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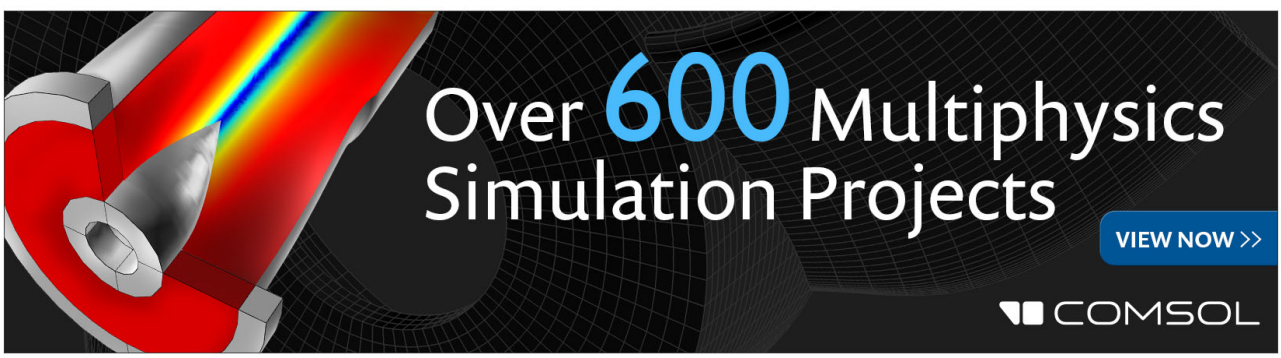

Coulomb blockade behavior in an indium nitride nanowire with disordered surface states

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We present electron transport phenomena in a single electron transistor based on an individual indium nitride nanowire. Meticulous Coulomb oscillations are observed at low temperatures. While the device shows single period Coulomb oscillation at high temperatures or at high bias voltages, additional satellite peaks along with the main Coulomb peak appear at low temperatures and low bias voltages. The quasiperiodic structure is attributed to the mixing of dissimilar Coulomb oscillations arising from two serially coupled islands embedded inadvertently in the surface metallic states of the nanowire. The proposed model is numerically simulated with good agreement with the experimental data. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3216071]

Semiconductor nanowires are promising candidates to serve as building blocks for next generation electronics with unprecedented operation speeds and packing densities.[1,2] A single electron transistor (SET) geometry consists of an individual nanowire island and involves the quantization of electron charge as well as energy. The device thus provides a versatile platform to probe the physics in the quasione dimension and also paves way for next generation electronics and optoelectronics converging to quantum limit. Indium nitride (InN) has attracted recent attention because of its revised direct band gap of 0.7–0.8 eV in the visible range[3] and, to this end, we study the single electron transport through an individual single crystal wurtzite InN nanowire in the SET configuration. The measured devices show a clear crossover from high voltage, high temperature single period Coulomb oscillation to low bias, low temperature multiple period oscillations. In this paper we disclose this unexplored phenomenon in disordered nanowires and associate it with the coexistence of multiple Coulomb islands in the granular surface states of nanowire.

Single crystalline wurtzite nanowires used in this device were grown by guided stream thermal chemical vapor deposition with trimethyl indium as indium source, ammonia as nitrogen source, and gold as catalyst.[4] The nanowires were first dispersed in isopropanol solution. A few droplets of this solution were then placed on Si substrates with micron-sized Pt/Ti measurement pads prefabricated on 300-nm-thick SiO_2 oxide surface. Subsequently, nanoscaled electrodes were fabricated by standard electron beam lithographic technology, which served as interconnectors between nanowires and Pt/Ti pads. Electron beam exposure and identification of the positions of the dispersed nanowires for e-beam writing purpose were performed using a field emission scanning electron microscope (FESEM). The nanometer electrodes of the SET were made of Ni (50 nm) covered with Au (50 nm) protection layer. The top-left inset of Fig. 1 shows an FESEM image of the measured device. The wire diameter is about 55 nm and the separation between the source and drain electrodes is approximately 80 nm. The low temperature measurements were performed with a symmetrical biasing scheme in a He^3/He^4 dilution refrigerator. The current voltage I-V_b characteristics of the SET device measured at temperature of 300, 4.2, and 0.38 K are marked in green, red and blue respectively [Fig. 1]. The zero bias resistance at room temperature is about 70 kΩ and increases to 1.46 MΩ at 0.38 K, marking the onset of Coulomb charging effects and the corresponding nonlinear current-voltage (I-V_b) characteristics. The offset voltage of the I-V_b characteristics at low temperatures (not shown here) correspond to a charging energy of about 13 K (or, $e^2/2C_\Sigma = 1.12$ meV, C_Σ is the total capacitance seen by the nanowire island), which accounts for the clear observation of I-V_g Coulomb oscillations at 4.2 K.

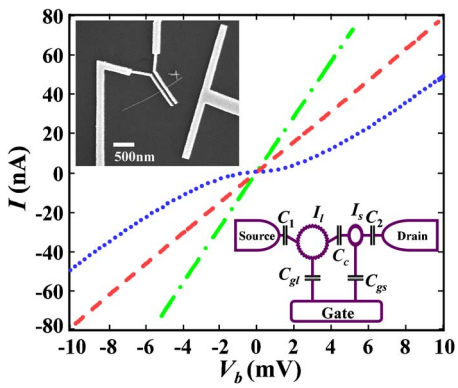

FIG. 1. (Color online) I-V_b characteristics at $T=0.38$ K (blue dotted line), 4.2 K (red dashed line), and 300 K (green dot-dashed line) showing unambiguous Coulomb blockade effect at low temperature. Top left inset is the scanning electron micrograph of the measured device. The bottom right inset is the schematic employed in modeling the measured device.

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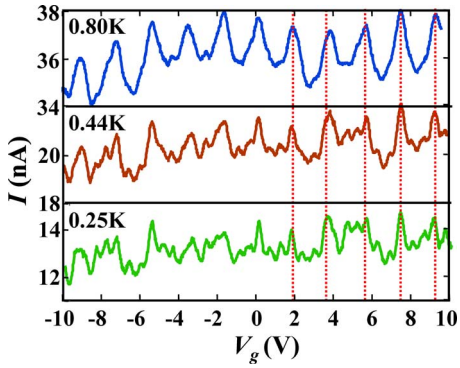

FIG. 2. (Color online) Coulomb oscillations at $T=0.8$ K, 0.44 K, and 0.25 K clearly showing satellite peaks in the vicinity of major peak at lower temperatures. All the curves are taken at $V_b=1$ mV. The vertical red-dotted lines are guide to the eye, representing the major peak position at several temperatures.

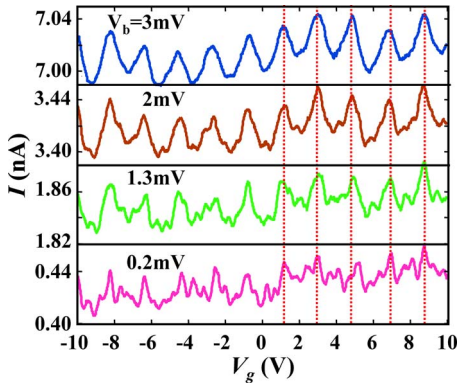

FIG. 3. (Color online) Coulomb oscillations at $V_b=3$ mV, 2 mV, 1.3 mV, and 0.2 mV showing clear onset of satellite peaks in the vicinity of major peak at lower bias voltages. All the curves are taken at $T=0.35$ K. The vertical red-dotted lines are guide to the eye, denoting the major peak position at different bias voltages.

Figure 2 shows such oscillations at a constant bias voltage V_b of 1 mV at three different temperatures. Unlike the orthodox single island Coulomb blockade model which predicts a sharp and prominent single period oscillation corresponding to e/C_g at low temperatures,[5] we observe additional peaks along with the main peak as the temperature was lowered. The newly added (short) periods can be attributed to the additional (larger) Coulomb islands with smaller charging energy, forming inadvertently in the vicinity of the initial smaller island. The schematic of the model is presented in the bottom inset of Fig. 1. There are two Coulomb islands, denoted as I_l and I_s, participating in the electron transport which are weakly coupled to the source and drain electrodes via left and right tunnel junctions, respectively, and the two islands are capacitively coupled to the gate electrode via two dissimilar capacitors C_{gl} and C_{gs}. The interaction between the two islands is tuned by a tunnel junction with a capacitance C_c and a resistance R_c. The applied gate voltage alters the chemical potential of the individual islands and this corresponds to a periodic oscillation in gate voltage with a period of e/C_{g1} and e/C_{g2} for the large and small islands, respectively. Now, the thermal energy k_BT (k_B is the Boltzman constant) is the average translational kinetic energy experienced by the electrons which can be viewed as a finite broadening or background energy providing excitation to the electron transport. The higher thermal energy smears the Coulomb charging levels contributed by large dot (I_l) and the single period corresponding to I_s alone survives. The periodicities in gate voltage determine as to which island plays a role in the single electron transport in the form of Coulomb oscillations. For instance, at higher temperatures, only the smaller island (I_s) with larger charging energy would be appreciable and at lower temperatures the additional bigger island (I_l) with a smaller charging energy emerges.

The measured I-V_g oscillations of the device at fixed $T=0.35$ K and at various bias voltages are presented in Fig. 3. The single period oscillation at high bias voltage evolves into multiple periodic oscillations with additional short periodicities as we lower the bias voltage. A close inspection reveals that satellite peaks gradually emerge on the both sides of the main peaks and the most interesting observation is that periodicity of the original peak still prevails. This is clearly demonstrated by the fast Fourier transform (FFT) of the measured data shown in Fig. 4(a). The inset of Fig. 4(a) shows FFT spectra of I-V_g curves taken at two bias voltages, $V_b=1.3$ mV and 3 mV, and the two amplitude peaks in each spectrum correspond to the two dominant periods of 1.81 and 0.95 V. Note that the FFT amplitude ratio, $A_{1.81\ \mathrm{V}}/A_{0.95\ \mathrm{V}}$, increases with increasing bias voltage. This is further illustrated in the main panel, which shows the normalized oscillation amplitude of these two peaks as a function of bias voltages with a clear bias voltage dependence of $A_{1.81\ \mathrm{V}}$ and $A_{0.95\ \mathrm{V}}$ and the oscillation amplitude of smaller period ($A_{0.95\ \mathrm{V}}$) increases with decreasing bias voltage. This confirms our observation of fine structures emerging on both

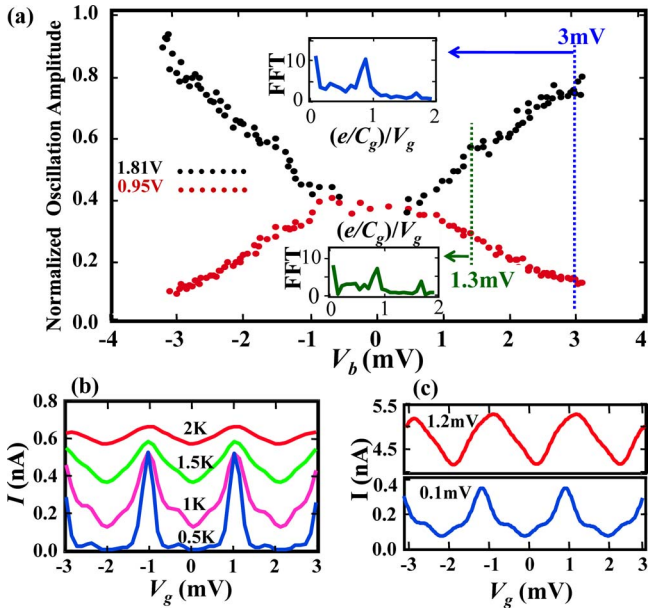

FIG. 4. (Color online) (a) FFT analysis of the measured I-V_g Coulomb oscillations at several bias voltages. The inset is the FFT spectra at $V_b=3$ and 1.3 mv which can be used to identify the two dominant periods presented in the oscillations. The first peak corresponds to a period of 1.81 V in V_g and the second peak represents 0.95 V in V_g. The main panel is the normalized oscillation amplitude extracted as a function of bias voltage. The black solid circles indicate the amplitude of 1.81 V period oscillation while the red solid circles denote the amplitude of 0.95 V period oscillation. Panels (b) and (c) are simulated I-V_g Coulomb oscillations. (b) shows I-V_g at $V_b=0.15$ mV at four temperatures: 0.5 K, 1 K, 1.5 K, and 2 K; (c) shows I-V_g at $T=1$ K at $V_b=1.2$ mV and 0.1 mV. We can clearly see the fine structures on both sides of the original peak at low bias voltages and at low temperatures.

sides of the original peak at low bias voltages in Fig. 2. A similar analysis is performed (not shown) as a function of temperature at a fixed low bias voltage and the result clearly indicates the onset of satellite peaks on both sides of the main peak at lower temperatures. The two prominent periods in the Coulomb oscillations inspire us to model the device using two coupled dissimilar Coulomb islands, and we numerically simulate this intuitive model using the standard Master equation approach in the sequential tunneling limit[5] and find qualitative agreement with the experimental results. The device parameters chosen for the simulation are C_1 =100 aF, R_1=26 kΩ, C_2=130 aF, R_2=26 kΩ, C_c=4 aF, and R_c=50 kΩ. The gate capacitances are C_{g1}=230.3 aF and 77.7 aF for the big and the small island, respectively. Figure 4(b) is the simulated I-V_g Coulomb oscillation subjected to a constant bias V_b=0.15 mV at several temperatures and Fig. 4(c) is the I-V_g oscillation at a fixed temperature T=1 K under two different bias conditions. We can clearly see that the fine structures on either side of the main peak emerge at low bias and low temperatures. Higher bias voltages open a window which surmounts the charging level spacing corresponding to the e/C_{gl} of the big dot; the small dot (I_s) alone prevails leading to a single period oscillation corresponding to e/C_{gs}. At low enough voltages, both the dots become appreciable and the Coulomb oscillation has complicated gate dependence depending on the ratio of C_{gl} and C_{gs}. The newly added short periods are thus attributed to additional Coulomb islands forming inadvertently in the vicinity of the initial island. This crossover from periodic oscillation at high temperatures to aperiodic oscillations at lower temperatures is not a measurement artifact or noise and has survived three complete thermal cycles (three different runs) from He^3/He^4 fridge to room temperature. If the aperiodic oscillation at low temperatures were to come from noise effects, it would not be reproducible in repeated measurements and the FFT of the measured signal would be a random conglomeration of oscillation periods. It is also straight forward to extend our model to multiple islands which become important at much lower temperatures. We have measured the I-V_g oscillations at 75 mK (not shown) and the interesting cross over from single period high bias oscillation to multiple period low bias traces is still retained.

The physics of InN is very unique compared to other III-V materials and has attracted a lot of recent attention. *Ab initio* calculations of band structures predict that the branch point energy of InN lies within the conduction band at the Γ-point and is thus responsible for the surface states.[6] The high-resolution electron-energy-loss spectroscopy measurements on clean InN surfaces provides an unambiguous proof of metallic or donor type surface accumulation states up to a thickness of about 5 nm.[7] The origin of surface states is twofold. First, it is an accepted inherent electronic band structure property of clean InN nanowires and second, the ambient oxygen forms native indium oxide, which is believed to cause large surface accumulation layer.[8] These two phenomena together can account for the robust surface accumulation states and it is thus justified to consider that in our device the electrons hop along the nanowire surface states. Moreover, these states by nature fall in disordered metallic regime. Similar crossover from periodic to quasi periodic I-V_g oscillations in disordered systems has already been reported and is well understood in GaAs wires.[9] Further, charge transport at very low temperatures in disordered system was also modeled as arising from mixed Coulomb oscillations of two dissimilar metal dots unintentionally formed in the disordered potential[10] and the crossover from periodic to quasiperiodic oscillations was attributed to incommensurate energy scales required to add charges to the two dots.

Further, the I-V_g Coulomb oscillations are taken under external magnetic fields up to 5 T. The striking observation is that satellite peak structure along with the main peak survives even in high magnetic fields. There is neither shift in the peak position nor observable change in the peak height. It is widely believed that electron transport through Coulomb charging system with continuous density of states is insensitive to the magnetic field, and our model of weakly coupled Coulomb islands are thus justified.

In summary we present a single electron transistor based on an individual indium nitride nanowire. The interesting crossover from high voltage, high temperature single period Coulomb oscillation to low bias, low temperature multiple period oscillations implies the interesting interplay of Coulomb charging effects from more than one Coulomb island.

The tunnel barriers between the islands arise inadvertently due to large fluctuations in the underlying disordered potential. We propose and simulate an intuitive model explaining the observed phenomena. The present work sheds light on the unexplored single electron charging behavior and transport of InN nanowires and is an encouraging development toward the InN based electronics and optoelectronics devices.

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