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# Schottky diodes based on a single GaN nanowire

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**Abstract**
On a single GaN nanowire, obtained by chemical vapour deposition, several Schottky-junction diodes were fabricated and their electrical transport properties were studied. Alternately attached metal electrodes of Al and Ti/Au formed a Schottky barrier junction (for Al) or an ohmic contact (for Ti/Au), resulting in several diodes on a single nanowire. The current–voltage measurements exhibited clear rectifying behaviour and no reverse-bias breakdown was observed up to the measured voltage, −5 V. The forward-bias threshold voltage was observed to decrease linearly with temperature, from 0.4 V at 280 K to 1 V at 10 K.

(Some figures in this article are in colour only in the electronic version)

## 1. Introduction

A one-dimensional nanocrystal such as a nanowire or tube can serve as a sample for studying the low-dimensional phenomena or a building block of nanodevices [1–4], the carbon nanotube (CNT) being the most extensively studied. Many experimental and theoretical studies have been carried out for electrical transport properties of CNTs, and various CNT-based devices have been proposed with some being realized [4–8]. Such device development is incomplete, however, since controlling electronic properties is prerequisite but no method to control the chirality of CNTs has been established. In this regard, the nanowires of semiconducting Si, GaN and GaAs have a great advantage for device application since their transport properties can be modified by impurity doping and there are well known recipes for ohmic contacts. Despite such advantages, only a few studies on electrical transport and device applications of the semiconducting nanowires have been carried out [3, 9, 10].

This paper reports our electrical transport measurements of a Schottky-junction diode made of a single GaN nanowire. On a single GaN nanowire, obtained by chemical vapour deposition (CVD), several Schottky-junction diodes were fabricated and their electrical transport properties were studied. Alternately attached metal electrodes of Al and Ti/Au formed a Schottky-barrier junction (for Al) or an ohmic contact (for Ti/Au), resulting in several diodes on a single nanowire. The current–voltage ($I$–$V$) measurements exhibited clear rectifying behaviour without any reverse-bias breakdown up to −5 V. The forward-bias threshold voltage decreased linearly with temperature, from 0.4 V at 280 K to 1 V at 10 K.

The GaN semiconductor has a large direct bandgap of 3.4 eV, which makes it attractive for UV or blue emitter/detector, high-speed field-effect transistor and high-temperature microelectronic devices [11–13]. Recently there have been several reports on the synthesis of GaN nanowires by arc discharge, laser-assisted catalytic growth, direct reaction of the mixture etc [14–20]. We synthesized the nanowires using Ni catalyst by direct reaction of the mixture of Ga metal and GaN powder with flowing ammonia at 1000 °C using thermal CVD. The scanning electron microscope (SEM) studies showed the high-purity nanowires uniformly distributed on the alumina substrate, with lengths up to several hundred microns and diameters of 30–70 nm. The detailed transmission electron microscope study showed the nanowires have a single-crystal hexagonal wurtzite structure [21].

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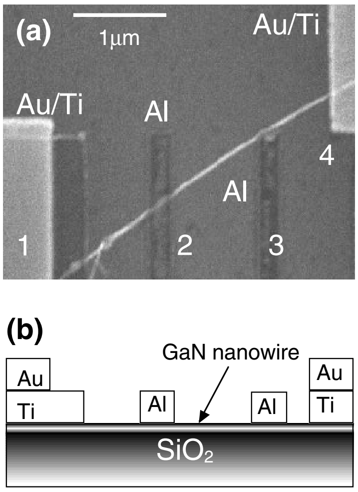

**Figure 1.** (a) The SEM image of the sample used in this study. It represents a GaN nanowire with two ohmic-contacted Ti/Au (1 and 4) and two Schottky-contacted Al electrodes (2 and 3). (b) The schematic side view of a GaN nanowire device.

## 2. Experiment

A droplet of dispersed solution containing nanowires was dropped on to the Si substrate with a 500 nm thermally grown $SiO_2$ layer. Once the solution is blown dry, the wires remain fixed on the surface. Electrical contacts were made to a single nanowire as follows. First, alignment marks consisting of a metal dot array with about 1 $\mu$m spacing were fabricated to identify the location of the nanowires. A suitable nanowire was selected by using the optical microscope and SEM. Once the nanowire was found, its position was determined relative to the alignment marks. A two-layer e-beam resist (PMMA/copolymer) was then spun over the sample and the patterns for electrical leads were generated using e-beam lithography techniques onto the pre-selected nanowire. Then, 20 nm of Ti and 50 nm of Au were deposited successively on the contact area by thermal evaporation, followed by lift-off and forming the electrodes. It is known that Ti, after an optimum annealing process, becomes a good material with low ohmic contact to GaN [22]. Ohmic contacts between the GaN nanowire and the Ti/Au electrodes were achieved by rapid thermal annealing at 400–500 °C for 30 s. After establishing such contacts, Al metal was deposited onto the pre-patterned nanowire to form a Schottky-barrier junction by thermal evaporation. The diameter of the nanowire was about 50 nm. Figure 1(a) shows the SEM image of a GaN nanowire with two ohmic-contacted Ti/Au electrodes (1 and 4) and two Schottky-contacted Al electrodes (2 and 3). The schematic side view is shown in figure 1(b).

## 3. Results and discussion

Figure 2(a) represents the $I$–$V$ characteristics between the two contacts (electrodes 1 and 4) at 288 and 4.2 K. It shows linear behaviour with the total resistance of $R = 2R_C + R_{NW} \approx 450\,\mathrm{k}\Omega$ at room temperature, where $R_C$ is the contact resistance and $R_{NW}$ is the nanowire resistance, assuming identical resistance for the two contacts. Each contact resistance $R_C$ might be smaller than 225 k$\Omega$ with the contact area of 50 nm × 1000 nm. This gives a contact resistivity smaller than $1.12 \times 10^{-4}\ \Omega\ \mathrm{cm}^2$ at room temperature [22].

We measured the $I$–$V$ characteristics between an Al electrode (2) and a Ti/Au electrode (1) at various temperatures as shown in figure 2(b). It exhibits clear rectifying behaviour at all the measured temperatures with the turn-on voltages of 0.4–1.1 V. The reverse-bias breakdown was not observed up to −5 V. Since a positive bias voltage was applied to the Al electrode, the observed $I$–$V$ curves represent n-type Schottky-diode characteristics. This means that our GaN nanowire is an n-type semiconductor, consistent with the previous experimental result [21]. Any selection of Al and Ti/Au electrodes (e.g. 2–4, 3–1 and 3–4) gives similar rectifying behaviour. The inset of figure 2(b) shows the semi-log plot of the forward-bias characteristics at various temperatures.

For an ideal Schottky-junction diode, the current is given by [23]

$$I = I_0\{\exp(eV/k_BT) - 1\}, \tag{1}$$

where $I_0$ is the reverse bias saturation current given by

$$I_0 = AT^2\exp\{-e(\phi_b - \Delta\phi_{bi})/k_BT\}. \tag{2}$$

Here $A$ is the Richardson constant and $\Delta\phi_{bi}$ is the barrier change due to the bias voltage and the thermal fluctuation. For many reasons, the $I$–$V$ characteristics of Schottky diodes deviate from the ideal behaviour. We fitted the $I$–$V$ curve at room temperature to the generalized diode equation [23]

$$I = I_0\{\exp(e(V - V_{th})/nk_BT) - 1\} \tag{3}$$

where $V_{th}$ is the voltage where the current begins to increase in the forward direction (the forward-bias threshold voltage) and $n$ is the ideality factor, becoming close to unity if thermionic emission is the dominant transport mechanism [23]. The solid curves in figure 2(b) represent fitted curves. At room temperature we have obtained $n = 17.8$, with great deviation from unity.

Such a large departure of the ideality factor $n$ from unity may be attributed to the existence of an insulating interfacial layer between the Al electrode and the GaN nanowire. Two possible scenarios can be considered. First, thermally evaporated Al reacts with the residual oxygen gas in the vacuum chamber to form $AlO_x$. Such a scenario, however, does not explain why the $AlO_x$ layer is formed dominantly at the interface. Second, an alternative scenario is the formation of AlN at the interface. Evaporated Al attracts N in GaN, forming an AlN layer at the interface and N deficiency in GaN. This is more likely in our device. The insulating interfacial layer is known to cause significant departure of $n$ from unity [24], and large $n$ values were also reported in metal/semiconductive polymer Schottky devices [25].

The $I$–$V$ characteristics of our Schottky diode exhibited temperature dependence widely different from that of conventional semiconductor-based ones. With increasing temperature, $V_{th}$ decreased rapidly as shown in the inset of figure 3. The overall feature of the $I$–$V$ characteristics, however, remains unchanged. If the $I$–$V$ curves are displaced parallel to the voltage axis by amount $V_{th}$, they nearly merge into one curve. Such scaling behaviour is evident

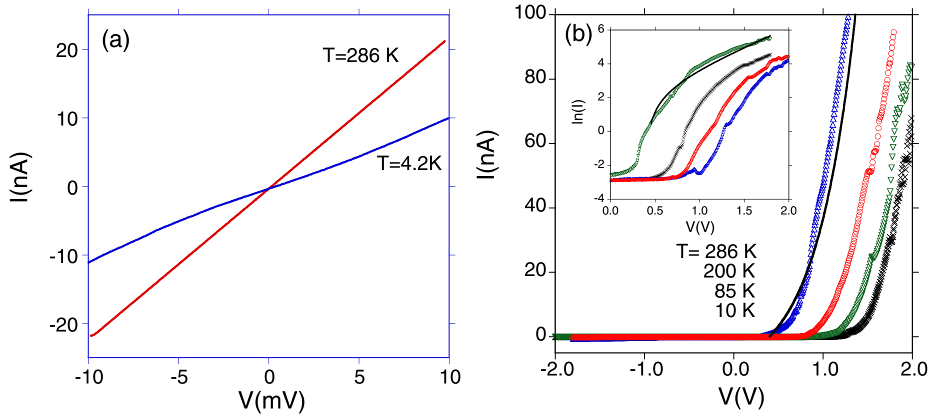

**Figure 2.** (a) $I$–$V$ curves between two GaN–Ti/Au contacts at 288 and 4.2 K. (b) The $I$–$V$ characteristics between an Al electrode (2) and a Ti/Au electrode (1) at 10, 85, 200 and 286 K respectively starting from the right. A positive bias voltage is applied to the Al electrode. The solid curves represent the fitted curves to generalized diode equation. Inset: the logarithmic current versus the forward-bias voltage at 10, 85, 200 and 286 K respectively starting from the right.

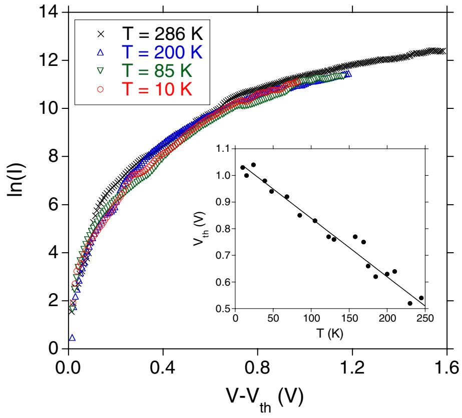

**Figure 3.** The scaled temperature dependent $I$–$V$ characteristics in a logarithmic scale with the inclusion of the offset voltage $V_{th}$. Inset: the forward-bias threshold voltage $V_{th}$ as a function of temperature, defined as the voltage where the current begins to increase in the forward-bias direction.

in figure 3 with $\log(I)$ versus $(V - V_{th})$ plots at four different temperatures. It clearly shows that the temperature dependence of the $I$–$V$ characteristics is mainly attributable to the change of the forward-bias threshold voltage. Such a turn-on voltage for forward-bias current across the Schottky junction implies the existence of non-negligible built-in contact potential between the GaN nanowire and the Al electrode, probably due to an insulating interfacial barrier.

For an ideal Schottky diode, the forward-bias threshold voltage $V_{th}$ is expected to decrease with temperature $T$ due to the thermal fluctuation. With assumption of linear dependence, it can be written in a general form [23]

$$V_{th} = V_{th}^{0} - CkT/e, \tag{4}$$

where $C = 1$ corresponds to the ideal case. For our Schottky diode, $V_{th}$ exhibited linear dependence on $T$ as shown in the inset of figure 3 but with $C \approx 25$, far greater than the ideal value of unity. $V_{th}$ increased linearly with $T$ from about 0.4 V at 280 K to 1 V at 10 K. Such a rapid temperature dependence of $V_{th}$ is rather difficult to explain with the conventional theory. One might possibly resort to the difference in thermal expansion coefficients between metallic Al and the semiconducting GaN nanowire. In view of the fact that the Al/GaN-nanowire Schottky contact forms naturally (without thermal annealing), and the thermal expansion coefficient of Al is about ten times that of GaN, the electrical properties of the naturally formed Schottky contact are expected be very sensitive to temperature, particularly for nanosize junctions. However, we found that the $I$–$V$ characteristics of the Al/GaN junction are quite reproducible during the thermal cycling. Further systematic studies would be required to clarify the detailed mechanism.

## 4. Summary

In summary, we have fabricated a Schottky-junction diode, utilizing a GaN nanowire, and studied its electrical transport properties. Two kinds of metal electrode, Al and Ti/Au, were incorporated into an individual GaN nanowire. A Schottky-barrier junction was formed in the Al electrode while an ohmic contact was formed in the Ti/Au electrode. The measured $I$–$V$ characteristic exhibited a clear rectifying behaviour and no reverse-bias breakdown was observed up to the measured voltage, −5 V. We have also found that the forward-bias threshold voltage increased linearly as the temperature was lowered from about 0.4 V at 280 K to 1 V at 10 K.

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