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Rectifying Effect in Boron Nanowire Devices

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Abstract

It has been found that Ni forms ohmic contacts and Ti forms Schottky-barrier contacts to boron nanowires. Using two-step electron beam lithography, Ni and Ti electrodes are subsequently attached onto the ends of a single boron nanowire. As a result, a nanoscale rectifier is created using a boron nanowire.

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I. INTRODUCTION

One-dimensional (1D) systems, such as nanotubes and nanowires, may serve as building blocks for the next-generation electronic devices. Various devices based on nanotubes or nanowires have been achieved. They include field-effect transistors [1,2], *p-n* diodes [3,4], Schottky-barrier rectifiers [5,6], memory devices and logic circuits [7-9]. Contact is the first problem that needs to be studied and controlled in order to investigate current transport through these devices. It is believed that in many experiments, a Schottky barrier exists at the contact [10-14] and the electrode metal plays an important role in device performance [12,14].

Bulk boron and metal-boride phases are highly refractory, chemically stable, strong, and hard [15]. Theoretical studies have proposed that 1D systems made of boron should be stable and possibly exhibit even higher electrical conductivities than carbon nanotubes [16,17]. Bulk boron shows *p*-type semiconducting behavior, and can be doped to *n*-type [18]. In addition, due to its covalent bonding, boron should be less susceptible to electromigration. We aim to construct boron-based building blocks and interconnects for nanoelectronic devices, which should benefit from enhanced mechanical stability, prolonged lifetime and improved performance because of the excellent physical characteristics of this material.

Compared to *p-n* diodes, Schottky diodes have the advantages of higher speed, small threshold voltages and much higher currents at a given applied bias [19]. In this experiment, we have fabricated a Ti electrode on one end and a Ni electrode on the other end of single boron nanowires (BNWs) using a two-step electron beam lithography (EBL) technique. Such devices function as nanowire rectifiers.

II. EXPERIMENTAL

BNWs were synthesized by a catalyzed chemical vapor deposition method [20]. After synthesis, the nanowires were transferred to an octanol solution and then dispersed on a *p*-type heavily doped Si substrate capped with 500 nm oxide [21]. The coordinates of the nanowires were calculated accurately based on the predefined alignment marks, which allowed controlled fabrication of contact electrodes to the nanowires.

The electrodes made of different metals were drawn on two different layers in the electron-beam exposure-pattern file. The pattern was designed based on the nanowires' position. To get a clean liftoff, a bi-layer electron beam resist was used. The exposure was done on JEOL JBX-5D11(U). For the first step, only one layer of the pattern was exposed. After exposure, the sample was taken out of the EBL machine and developed in 1:2 methyl isobutyl ketone: isopropanol for 1 minute followed by a thorough rinse in isopropanol. Then the sample was loaded into the electron beam evaporator (CHA SEC600) for deposition of the first metal electrode, which was formed by 20 nm Ti covered by 150 nm Au. Liftoff was done after deposition. The whole process was repeated to evaporate the electrode made of a different metal – in this case, 40 nm Ni covered by 150 nm Au. Using this two-step EBL process, metallic electrodes with different work functions were fabricated on a single BNW.

III. RESULTS AND DISCUSSION

A previous study showed that Ni forms ohmic contacts to BNWs, and Ti forms Schottky-barrier contacts [21]. Therefore, we expect to observe rectifying effects in BNW devices with these two contacts at the two ends. After device fabrication, electrical-transport measurements were performed using an Agilent 4156C semiconductor parametric analyzer.

Fig. 1(a) is a scanning-electron-microscopy (SEM) image of a BNW sample with different metal electrodes attached. The electrode shown on the top is made of Ti/Au, and the one on the bottom is Ni/Au. Fig. 1(b) shows the schematic of the 2-point electrical measurement setup. The Ti/Au electrode is grounded and the Ni/Au electrode is connected to a voltage source. The rectifying effect is clearly seen from the *I* – *V* curve shown in Fig. 1(c). The inset of the figure shows an exponential curve (dashed line, after zooming in) fitted by the diode equation [6],

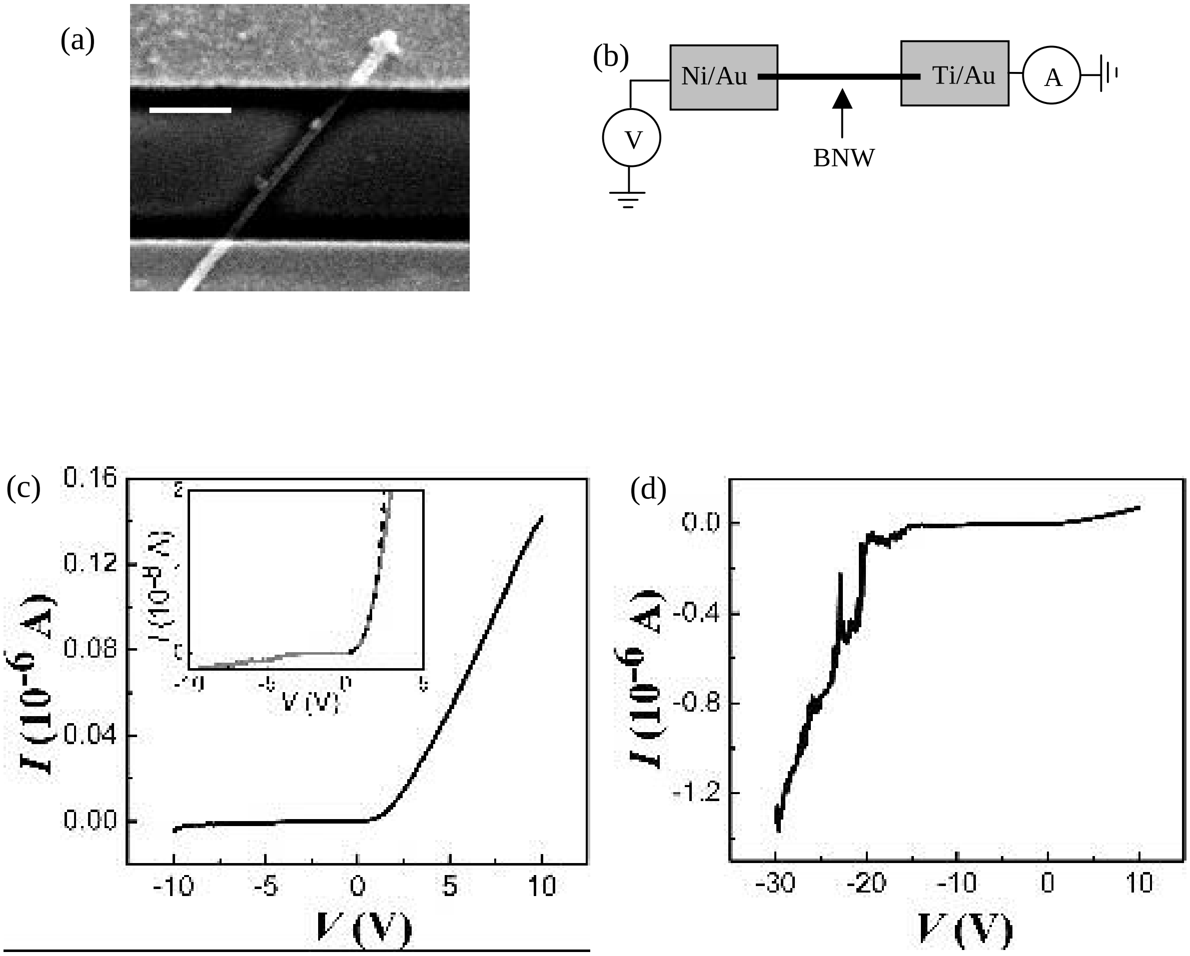

Fig. 1. (a) SEM image of a BNW device with different metal electrodes attached. The scale bar is 500nm. (b) Schematic of the measurement circuit. (c) *I* –*V* curve of a BNW device. Inset: exponential fitting, displayed after zooming in. (d) Break-down happened at reverse bias of about -20 V.

$$I = I_s \cdot \left[\exp\left(\frac{e(V - V_{th})}{\eta k_B T} \right) - 1 \right] \qquad (1)$$

where I_s is the saturation current, and V_{th} is the forward bias threshold voltage. From this I-V curve, we determined $I_s = 7\text{x}10^{-10}$ A, and $V_{th} = 0.25$ V. A best fitting curve gives $\eta = 25.5$. It is seen that the fitted line agrees well with the experimental data at the range of $0.25 \text{ V} < V < 1.9$ V. The high ideality factor, η, is attributed to the interfacial contact between the two electrodes and the nanowire [6]. Furthermore, at bias voltage higher than 1.9 V, the $I - V$ curve of the device becomes linear, which gives device resistance around 60 MΩ. This value is close to the intrinsic resistance of the BNW we obtained before [21]. Fig. 1(d) shows the breakdown of the device at a reverse bias around -20 V.

The work functions (Φ) of Ni and Ti are $\Phi_{\text{Ni}} = 5.15$ eV, $\Phi_{\text{Ti}} = 4.33$ eV, respectively [19]. β-rhombohedral boron has a work function around 4.30 eV and a band gap around 1.56 eV [15,22]. For our *p*-type BNW, it is reasonable to surmise that its Fermi level comes closer to the valence band compared to intrinsic boron material, giving a larger work function that exceeds the work function of Ti, *i.e.* 4.33 eV. Thus, the work function relation for these three materials is: $\Phi_{\text{Ni}} > \Phi_{\text{BNW}} > \Phi_{\text{Ti}}$. A band diagram is drawn in Fig. 2(a) based on this relation to explain the behavior of the device. Because $\Phi_{\text{Ni}} > \Phi_{\text{BNW}}$, no barrier is formed at the Ni-BNW contact for hole-carrier transport, thus yielding an ohmic contact. However, for the BNW-Ti contact, a Schottky barrier is formed due to $\Phi_{\text{Ti}} < \Phi_{\text{BNW}}$. Here Φ_{B} denotes the Schottky barrier height. This barrier height can be characterized by the temperature-dependent $I - V$ measurements; experiments to determine Φ_{B} are currently underway.

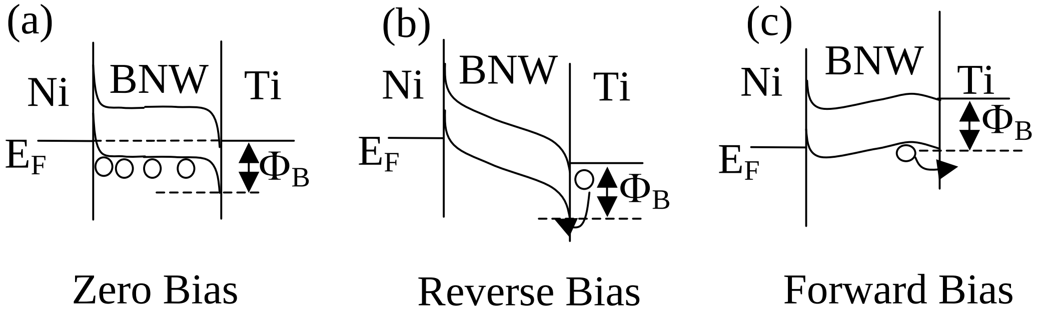

Fig.2. Band diagram for the device shown in Fig. 1. (a) Zero bias. (b) Reverse bias. (c) Forward bias.

When a negative bias (reverse bias) is applied to the Ni side, holes attempting to move from the Ti to the BNW encounter a Schottky barrier (Φ_{B}) (Fig. 2(b)), yielding a low current. In contrast, when a positive bias (forward bias) is applied to the Ni side, holes from the BNW only need overcome a much smaller potential barrier than Φ_{B} in order to reach the Ti electrode (Fig. 2(c)), thus giving rise to the rectifying effect. Such behavior has been observed in four different devices. The exponential-to-linear transition in the $I - V$ curve is attributed to the resistance of the BNW. When the voltage is beyond a threshold, the resistance of the BNW dominates the behavior of the device, giving the linear part in the $I - V$ curve.

IV. CONCLUSION

Contact electrodes with different work functions have been fabricated on boron nanowires using two-step electron-beam lithography. Rectifying effects are observed in such BNW devices. We have demonstrated that different contacts, ohmic and Schottky, can be achieved on a single-nanowire device.

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