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Temperature-dependent single-electron tunneling effect in lightly and heavily doped GaN nanowires

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We studied the electrical transport properties of GaN nanowires with two different doping levels. Measurements taken at various temperatures demonstrate that the electrical transport depends mainly on the single-electron tunneling effect up to a relatively high temperature of ~150 K. The aperiodic oscillations which we observed were attributed to single-electron tunneling through multiple quantum dots within the nanowire, which originated from various defects and the inhomogeneous distribution of the dopants.

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Recently, carbon nanotubes (CNT's) and various kinds of nanowires have attracted a considerable amount of attention because of their many practical applications in optical, electronic, and chemical devices.[1–7] Unlike CNT's, many types of nanowire are inherently semiconducting and, thus, it is relatively easy to control their electrical properties through impurity doping techniques that are well established in conventional semiconductor technology. Furthermore, their well-defined optical gap, ranging from the visible to the ultraviolet spectrum, can be exploited for many applications, such as nanosized optical sensors, detectors, and photochemical sensors.[3,4,8] Indeed, semiconducting nanowires are increasingly being recognized as promising candidates for the building blocks of bottom-up nanoelectronic devices.

Most of the studies which have been conducted so far on nanowires have focused on their potential applications in electronic and optical devices. However, few intensive studies have been done on the transport properties of nanowires,[9] and the interesting quantum transport phenomena associated with their low-dimensional nature require further study. It is well known that electrical transport is mainly governed by the electron charging and confinement effects, which are due to the quantization of energy levels in the quantum dots.[10] Several groups reported similar quantum dot phenomena in CNT's with metallic contacts.[11–13] We therefore expected that similar quantum behavior should be able to be observed in nanowires of comparable size. Indeed, Franceschi *et al.*[9] found in their transport study that an InP nanowire behaves in the same way as a quantum dot at sufficiently low temperature, when the charging energy becomes greater than the thermal energy. Herein, we report the findings of our electrical transport studies of GaN nanowires with mesoscopic metallic electrodes. Experiments were conducted on several nanowires with two different doping levels. The observed oscillatory gate voltage dependence that was observed in the samples with different doping levels appears to have the Coulomb blockade as its origin.

In this Brief Report, single crystalline GaN nanowires were synthesized on an NiO catalyzed Al_2O_3 substrate by using a simple thermal vapor deposition method.[14] Two different kinds of GaN nanowires were prepared. One was a lightly doped semiconducting GaN nanowire, which was intrinsically doped due to N deficiencies, and the other was a heavily doped metallic nanowire, whose heavy doping was due to the excess Ga content. Since the N vacancies control the electrical properties of the nanowire, we can tune the desired electrical properties of the nanowire, by adjusting the N concentration from a lightly doped semiconductor to a heavily doped one. In this experiment, the N concentration of the GaN nanowires was controlled by varying the NH_3 flow rate. A higher flow rate gives a higher N concentration. The individual GaN nanowires were prepared on a 500 nm thick thermally grown SiO_2 layer with a heavily doped Si substrate underneath, which is used as a back gate. To make the electrical contacts between the GaN nanowire and the Ti/Au electrodes stable, we patterned the Ti/Au contacts and used a rapid thermal annealing technique at 400–500 C for 30 s in a high vacuum.

The lower inset of Fig. 1 shows a scanning electron microscope (SEM) image of a heavily doped GaN wire, which is attached to two Ti/Au electrodes. The diameter of the nanowire is 34 nm and the distance between the source and the drain electrodes is 588 nm. The temperature dependence of the current-voltage (*I*-*V*) characteristics near zero-bias voltage is shown in the main panel of Fig. 1. A slightly nonlinear *I*-*V* starts to develop below ~30 K, indicating a small depletion of conductance within the width ~8 mV. The conductance near zero-bias voltage decreases from 5.37 μS to 3.14 μS as the sample is cooled from 237 K to 6 K. The upper inset of Fig. 1 shows the semilog plot of the temperature dependence of the conductance near zero-bias voltage. The sample conductance decreased by twofold as the temperature was lowered from room temperature. Due to there being a small change in the conductance between room

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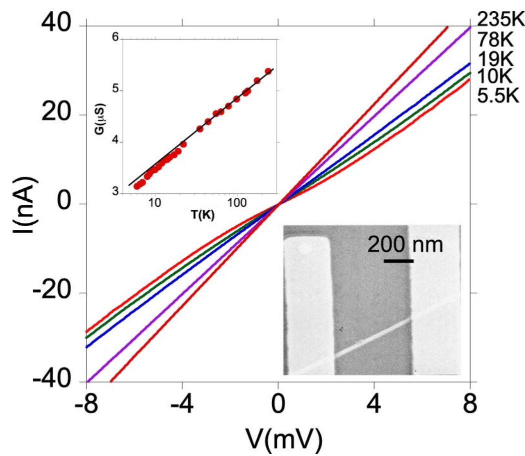

FIG. 1. The temperature-dependent *I-V* curves of the heavily doped GaN nanowire. The temperatures were 235 K, 78 K, 19 K, 10 K, and 5.5 K from the above curve. The upper inset displays the semilog plot of resistances near zero-bias voltage. The lower inset shows the SEM image of the sample used in this study.

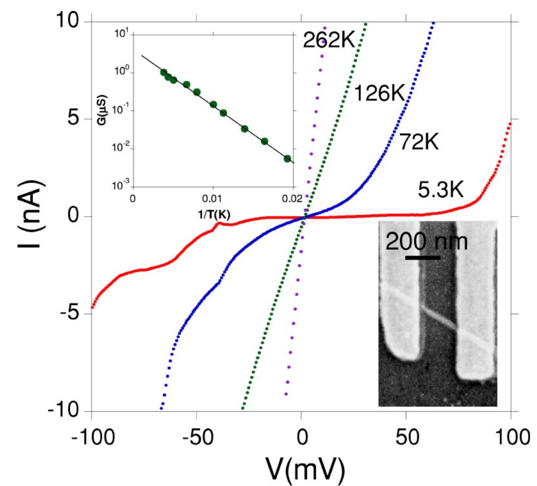

FIG. 2. The temperature-dependent *I-V* curves of the lightly doped GaN nanowire. The temperatures were 262 K, 126 K, 72 K, and 5.3 K from the above curve. The upper inset shows the resistance as a function of inverse temperature $(1/T)$. The lower inset shows the SEM image of the sample used in this study.

temperature and 5 K, it is not easy to tell whether the sample follows a logarithmic or a power-law temperature dependence. Logarithmic temperature dependence is a well-known signature of electron-electron interactions in two-dimensional disordered systems.[17] However, the transport in nanowires may not have such a temperature dependence, since our GaN nanowires are close to one dimensional in nature. It has been shown by Altshuler *et al.* that one-dimensional weak localization with electron-electron interactions can generate a power-law dependence $(G \sim T^{\alpha})$ with an exponent in the range of $\alpha = 0.25 - 0.50$, depending on the inelastic scattering process.[16] The power-law temperature dependence commonly found in CNT's has been attributed to Luttinger liquid behavior.[15] The temperature dependence of our sample appears to follow a power law with a slope between 0.1 and 0.2 in the log-log plot (not shown here). We note that the exponent that we obtained is much smaller than the reported value $(\alpha = 0.6)$ for a single-walled CNT.[15] It is also interesting to note that power-law behavior with an unusually small exponent was found in a multiwalled CNT system,[17] in which extra scattering centers can easily be generated in comparison with a single-wall CNT. In the same context, we identified the origin of the similar behavior that was observed in the GaN nanowire, as resulting from the high concentration of N deficiencies, which can act as scattering centers. Thus, this unusual behavior is due to the combined effect of localization and the strong electron-electron interactions, as would be expected in a disordered low-dimensional system. Since our GaN nanowires contain high concentrations of N deficiencies, which can act as scattering centers, the unusually low power law of the logarithmic temperature dependence could have originated from the combined effects of the localization and the strong electron-electron interactions, as would be expected in a disordered low-dimensional system.

Figure 2 shows the temperature-dependent *I-V* curves of the lightly doped GaN nanowire at zero gate voltage. A SEM image of the sample is shown in the lower inset. The diameter of the nanowire and the length between the source and drain electrodes were about 40 nm and 220 nm, respectively. The conductance near zero-bias voltage decreased exponentially from 1.03 μS to 0.003 μS as the temperature was lowered from 262 K to 42 K. As shown in the upper inset of Fig. 2, the *I-V* curves become highly nonlinear and exhibit asymmetric gap structures in the range $-40\ \text{mV} \lesssim V \lesssim 60\ \text{mV}$ at 5.3 K. The temperature dependence of the electrical resistance shows activation behavior, $\exp(-E_a/k_BT)$ with $E_a = 29$ meV, as shown in the upper inset of Fig. 2. Similar activation behavior has been observed in various nanowires, such as In_2O_3, GaN, and single-walled CNT's, and is known to be characteristic of the presence of a Schottky barrier, which is formed between the metallic electrode and semiconducting nanowire or CNT.[18–20]

To obtain further insights into the transport properties of our GaN nanowires, we measured the source-drain current, while varying the gate voltage (V_g) at various temperatures. The results obtained from a heavily doped GaN nanowire are shown in Fig. 3. The distinct oscillations in the source-drain current which can be seen at low temperatures continue to persist at temperatures above ~45 K. Aperiodic variations of the conductance as a function of chemical potential or gate voltage have been reported in various mesoscopic systems, and are well understood as universal conductance fluctuations (UCF's).[22] These UCF's, which are characterized by reproducible fluctuations of amplitude $\sim e^2/h$, irrespective of the sample size and the material being investigated, occur in the weakly disordered regime, in which the conductance at low temperature is comparable to or greater than e^2/h. It is unlikely that these UCF's are the cause of the observed oscillations, since the low-temperature conductance of our heavily doped GaN nanowire is $\sim 0.08\ e^2/h$, which is about an order of magnitude smaller than the quantum conductance. Also, we found that the oscillating patterns were unchanged after several temperature cycles, which is not consistent with the usual UCF phenomenon. The almost linear

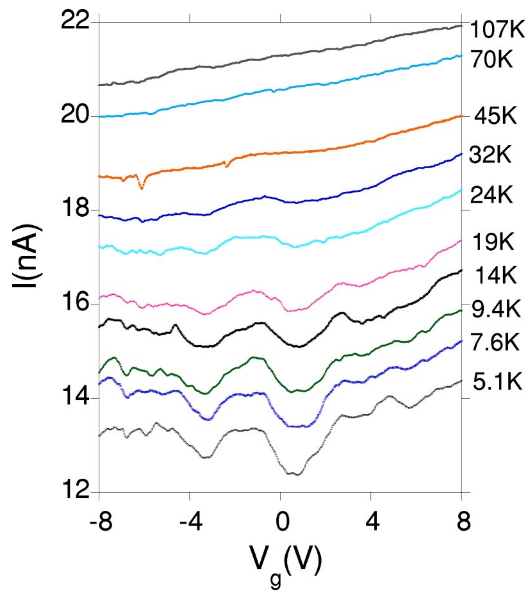

FIG. 3. The temperature-dependent current change for the heavily doped GaN nanowire as a function of V_g at several temperatures. The source-drain bias voltage was 4.25 mV. The gate bias varies from +8 V to −8 V.

I-V curves shown in Fig. 1 appear to rule out the Coulomb blockade as the origin of this phenomenon, since the Coulomb blockade effect requires that there be a high enough tunnel barrier between the contacts and the heavily doped nanowire to prevent the overlapping of the electron wave functions on both sides. A rough estimation of the single-electron charging energy can be obtained from the relations $E_c = e^2/2C = 2.5$ meV, where the capacitance of the nanowire is given by $C \approx 2\pi\epsilon_0\epsilon L/\ln(4h/d) = 32$ aF, where L is the source-drain length (588 nm), d is the diameter of the nanowire (34 nm), and h and ϵ are the thickness (500 nm) and dielectric constant (4) of SiO_2, respectively.[17] Thus, the temperature that matches the charging energy is found to be $T=29$ K and the Coulomb oscillations are expected to be observed below this temperature. Since the estimation of the charging energy is performed assuming that the whole wire is a single island, the estimated temperature is lower than our experimental observation. It should be noted that the charging energy is inherently underestimated if multiple connected quantum wires or dots can be formed in the heavily doped nanowire, which is likely to be due to either the nonuniform distribution of the dopants or to disorders. Grain boundaries of a reasonable size can provide high enough potential barriers for Coulomb blockage to occur at a sufficiently low temperature.[13,14]

Figure 4 shows the semilogarithmic plot of the source-drain current as a function of V_g for the lightly doped GaN nanowire at several representative temperatures. The background conductance increases as the applied gate voltage V_g increases, which is characteristic of an *n*-type semiconductor field-effect transistor (FET).[19,21] As the temperature is lowered below 150 K, aperiodic current oscillations occur on top of the background *n*-type FET effect. The structure of the curve becomes distinct at a temperature of 5.3 K. As shown in Figs. 4(a) and 4(b), the abrupt increase in conductance that

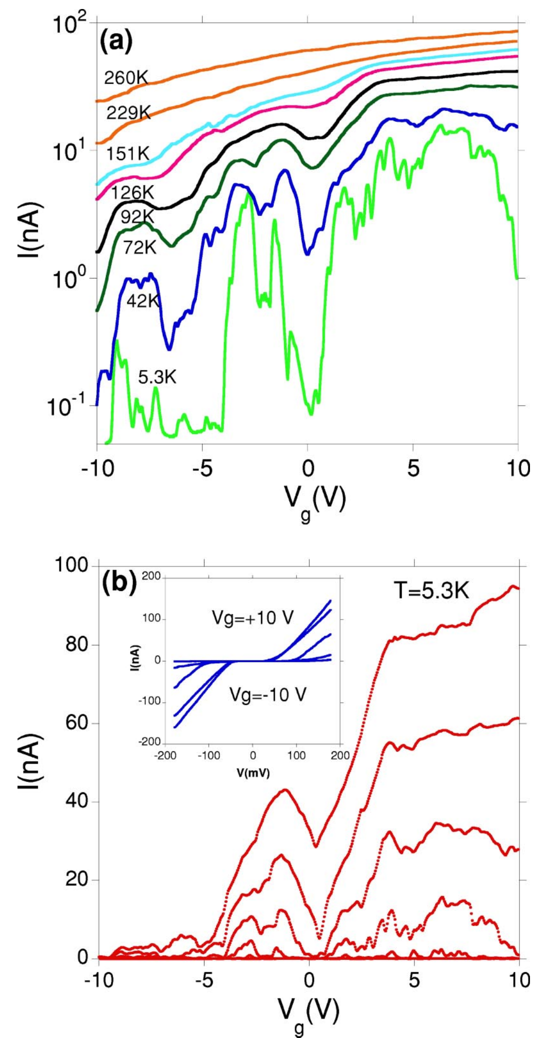

FIG. 4. (a) The logarithmic plot of the temperature-dependent current change for the lightly doped GaN nanowire as a function of V_g at several temperatures. The source-drain bias voltage was 30 mV. (b) $I-V_g$ curves as a function of V. The source-drain bias voltage varies from 0 to +135 mV with six voltage steps. The inset shows the *I-V* curves as a function of $V_g = +10$ V−−10 V with the five steps.

depends only on the applied bias voltage is associated with the lining up of the electronic energy states of the nanowire with the Fermi level of the electrodes. Once again, the highly aperiodic oscillations can be attributed to the electron tunneling through multiple quantum dots formed within the nanowire, as seen in the heavily doped wire. Considering the geometrical factors, the source-drain length of 221 nm and the nanowire diameter of 40 nm, we obtain an approximate value for the charging energy E_c of 6.4 meV, which corresponds to $T=74$ K. The charging energies determined from the geometrical factors were generally less than the experimentally determined values, which could be attributed to the formation of multiple islands within the nanowire. Figure 4(b) shows the gate-response curves at 5.3 K at various source-drain voltages. These curves also show clear aperiodic structures. The *I-V* curves at various V_g's clearly show a pronounced gap structure, as shown in the inset of Fig. 4(b).

The threshold voltage for electrical conduction at low temperatures can be expressed by the relation $eV_{th}=E_{eff}+E_a$, where E_{eff}(=13 meV) is the effective charging energy and E_a(=29 meV) is the activation energy for the Schottky barrier. The estimated threshold voltage is not far from the averaged V_{th}(∼45 meV) obtained from the *I-V* data at $V_g = +10$ V shown in the inset of Fig. 4(b).

In summary, we studied the electrical transport properties of GaN nanowires with two different doping levels in a field-effect transistor geometry. In both cases, the conductance was found to vary as a function of the gate voltage, and this variation was attributed to a single-electron tunneling effect. The large energy gap that was observed in the lightly doped samples can be understood by considering both the effective Coulomb gap resulting from the granular effect and the Schottky barrier. The observed aperiodic gate modulation also supports the hypothesis that the multiple dots within the nanowire are the result of the granular effect. In the heavily doped nanowire, the ill defined gap structure is likely to be due to an averaging effect between the various grain boundaries that do not have a clear potential barrier, as is to be expected in the case of a Schottky barrier.

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