A novel two-way mode of current switching dependent on activated charge transport

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Abstract. We demonstrate a fully printed transistor with a planar triode geometry, using nanoparticulate silicon as the semiconductor material, which has a unique mode of operation as an electrically controlled two-way (double throw) switch. A signal applied to the base changes the direction of the current from between the collector and base to between the base and emitter. We further show that the switching characteristic results from the activated charge transport in the semiconductor material, and that it is independent of the dominant carrier type in the semiconductor and the nature of the junction between the semiconductor and the three contacts. The same equivalent circuit, and hence similar device characteristics, can be produced using any other material combination with non-linear current-voltage characteristics, such as a suitable combination of semiconducting and conducting materials, such that a Schottky junction is present at all three contacts. We present performance results for two design variants of the printed transistor and confirm our interpretation of the device's operation by constructing a model circuit using individual varistors.

Over the last 65 years the transistor has revolutionised industrial and consumer electronics [1]. Originally conceived and developed as a signal amplifier [2, 3, 4], its main use today is as an electrically driven switch in computer logic [1], memory addressing and driving displays [5]. In general terms a transistor is a three terminal electronic device (triode) which exhibits a transconductance. There are two classes of transistor: field effect transistors [1, 2, 5] and junction transistors [3, 4]. In field effect transistors the current between two contacts (the source and drain) through a semiconductor material is either restricted or enhanced by an internal electric field resulting from the application of a potential to the gate electrode. In junction transistors, injection of charge by a current through the base modulates the potential barriers between the base and the emitter and between the base and collector respectively. Both classes of transistor can therefore function as simple switches in which a signal applied to the base (or gate) controls the current between the emitter and collector (or source and drain). Here we demonstrate a fully printed electronic device with a similar triode configuration, using nanoparticulate silicon as the semiconductor material [6, 7], which has a unique mode of operation as an electrically controlled two-way (double throw) switch. By analogy with the junction transistor and the vacuum tube, we denote the electrodes as emitter, base and collector. A signal applied to the base changes the direction of the current from between the collector and base to between the base and emitter. We further show that the switching characteristic results from the

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activated charge transport in the semiconductor material, and that it is independent of the dominant carrier type in the semiconductor and the nature of the junction between the semiconductor and the three contacts.

The devices were produced by screen printing patterns of conducting and semiconducting inks on plain paper substrates, with the contacts arranged in a coplanar geometry. The printed silicon layers consist of a dense network of nanoparticles [8, 9, 10], produced by high energy milling of bulk material, which typically have a log-normal size distribution with a median size of approximately 100 nm and a logarithmic standard deviation around 1.45 [8, 10]. In the printed layer the network structure can be described as a fractal structure of interconnecting clusters of particles [9, 10]. The size of these clusters and their connectivity depends strongly on the substrate material and ink composition as well as the deposition process [9, 10], but their internal topology is similar. Typically for the material used here, the primary clusters contain 600 ± 200 individual particles, and have a size of approximately 500 nm [10]. The individual silicon particles are polycrystalline, with a typical grain size of 10 nm and have predominantly (111) faceted surfaces [7, 8] which have no noticeable oxide shell [7].

The combination of a highly interconnected network of particles with many interfaces between particles along any percolation path leads to a thermally activated hopping transport of charge. It is this property, which forms the basis for the application of this material system in commercially available printed thermistors [11], and, more importantly, which enables the current switching function presented here. The current-voltage characteristics of the printed silicon material between two metal contacts exhibit a non-linear response of the current I on the potential difference V, which can be described by the form

$$I = I_0\left(\exp\left(\frac{e(V - IR_S)}{nkT}\right) - \exp\left(\frac{-e(V - IR_S)}{nkT}\right)\right), \tag{1}$$

where k is Boltzmann's constant and T is the absolute temperature. These characteristics are indicative of a varistor composed of back-to-back diodes, in which each diode has the same reverse saturation current I_0 and ideality factor n, with an additional series resistance R_S. As discussed in the supplementary information, both the saturation current, which represents the activation energy for hopping, and the ideality factor, which is influenced by the number of junctions in the percolation path, have non-trivial temperature dependences, indicating the freezing out of some conducting pathways at low temperatures.

If a third contact is added to the silicon layer to form a three terminal device, the equivalent circuit becomes a triangular arrangement of three varistors as shown in figure 1 (a). The behaviour of the circuit can be predicted in terms of the potentials applied to each terminal and the voltage dependent resistance between them. The resistance between any pair of terminals is high if the potential difference between them is low, and consequently a current only passes for a high potential difference. Hence if the emitter is maintained at zero and a positive bias is applied to the collector, there will be a current into the collector and out of the emitter. By analogy with a transistor, this can be conveniently regarded as the off-current. If the base is then biased positively there will be a current from the base to the emitter. Conversely, if the base is biased negatively there will be a current into the collector and out of the base. Therefore, not only is the sense of the current through the base reversed as expected when the potential is changed, but its route through the circuit is also diverted. In terms of the mechanically operated analogue shown schematically in figure 1(b), in the conventional mode of operation of a transistor applying a signal to the base corresponds to a simple switch closing the gap between the emitter and collector. In figure 1(c), the operation of this new device is fundamentally different, in that applying a signal to the base corresponds to rotating the arm of a two-way switch so that it connects either the emitter and base or the base and collector.

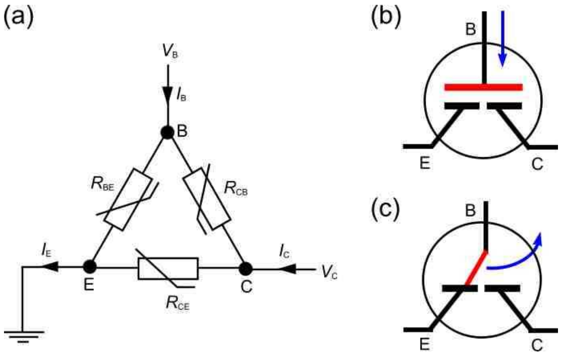

Figure 1: (a) Equivalent circuit of the current switching device as a triangular network of varistors, R_{CE} connecting the collector (C) to the emitter (E), R_{CB} connecting the collector to the base (B), and R_{BE} connecting the base to the emitter (E). Under applied potentials V_B and V_C the currents into the base and collector are I_C and I_B respectively. The emitter potential V_E is by definition zero, and the current out of the emitter I_E is equal to the sum of I_B and I_E. (b) Mechanical switch analogue of a normal mode of transistor operation in which application of a signal to the base is equivalent to a vertical motion of the plunger to complete the circuit between E and C. (c) Mechanical switch analogue of the current switching mode in which application of a signal to the base is equivalent to a rotation of the lever to switch the circuit from between E and B to between B and C.

The first device, consisting only of metal contacts and silicon printed on a plain paper substrate, and its transfer characteristics are shown in Figure 2. Superficially the construction of this device is similar to that of both a junction FET [12] and a metal-semiconductor FET [13], as well as the original point contact transistor [14], which also only consist of a semiconductor body and metal contacts. In a junction FET, a depletion layer is formed in the semiconductor body by a Schottky barrier at the gate electrode, which restricts current flow between the source and drain which have ohmic contacts. If the semiconductor body is n-type, applying a positive potential to the gate will increase the size of the depletion region and restrict the current further, whereas for a p-type semiconductor a negative potential will have the same effect.

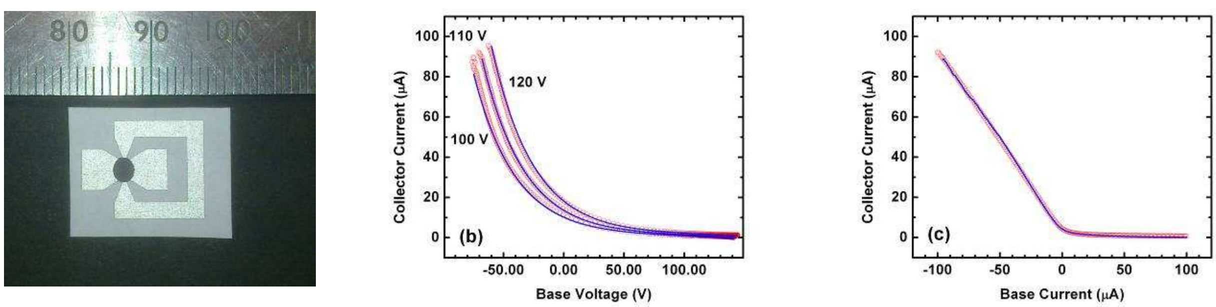

Figure 2: (a) Photograph of an electrically driven current double throw switch with silver contacts and an n-type silicon semiconductor layer printed on a plain paper substrate. (b) Dependence of the collector current on the potential applied to the base for collector potentials of 100V, 110V and 120V. The solid lines represent a least-squares fit of the model function (eq. 2) to all three data sets simultaneously. (c) Dependence of the collector current on the current injected at the base for a collector potential of 100V. The solid line represents the same calculated data as in (b).

In the point contact transistor, the contact to the base is ohmic allowing the injection of charge, and there are depletion regions arising from Schottky barriers at the emitter and collector electrodes.

Injection of electrons into a p-type semiconductor body will reduce the effective potential barrier between the emitter and collector enabling an increase in the current. Similarly, holes need to be injected into an n-type semiconducting body to increase the current. Both of these types of transistors can therefore be expected to show the opposite response to an applied gate or base potential if the type of semiconductor is changed. In contrast, for the device presented in this paper, because the properties are determined primarily by the non-linear resistance characteristics, its qualitative behaviour is independent of whether the semiconductor body is p-type or n-type, as shown for the example devices below.

In the device shown in Figure 2(a), there are two electrodes forming the base which are connected together and positioned midway between the emitter and base contacts, with the silicon printed on top to bridge all the contacts. Figures 2(b) and 2(c) show the collector current as a function of the base voltage and base current respectively, for a device with silver contacts and an n-type silicon layer. The solid lines represent a single unweighted least-square fit to the current-voltage transfer characteristics shown in figure 2(b), using a model function which neglects the series resistance and adds the internal currents between the base and the collector and between the collector and the emitter:

$$I \approx I_{CB}\left(\exp\left(\frac{e(V_C - V_B)}{nkT}\right) - \exp\left(-\frac{e(V_C - V_B)}{nkT}\right)\right) + I_{CE}\left(\exp\left(\frac{e(V_C - V_E)}{nkT}\right) - \exp\left(-\frac{e(V_C - V_E)}{nkT}\right)\right), \qquad (2)$$

where V_E, V_B, and V_C are the potentials applied to the emitter, base and collector respectively. In equation (2), only the saturation currents I_{CB} and I_{CE} in each branch were allowed to vary independently of each other. The ideality factor, n, being a material constant, was assumed to be the same for each and found to be 1341 ± 6, which is consistent with that obtained at room temperature in the studies of the material. The saturation current for the collector-base channel was, at 0.52 ± 0.01 μA, a factor of 10 higher than that of the longer collector-emitter channel, 0.053 ± 0.003 μA. This difference in conductivity of the two channels results in the near perfect linearity and very low off-current in the current-current transfer characteristics shown in figure 2(c). The solid line shown is the current calculated, according to the model given in equation (2), for the applied base voltage transferred to the corresponding values of the base current.

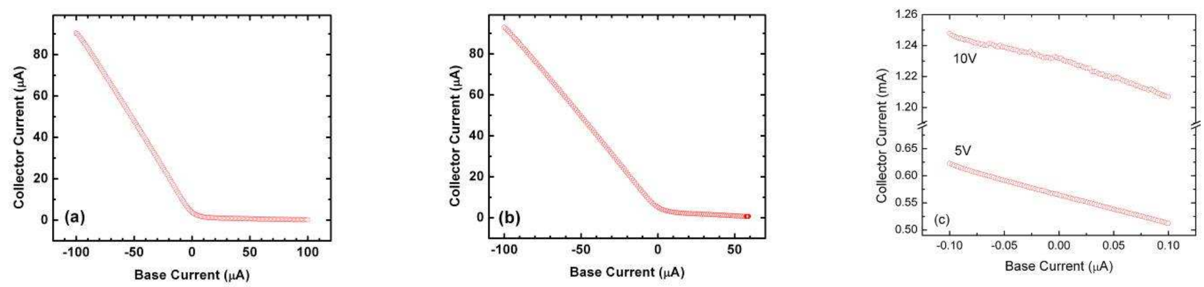

Figure 3: Dependence of the collector current on the base current for devices similar to that shown in Figure 2(a) with: (a) silver contacts and a p-type silicon semiconductor layer for a collector potential of 100V, (b) a p-type silicon semiconductor layer and conducting oxide contacts for a collector potential of 120V, and (c) silver contacts and a conducting oxide semiconductor layer for collector potentials of 5V and 10V. Both p-type silicon devices show similar current switching transfer characteristics to the n-type silicon device shown in Figure 2, whereas the oxide device exhibits no current switching.

Figures 3(a) and 3(b) show the current-current transfer characteristics for similar devices constructed with p-type silicon and two different electrode materials, silver and an ITO based semiconducting ink (Du Pont 7162), which has linear a current-voltage characteristic. The third transfer characteristics shown in Figure 3(c) are for a similar device constructed using silver contacts and the linear response

Du Pont 7162 as the active semiconductor, instead of the printed silicon nanoparticles. Qualitatively there is no difference between the three switches which have printed silicon as the semiconductor layer. A positive base current switches off the collector current irrespective of whether the semiconductor body is p-type or n-type, and this behaviour is not influenced by the junction with the contact material. In contrast, the transfer characteristics for the ITO based semiconductor are linear with no indication of switching. The equivalent circuit in this case is a triangular network of three fixed resistors.

Figure 4 shows a photograph and transfer characteristics of a printed device which is symmetrical under interchange of any pair of terminals. A consequence of this design is that the conductivity of the emitter-collector channel is equal to that of the collector-base channel. Consequently there is a larger off-current, which has weak voltage dependence and a shift of the current-current transfer characteristics (Fig 4(b)).

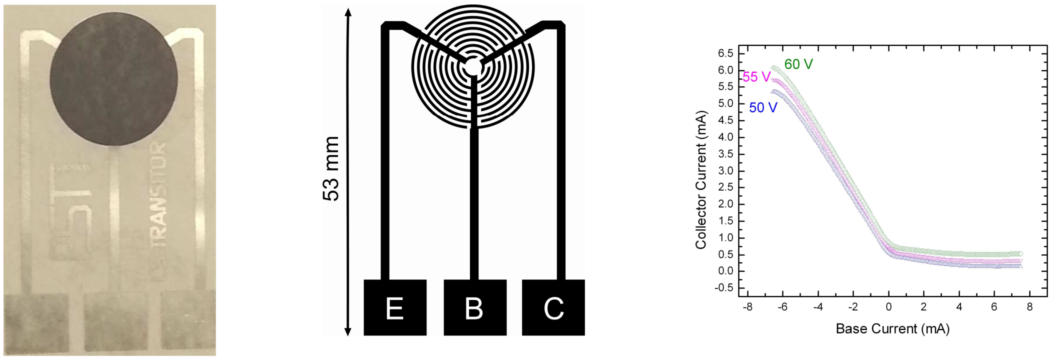

Figure 4: (a) Photograph of an electrically driven double throw switch with 3 symmetric silver contacts and a p-type silicon semiconductor layer printed on a plain paper substrate. (b) Schematic of the interdigitated electrodes, which exhibit rotational symmetry in the active area. (c) Dependence of the collector current on the current into the base for collector potentials of 50 V, 55 V and 60 V.

To confirm that it is the non-linear *IV* characteristics of the material which lead to the switching behaviour, the model circuit shown in Figure 1(a) was constructed using three individual varistors of the type SIOV-S14K75, manufactured by TDK EPCOS. The transfer characteristics are shown in Figure 5(a) for the collector current I_C as a function of base current I_B for a collector potential of 100V, and in Figure 5(b) as a function of base voltage V_B for collector potentials of 20V, 60V and 100V. The current-current transfer characteristics show a near perfect switching behaviour with a linear response of negative slope slightly less than unity for negative base current, and a low off-current for positive base current. Also, as seen in Figure 5(b) there is a well-defined base potential at which the current switches, and this switch-on voltage is dependent on the potential applied to the collector.

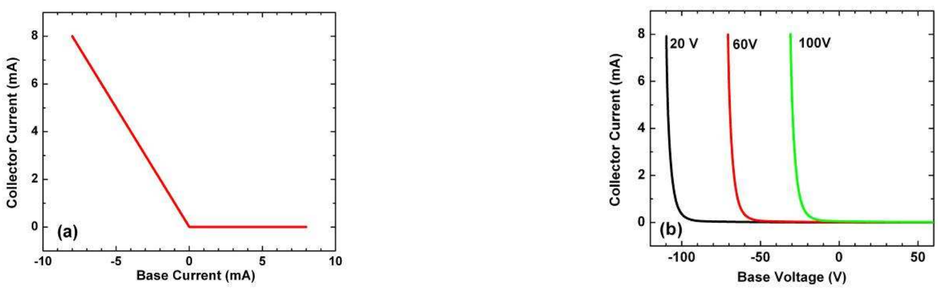

Figure 5: (a) current-current transfer characteristics at a collector potential of 100V, and (b) current-voltage transfer characteristics for collector potentials of 20V, 60V and 100V, for the model circuit.

Because a two-way switch can always fulfil the same function as a simple switch, its simplicity of processing and choice of materials recommend its use as an alternative to insulated gate FETs in large area and flexible electronics [7, 15], particularly in applications where a significant base current can be offset against the simplicity of not requiring a compatible gate insulator. Examples are the pixel switches for current driven displays such as organic and inorganic light emitting diodes and electroluminescent elements, or in addressing ferroelectric [16] or magnetic memory. However, the most interesting applications will be those which use the full capabilities of the two-way switching in new ways, for example to simplify the construction of logic gates or to gate matched pairs of sensors.

Finally, it should be noted that the same equivalent circuit, and hence similar device characteristics, can be produced using any other material combination with non-linear current-voltage characteristics. Although it is simpler to employ a material which is intrinsically non-linear, like the printed silicon used here, the same effect could be achieved by combining the construction principles of the MESFET and the point contact transistor so that a Schottky junction is present at all three contacts. The semiconductor body of the device may then be a bulk crystalline material, a CVD deposited film, an organic semiconductor [15, 17] or even a graphene layer [18]. Such a device can be constructed using conventional semiconductor fabrication [1], or thin film techniques [5]. Alternatively, the same principles could be simply adapted to nanoscale devices, such as those constructed from nanotubes [19,20], nanowires [21] or structured nanocrystals [22], which would benefit from the simplicity of not requiring a gate insulator or semiconductor heterojunction.

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