procedures are compatible with plastic substrates and with transistor channel lengths that are considerably shorter than those described here. (Similar fluidic channel systems have been used to mold source/drain electrodes for organic transistors with channel lengths of ~2 μm.)[9] They are also suitable for building microfluidic transistors with other fluidic conductors and organic or inorganic semiconductors. Designs in which fluid motion alters the transistor channel length rather than, or in addition to, the channel width are also possible. The simplicity of the fabrication procedures, the flexibility of the tuning approach, and its inherent compatibility with "soft" semiconductor materials and plastic microfluidic networks, all suggest that devices of this type have the potential to be useful for fundamental studies and applied work in organic electronics and microfluidics.

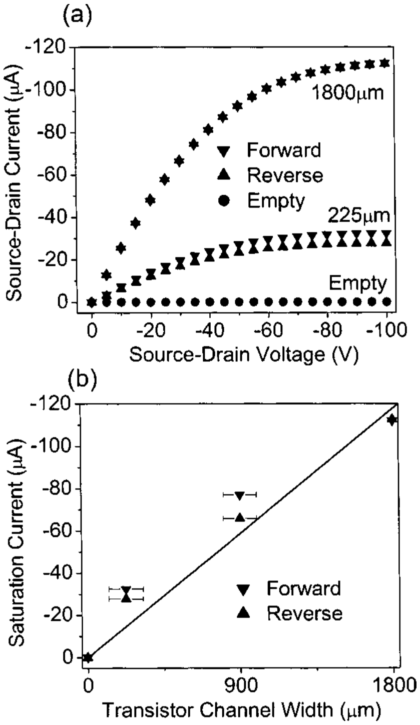

FIG. 4. Part (a) shows current/voltage characteristics of a microfluidic transistor evaluated at three tuning states with a gate voltage of −100 V. Curves measured during filling and emptying cycles (forward and reverse) are presented. Part (b) shows the associated saturation currents.

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