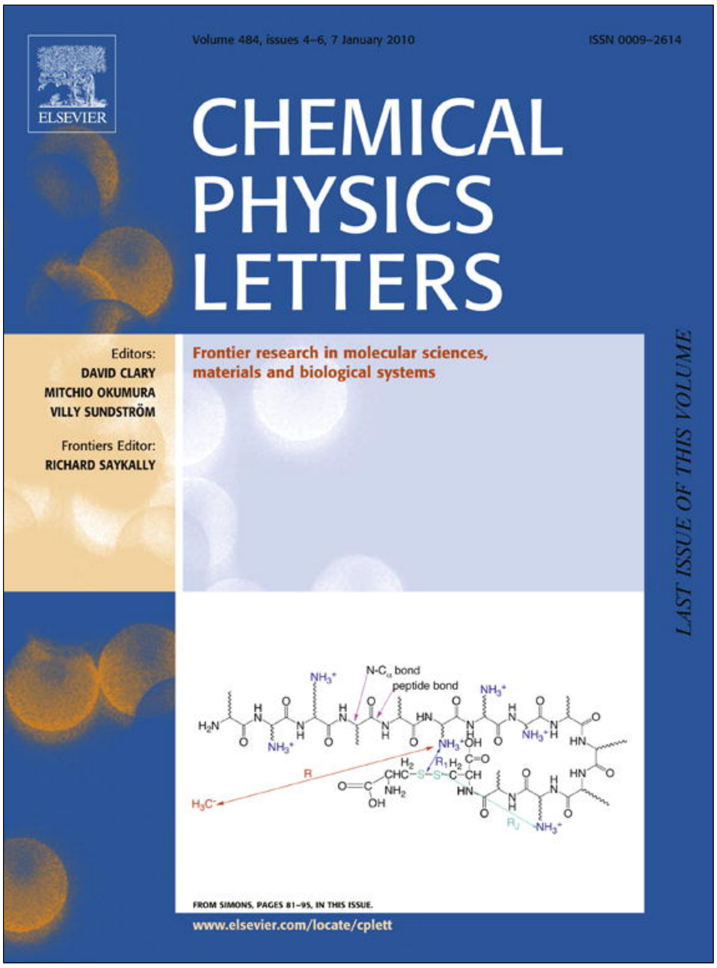
Volume 484, issues 4–6, 7 January 2010
ISSN 0009-2614
ELSEVIER
CHEMICAL PHYSICS LETTERS
Editors:
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Frontiers Editor:
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Frontier research in molecular sciences, materials and biological systems
LAST ISSUE OF THIS VOLUME
FROM SIMONS, PAGES 81–95, IN THIS ISSUE.
www.elsevier.com/locate/cplett

Chemical Physics Letters 484 (2010) 96–99

Contents lists available at ScienceDirect

Chemical Physics Letters

journal homepage: www.elsevier.com/locate/cplett

Measuring the transport property of ZnO tetrapod using in situ nanoprobes

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ARTICLE INFO

Article history:
Received 11 October 2009
In final form 10 November 2009
Available online 13 November 2009

ABSTRACT

The electrical transport characteristic of a ZnO tetrapod has been measured by in situ nanoprobes. By contacting the three legs of a tetrapod as the 'gate', source and drain, some control and tunability have been achieved in the output voltage/current, in analogous to the operation of a field effect transistor. A simple logic circuit has also been demonstrated.

Zinc oxide (ZnO) is a wide bandgap semiconductor with high excitation energy of 60 meV at room temperature, which has attracted a great attention for applications such as light emitting diode (LED) [1], gas sensor [2], strain sensor [3] ultraviolet (UV) photodetector [4] solar cell [5] power generation [6] and piezotronics [7]. Owing to the unique crystallographic structure and the polar surfaces, ZnO have been found to exhibit a wide range of structural morphology, such as nanowire [8] nanobelt [9] nanoring [10] nanohelix [11] nanocage [12] tetrapod [13] etc. Tetrapod is a structure that is created owing to the co-existence of two ZnO phases: cubic and wurtzite. The cubic phase ZnO is at the core, and four legs with [0 0 0 1] wurtsite structure extend along the ⟨1 1 1⟩ of the cubic structure [14]. This structure is created due to the fast growth of the wurtzite phase along [0 0 0 1] polar axis.

The transport properties of 'Y' shape carbon nanotubes [15,16] and CdSe tetrapod [17] have been reported. In this Letter, using a 4-probe technique inside a scanning electron microscope, we have explored the transport property of a ZnO tetrapod by directly contacting metal probe at the 3 legs of the tetrapod. Using the geometrical shape offered by tetrapod, two legs as source and drain and the other as 'gate', the electrical transport characteristics can be tuned.

In the current study, the ZnO tetrapods were synthesized by a vapor solid deposition process, as reported previously [18]. Collected ZnO tetrapods were ultrasonicated in ethanol solvent, and then dispersed on a silicon wafer that was covered by a 200 nm thick oxidation layer to prevent current leakage and dried on a hotplate at 80 °C. The electrical characterization was carried out in the field emission scanning electron microscopy LEO 1550 (FE-SEM), which is equipped with a S100 Zyvex S100 manipulator system. The manipulator has four individual heads, each can move independently in *X*, *Y*, *Z* directions that are controlled by motors in course mode and piezoelectric actuators in fine mode. A tungsten wire with a diameter of 250 microns was etched to form a tip at one end with ~200 nm in radius using electrochemical method and pre-cleaned in isopropyl alcohol (IPA) to remove surface oxidation layer for serving as probe to achieve electrical contact with the ZnO tetrapod. A Keithley 4200 semiconductor characterization system (Keithley 4200-SCS) equipped with pre-amplifier was employed to apply the voltage and measure the current from each branch of the tetrapod.

We first studied the *I*–*V* characteristic of ZnO tetrapod with the tungsten (W) tip directly in contacting with each of the branches as shown in Fig. 1. The *I*–*V* curve in Fig. 1 shows that the transport follows a metal–semiconductor–metal (M–S–M) structure with back-to-back Schottky contacts at the two ends [19]. This is the result of direct contacting of W tips with the tetrapod without welding.

In our ZnO-tetrapod devices, only three branches contacted with the substrate and one branch faced up because each pair of the two branches has an angle of about 109°. To improve the contact and largely reduce the contact resistance, we locally deposited a thin layer of Pt using a Nova 3D focused ion beam (FIB) microscope, and the deposition area was confined within $4 \times 1\ \mu m^2$, as shown in the inset SEM image in Fig. 2. The dual-beam FIB was operated at an acceleration voltage of 30 kV and Ga-ion current of 10 pA. The electron probe formed under such conditions is confined to minimize the Ga contamination. The incident angle, defined as the angle between the incident Ga-ion beam and the surface of the Si-substrate is about 90°. Linear *I*–*V* characteristics were received between each pair of the three branches (Fig. 2). The A–B, B–C, and A–C branch have nearly the same *I*–*V* characteristic. The resistance between each pair of branches was derived as 24 kΩ (A–B), 24 kΩ (A–C), 28 kΩ (B–C), in consistent with the data

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doi:10.1016/j.cplett.2009.11.014

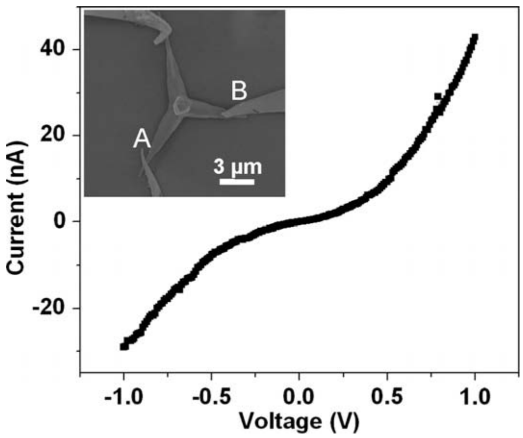

Fig. 1. Typical *I-V* characteristic of ZnO tetrapod measured by using tungsten (W) tips directly in contacting with the branches. Inset is an SEM image of the measured ZnO tetrapod.

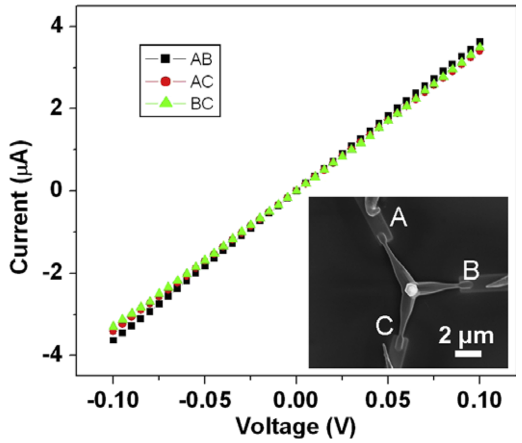

Fig. 2. *I-V* characteristics of three pairs of branches (AB, AC, BC) of a ZnO tetrapod that was deposited with Pt electrodes at the tips. Inset is an SEM image of the measured ZnO tetrapod.

Table 1
Measured resistance the three branches of a tetrapod and the corresponding conductivity. The variation in the measured conductivity is due to the inaccuracy in quantifying the dimension of the pole especially at the tip side.

	Resistance (kΩ)	Conductivity (Sm^{-1})
Branch-A	10	2000
Branch-C	14	1500
Branch-B	14	917

received previously. The resistance of each branch is listed in the Table 1.

The resistance is proportional to the length, resistivity of the material, and the reverse of the sectional area. Each branch of the ZnO tetrapod is approximately in the shape of a truncated cone. The resistance is very sensitivity to the diameter of the ZnO-tetrapod tip. Using a truncated cone-shape as an approximation for representing the tetrapod, the resistance of each branch is:

$$R = \frac{4\rho}{\pi \tan(\alpha/2)}\left(\frac{1}{D_0} - \frac{1}{D}\right) \tag{1}$$

where ρ is the resistivity of ZnO, D_0 and D are the diameters of the branch at its thickest and thinnest parts, respectively, and α is the cone angle of the tetrapod branch. By measuring the D_0, D, and α directly from the SEM image, and deriving the resistance from the *I–V* curve, we get the conductivity of the ZnO tetrapod is 1.0–2.0 k Sm^{-1} (see Table 1).

To test the effect of the interaction among the three terminals of the tetrapod, a DC voltage (V_g) is applied at one of the three branches as a 'gate', while the other two branches serve as source and drain (shown in Fig. 3a). The current flow through the source and drain is monitored by source measurement units (SMUs) of Keithley 4200-SCS. First, we measured current flowing through the source, drain and gate at different gate voltages. Fig. 3b–f show the 'gating' effect of the ZnO tetrapod. Different gating voltages (−0.1, −0.05, 0, 0.05 and 0.1 V) applied on the gate branch, and a proportional displacement of the current with V_g and V_s can be

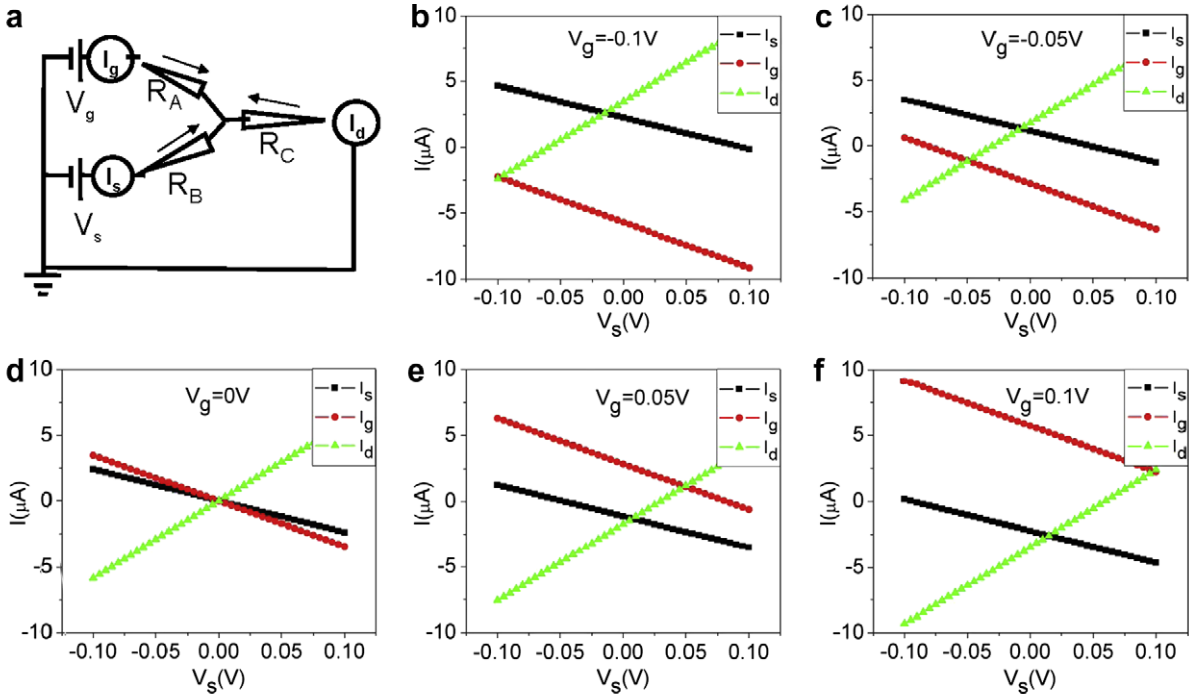

Fig. 3. (a) Schematic circuit for the measurement of "gating" effect of a ZnO tetrapod. The current flow through the source (I_s), drain (I_d) and gate (I_g) under different gating voltages of (b) −0.2 V, (c) −0.1 V, (d) 0 V, (e) 0.1 V and (f) 0.2 V.

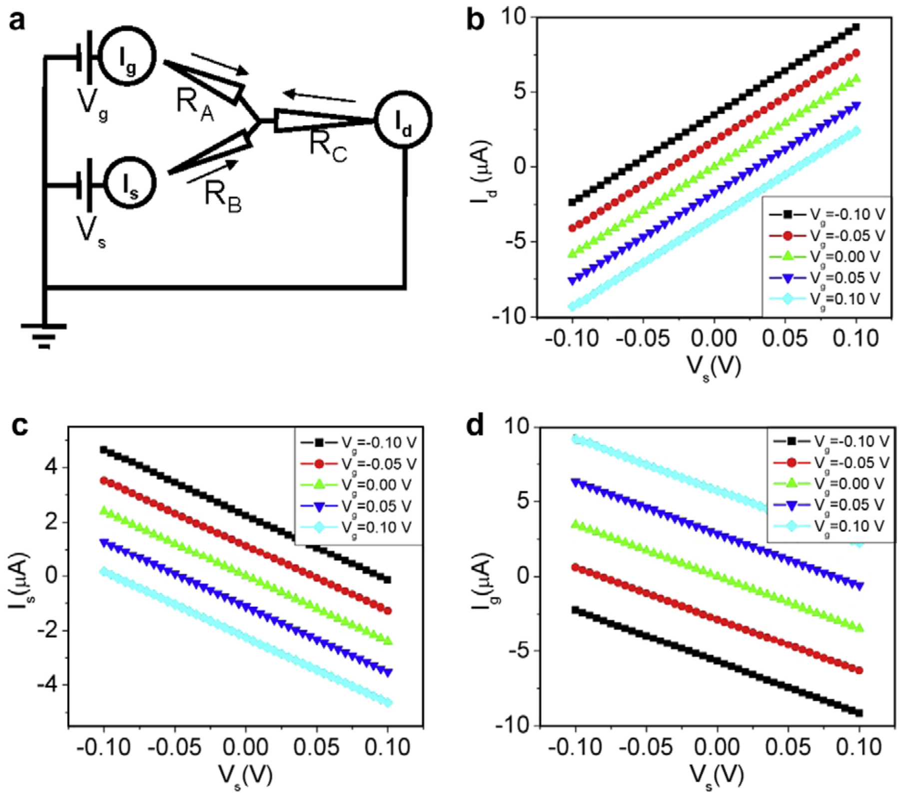

Fig. 4. (a) Schematic circuit for the measurement of "gating" effect of a ZnO tetrapod. The current flowing through (b) drain, (c) source and (d) gate electrode at different gating voltages.

observed in Fig. 3. The current flow through each branch can be derived based on the Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL), which give:

$$I_g = \frac{V_g(R_C + R_B) - V_s R_C}{R} \tag{2}$$

$$I_s = \frac{V_s(R_A + R_C) - V_g R_C}{R} \tag{3}$$

$$I_d = -\frac{V_g R_B + V_s R_A}{R} \tag{4}$$

here $R = R_A R_B + R_B R_C + R_C R_A$, R_A, R_B, R_C, are the resistance of each branch respectively, V_g is the gate voltage, and V_s is the source voltage. From the formula above, we can see that the currents in the branches are linear proportional to $(-R_C)/R$, $(R_A + R_C)/R$, and $(-R_A)/R$, respectively, at a given gate voltage. This result indicates that the tetrapod is effectively a current splitter.

The current flowing through each branch at different gate voltage was monitored (Fig. 4). Fig. 4b shows the current flowing through the drain terminal, at a constant source voltage, the current decreases linearly when the gate voltage increases. From the electrical characteristics of the ZnO tetrapod, it is clear that the current flowing through the source and drain can be modulated by the gate voltage, but the operation mode of the device is quite different from that of the conventional FET that is controlled by the carrier density and the thickness of the channel. The ZnO tetrapod is a current splitter that can be controlled by the 'gate' voltage.

The unique shape of the tetrapod can also be used as a logic component. Two of the branches (gate and source branch) are employed as two inputs and the other one (drain branch) can be served as an output. A constant voltage (−0.1, −0.05, 0, 0.05, 0.1 V) is applied on the gate branch, and a sweeping voltage from −0.1 to 0.1 V is applied on the source branch, and the voltage of drain branch is monitored. The positive voltage can be described as logic state of '1', and negative voltage including zero can be described as logic state of '0'. The output branch presents logic state of '1' only when both the gate and source branch are at logic state '1', otherwise the output will present logic state '0', which has the same logic property of 'AND' logic component [20,21].

In summary, the electrical transport characteristic of a ZnO tetrapod has been measured by in situ nanoprobes. By contacting the three legs of a tetrapod as the 'gate', source and drain, some control and tunability has been achieved in the output voltage/current, in analogous to the operation of a field effect transistor. A simple logic circuit has also been demonstrated.

Acknowledgments

This research was supported by DARPA (Army/AMOCOM/REDSTONE AR, W31P4Q-08-1-0009), BESDOE (DE-FG-02—07ER46394), Air Force Office (FA9550-08-1-0046), DARPA/ARO W911NF-08-1-0249, NSF. Yudong Gu thank the partial fellowship supported by the China Scholarship Council (CSC) (No. 20083019).

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