

# Single-electron transistors in GaN/AlGaN heterostructures

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(Received 24 February 2006; accepted 26 May 2006; published online 17 July 2006)

We report transport properties of two single-electron transistors (SETs) on a GaN/AlGaN heterostructure. The first SET formed accidentally in a quantum point contact near pinchoff. Its small size produces large energy scales (a charging energy of 7.5 meV and well-resolved excited states). The second, intentionally fabricated SET is much larger. More than 100 uniformly spaced Coulomb oscillations yield a charging energy of 0.85 meV. Excited states are not resolvable in Coulomb diamonds, and Coulomb blockade peak height remains constant with increasing temperature, indicating that transport is through multiple quantum levels even at the 450 mK base electron temperature of our measurements. Coulomb oscillations of both SETs are highly stable, comparable to the best GaAs SETs. © 2006 American Institute of Physics.

[DOI: 10.1063/1.2226454]

Semiconductor quantum dots have attracted intensive research interest in the past decade. The ability to tune not only energies of discrete quantum levels but also their coupling to neighboring quantum dots or leads makes these structures a plausible candidate for prototyping a quantum computer<sup>1</sup> and an excellent playground for studying many-electron physics.<sup>2</sup> Most transport experiments on quantum dots have been based on GaAs/AlGaAs heterostructures because of their mature growth and processing technologies.<sup>3</sup>

Our recent demonstration of quantum point contacts (QPCs) in GaN/AlGaN heterostructures suggests that GaN would be another interesting system for exploring mesoscopic physics.<sup>4</sup> Compared to GaAs, electrons in GaN have three times higher effective mass and also 30% lower dielectric constant, increasing the importance of electron-electron interactions relative to kinetic energy.<sup>5</sup> Strong electron-electron interaction is predicted to influence mesoscopic fluctuations in closed quantum dots, as manifested in Coulomb blockade peak-spacing statistics.<sup>6</sup> GaN also has a larger  $g$  factor and has been predicted to have a longer spin coherence lifetime.<sup>7</sup> Therefore a quantum dot in GaN would be an excellent candidate for studying many-body physics<sup>6,8</sup> and spin physics.

In this letter, we report fabrication and transport studies of two GaN single-electron transistors (SETs): quantum dots coupled to conducting leads. The devices studied in this experiment are formed in a top-gated GaN/AlGaN heterostructure,<sup>9,10</sup> whose two-dimensional electron gas (2DEG) is only 20 nm below the surface, with density  $n_s = 8.0 \times 10^{11} \text{ cm}^{-2}$  and mobility  $\mu = 80\,000 \text{ cm}^2/\text{V s}$ . The method of fabricating the device is very similar to that of Ref. 4, with one additional step. Our 2DEG is very shallow, resulting in high leakage current when gate metal is directly

deposited on the heterostructure surface. To suppress leakage current from the gates, we use atomic layer deposition to form a 30 nm thick alumina layer over the entire device, before fabricating gates by electron beam lithography and metal evaporation. The experiment was performed in a <sup>3</sup>He cryostat with a base temperature  $T=0.310 \text{ K}$ , using standard ac lock-in techniques, with a 20  $\mu\text{V}$ , 77 Hz excitation added to a variable dc voltage  $V_{sd}$ .

We have fabricated QPCs and measured the linear conductance as a function of gate voltage [Fig. 1(a)]. On two QPCs, the conductance plateaus are not quantized in units of  $2e^2/h$ . This deterioration of conductance quantization might be caused by impurities near the QPCs, or by the nonadiabaticity of the potential produced by the split gates. When these QPCs are nearly pinched off, multiple oscillations in conductance are observed, reminiscent of Coulomb oscillations in a single-electron transistor. Below we show data from one of these two QPCs. Similar behavior has previ-

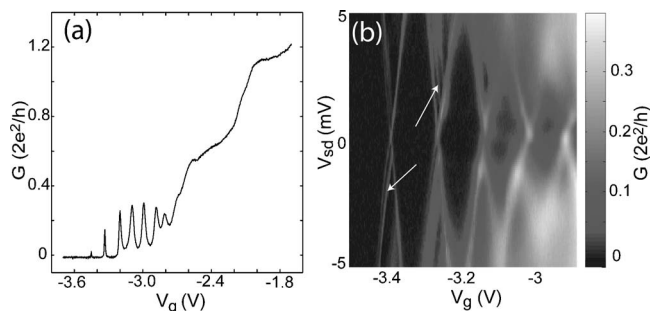


FIG. 1. (a) Linear conductance  $G$  as a function of gate voltage  $V_g$  of the QPC. Conductance plateaus appear near 1.2 and  $0.6(2e^2/h)$ , with several resonances before the QPC is pinched off. (b) Grayscale plot of nonlinear differential conductance  $\partial I/\partial V_{sd}(V_{sd}, V_g)$ . In addition to clear Coulomb diamonds, transport through excited levels appears as extra lines outside the diamonds (white arrows).

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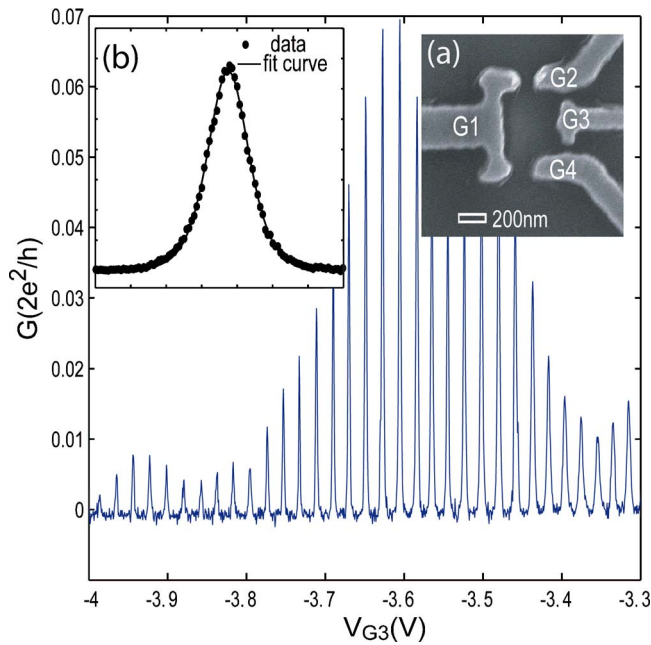


FIG. 2. (Color online) Linear conductance  $G$  vs the gate voltage  $V_{G3}$  of the SET. Clear Coulomb oscillations are observed. Inset (a): Electron micrograph of the SET. The coupling between the 2D reservoirs and the quantum dot can be tuned by controlling the voltages on gates  $G1$ ,  $G2$ , and  $G4$ . By varying the voltage on the plunger gate  $G3$ , the potential of the quantum dot is modified and the energy for adding an electron to the quantum dot is shifted into and out of resonance with the Fermi level of the 2D reservoirs. A peak in conductance occurs when the addition energy is aligned to the Fermi level so that an electron can tunnel onto and off of the quantum dot. All the data shown in this letter are measured by varying the plunger gate  $G3$ , with gates  $G1$ ,  $G2$ , and  $G4$  fixed at constant voltages. Inset (b): A conductance peak fit to the line shape expected in the classical Coulomb blockade regime (multilevel transport),  $G = G_{\max} \cosh^{-2}[\alpha(V_{G3} - V_{\max})/2.5k_B T]$  (Ref. 3), where  $G_{\max}$  is the peak conductance,  $\alpha$  is the conversion ratio from gate voltage to energy, and  $V_{\max}$  is the location in gate voltage of the conductance peak. The three fit parameters are  $G_{\max}$ ,  $V_{\max}$ , and  $\eta = k_B T / \alpha$ .

ously been observed in QPCs based on both Si and GaAs, though it is rarely published (see, for example, Ref. 11).

Nonlinear transport measurements can be used to extract the charging energy and the spectrum of excited states of the accidentally formed quantum dot. To confirm the origin of the conductance oscillations, we measure the nonlinear conductance as a function of source-drain bias and gate voltage [Fig. 1(b)]. The resulting clear ‘‘Coulomb diamonds’’ are characteristic of a single-electron transistor. The charging energy  $E_c \equiv e^2/C$  is larger for the diamonds at more negative voltage, reaching 7.5 meV for the last diamond, corresponding to a total capacitance  $C = 21$  aF. Modeling the dot as a disk embedded in GaN and ignoring nearby electrodes, the capacitance has the form  $C = 8\epsilon_r \epsilon_0 r$ , where  $r$  is the disk radius and  $\epsilon_r = 9$  is the approximate dielectric constant of GaN, and of the AlGaIn and AlO<sub>x</sub> which separate the 2DEG from the surface gates. From this we estimate the radius of the quantum dot to be 30 nm and the number of electrons in the dot to be 12 or fewer. Excited energy levels with a spacing of about 1 meV [indicated by the arrows in Fig. 1(b)] reasonably match the single particle level spacing expected for a 30 nm GaN dot,  $\Delta = \hbar^2/m^* r^2 = 0.5$  meV, where  $m^* = 0.2m_e$  is the effective electron mass.

Motivated by the observation of single-electron tunneling in GaN QPCs, we have fabricated single-electron transistors with more tunability and better-defined geometry. Re-

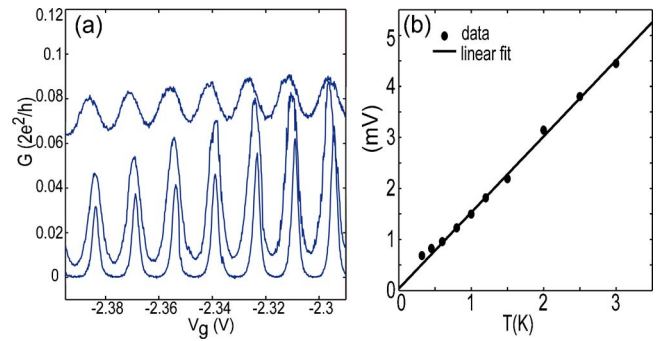


FIG. 3. (Color online) (a) Coulomb oscillations at three different temperatures. From bottom to top: 0.314, 1, and 3 K. (b) The fitting parameter  $\eta = k_B T / \alpha$  as a function of temperature. The line is the least squares fit to the data excluding the two lowest temperature points. The slope is equal to  $k_B / \alpha$ , yielding an estimate  $\alpha = 59$  meV/ $V_g$ .

sults presented below are from one such device. This single-electron transistor is defined by four gates on the surface [Fig. 2(a)]. By energizing the four gates with negative voltages, the 2DEG underneath can be depleted to form a droplet of electrons tunnel-coupled to source and drain leads. With the other three gates fixed at constant negative voltages, we measure linear conductance from source to drain as a function of the plunger gate voltage, yielding clear Coulomb oscillations (Fig. 2). These oscillations are stable over a wide range of gate voltage with minimal hysteresis and switching: more than 100 are observed before the conductance becomes smaller than our measurement’s noise floor. Note that Coulomb oscillations do not appear when only two or three gates are energized at negative voltages, indicating that the quantum dot is really confined by the potential produced by the four gates rather than originating from resonances in the individual point contacts as in our earlier SET.

At each temperature from 0.3 to 3 K we simultaneously fit a series of eight Coulomb blockade peaks using a thermally broadened line shape, which in each case fits substantially better than a lifetime-broadened (Lorentzian) form [Fig. 2(b) shows the fit at base temperature]. Figure 3(a) shows the data taken at  $T = 0.314$ , 1, and 3 K. The peaks broaden with increasing temperature, and the width is proportional to temperature except below 0.5 K [Fig. 3(b)]. At the crossover from single-level to multilevel transport, peak widths should jump from  $3.5k_B T / \alpha$  to  $4.35k_B T / \alpha$ .<sup>12</sup> However, we believe that we are always in the multilevel regime. The lithographic dimensions of our dot are  $\approx 400 \times 400$  nm<sup>2</sup>. We model the dot as a disk and approximate the dot radius as 150 nm: the lithographic radius of the device, less a depletion width equal to the depth of the 2DEG. This predicts a capacitance of 96 aF with a charging energy  $E_c \approx 1.7$  meV and a single particle level spacing  $\Delta \approx 18$   $\mu$ eV. But since the depth of the 2DEG below the surface of the heterostructure and oxide is only 50 nm, several times smaller than the lithographic radius of the quantum dot, the capacitance contributed from the four top split gates is comparable to the disk capacitance and not negligible. Therefore total capacitance of the dot should be higher than 96 aF, so 1.7 meV is an upper bound of the charging energy.

Over the range from base temperature  $T \approx 0.3$  K to  $T = 3$  K,  $E_c \gg k_B T = 25 - 250$   $\mu$ eV  $> \Delta$ , so multiple levels should participate in transport. The slope of the linear variation of peak width versus temperature yields  $\alpha = 59$  meV/ $V_g$ , with nearly zero offset. The saturation of width for the two lowest

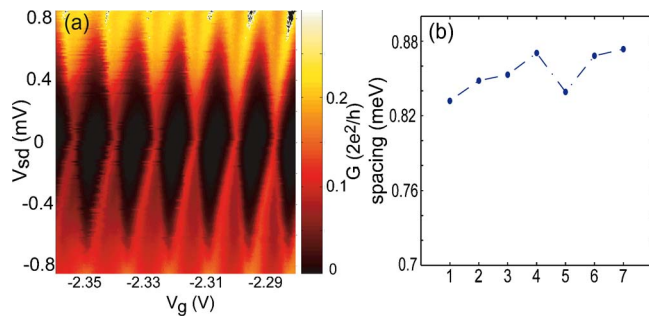


FIG. 4. (Color online) (a) Differential conductance  $dI/dV_{sd}$  as a function of plunger gate voltage  $V_g$  and source-drain bias  $V_{sd}$ . Stable and uniform Coulomb diamonds are observed. (b) Energy spacing between successive adjacent peaks. The average spacing is 0.85 meV with a fluctuation of tens of  $\mu\text{eV}$ .

temperature points suggests that the electron temperature is 0.450 K even when the  $^3\text{He}$  bath is cooled to 0.3 K. This is surprising but not shocking, given that we have not installed explicit low-temperature electrical filters.

To further investigate properties of the SET such as charging energy and excited energy level spacings, we have measured nonlinear transport [Fig. 4(a)]. The resulting Coulomb diamonds all have a similar size with a charging energy of  $\sim 0.8$  meV and show minimal switching events over 6 h of measurement. No clear features of excited levels appear parallel to the boundaries of the Coulomb diamonds, supporting our contention that the quantum dot is in the multilevel transport regime. To better estimate the energy spacing between consecutive electron additions, we fit each Coulomb blockade peak and take the difference  $\Delta V_g$  between successive peak positions derived from our fits. To convert  $\Delta V_g$  into an energy spacing we simply multiply by  $\alpha$  extracted from Fig. 3(b). The gaps between successive peaks are all about 0.85 meV, providing a more precise measurement of charging energy [Fig. 4(b)]. The charging energy has an overall trend of increasing slightly with more negative gate voltage—larger indices in Fig. 4(b) represent peaks at more negative voltage. This is due to a gradual reduction of the dot size. We have performed nonlinear transport around a more negative voltage  $V_g = -4.2$  V and found a charging energy of 1.4 meV from Coulomb diamonds, confirming this trend. On top of the smooth increase in charging energy, the fluctuations in peak spacings are of the same order as the estimated single energy level spacing  $\sim 18 \mu\text{eV}$ .

In conclusion, we have fabricated QPCs on a GaN/AlGaIn heterostructure and studied an accidental quan-

tum dot formed in a QPC. An intentionally fabricated SET on a GaN/AlGaIn heterostructure showed more than a hundred consecutive Coulomb oscillations. This SET is in the multilevel transport regime, with no excited levels. In order to resolve the excited level spectrum, explore interesting phenomena such as Kondo effect, and investigate how the strong electron-electron interactions affect peak-spacing statistics, we plan to study the SET at temperature lower than 0.1 K to achieve single-level transport:  $\Delta \sim 18 \mu\text{eV} > k_B T \sim 8.6 \mu\text{eV}$ . We also plan to fabricate SETs with double the single particle level spacing (40  $\mu\text{eV}$ ) by reducing the lithographic dot dimension from 400 to 300 nm.

The authors thank R. M. Potok for valuable discussions. Two of the authors (D.G.G and H.T.C) acknowledge support from fellowships from the Sloan Foundation, Research Corporation, and Packard Foundation. The work at Stanford was performed in part at the Stanford Nanofabrication Facility of NNIN supported by the National Science Foundation under Grant No. ECS-9731293. Another author (R.J.M) acknowledges the Office of Naval Research, Air Force Contract No. F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and not necessarily endorsed by the United States Air Force.

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