Unusually Strong Space-Charge-Limited Current in Thin Wires

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The current-voltage characteristics of thin wires are often observed to be nonlinear, and this behavior has been ascribed to Schottky barriers at the contacts. We present electronic transport measurements on GaN nanorods and demonstrate that the nonlinear behavior originates instead from space-charge-limited current. A theory of space-charge-limited current in thin wires corroborates the experiments and shows that poor screening in high-aspect ratio materials leads to a dramatic enhancement of space-charge limited current, resulting in new scaling in terms of the aspect ratio.

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Nanorods and nanowires made of different semiconducting materials have been extensively characterized electrically [1–9]. For most applications, a linear current-voltage relationship is desirable, usually requiring Ohmic contact to doped wires. However, even in situations where these conditions should be met, it is often observed that the current-voltage characteristics are nonlinear. Invariably, this behavior is explained by the presence of Schottky barriers at the contacts, despite the fact that such models sometimes give poor descriptions of the experimental data. Properly identifying the factors that influence electrical transport characteristics is important for device design but also because extraction of material parameters such as the mobility relies on analysis with specific models.

It is well known that in bulk insulating and semiconductor materials, space-charge-limited (SCL) current leads to nonlinear, nonexponential I-V characteristics [10–12] with the relationship $I \propto V^2$. This behavior occurs in situations of mobility-dominated transport when the effective carrier concentration is low. This can arise due to low intrinsic doping, charge traps, or depletion widths at the contacts that are larger than the channel length (punchthrough). Thin wires should be particularly sensitive to SCL effects for several reasons: first, because electrostatic screening in high-aspect ratio systems is poor [13], the injected carriers cannot be effectively screened; second, carrier depletion due to surface states is expected to be more important in thin wires due to the large surface-to-volume ratio [14]; third, charge traps may readily be incorporated during growth [15].

In this Letter, we present electrical transport in individual GaN nanorods showing symmetric, nonlinear I-V characteristics. We show that the relationship $I \propto V^2$ is satisfied in these thin wires, a signature of SCL current. A theory for SCL transport in thin wires is presented and shows that SCL current is unusually strong due to a new scaling with the wire aspect ratio.

The growth and microstructural characterization of the GaN nanorods has been described in detail elsewhere [16]. Briefly, the nanorods were grown in a commercial metal-organic chemical vapor-deposition system on GaN/sapphire substrates using selective epitaxy, whereby a 30 nm thick SiN film with lithographically defined holes serves as a mask for the nanorod growth. For this work, the nanorod aspect ratio R/L ranged from 0.05 to 0.5, and the nanorods were up to a few microns in length. Electrical measurements on individual nanorods were carried out in two ways. In the first approach, electrical contacts were defined on top of randomly dispersed nanorods on SiO_2 substrates using optical lithography followed by electron beam evaporation of Ti/Au (10 nm/300 nm) and lift-off. The electrode pattern consists of arrays of interdigitated, individually addressable electrodes with spacing ranging from 1 to 4 μm. In the second approach, the vertical nanorods were individually contacted at their top end directly on the growth wafer using a Au-coated W STM tip, with a large area Ag paint serving as the back electrode.

Figure 1(a) shows a scanning electron microscope (SEM) image of an individual GaN nanorod with two Ti/Au side contacts, as well as the associated I-V characteristics for several of these devices. The I-V curves are clearly nonlinear and are fairly symmetric between positive and negative values of the source-drain voltage. An excellent description of the data is obtained by plotting I/V vs V as shown in Fig. 1(b). There, several of the positive and negative I-V traces of Fig. 1(a) are plotted, with the current normalized by that measured at 3 V. Clearly, straight lines are obtained, indicative of $I \propto V^2$ behavior; the values of the intercept suggest that a linear contribution to the I-V curve is small. The quadratic I-V characteristics cannot be explained by Schottky or tunneling barriers at the contacts. Indeed, Ti is often used to make low resistance contacts to bulk GaN [17] and has been shown to give Ohmic contacts to GaN nanowires even in the absence of

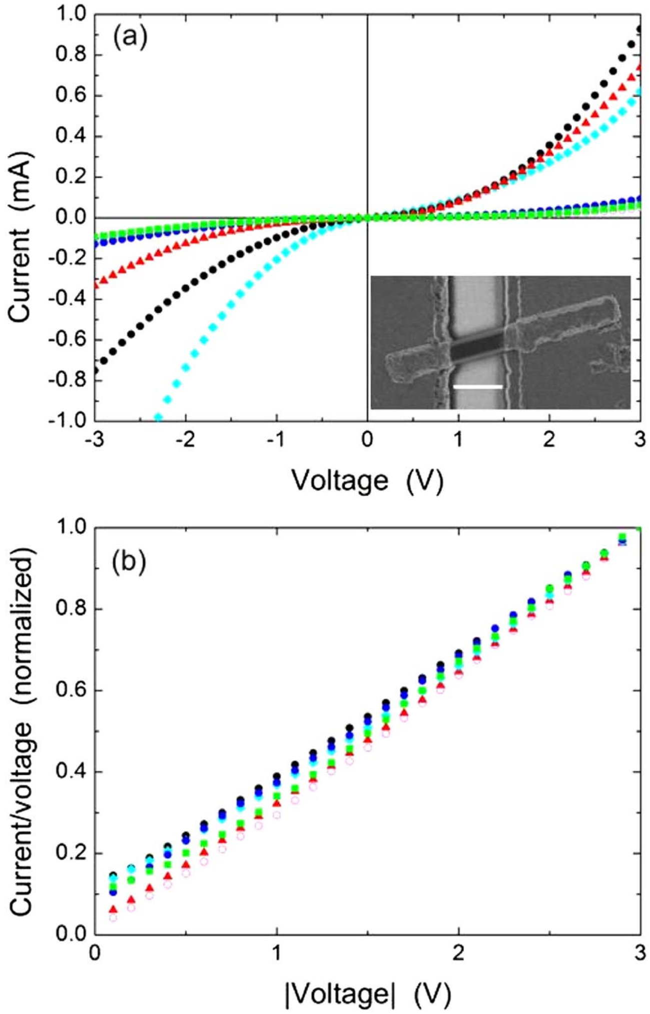

FIG. 1 (color online). (a) Current-voltage characteristics of several GaN nanowires. Inset shows a SEM image of one of the devices. Scale bar is 1 μm. (b) Data of panel (a) but plotted as current divided by voltage, versus voltage. The data for several positive and negative voltage sweeps from several different devices are plotted and normalized to 1 for an absolute voltage of 3 V.

annealing [5]. In addition, we also annealed several of the devices at 550 °C in vacuum for 15 min and found essentially no change in the I-V characteristics. Furthermore, for back-to-back Schottky barriers, the current is dominated by the reverse-biased Schottky barrier and has the form $1 - \exp(-eV/kT)$ in the absence of tunneling; this gives a linear I-V curve at low bias and saturation at larger bias, failing to even qualitatively describe our data. If tunneling is allowed, then explicit calculations for back-to-back Schottky contacts give an exponential behavior [4]. This is also born out in the well-known expressions for the I-V characteristics of two tunnel contacts which lead to a linear behavior at low bias and an exponential behavior at high bias [18].

To further support the argument that contacts are not responsible for the observed behavior, we used a Au-coated W STM tip to directly contact individual nanorods on the growth substrate and to probe the transition from injection-limited to SCL behavior. As we indicated earlier, a large area, low resistance Ag contact is painted on the back of the growth substrate; thus, the current is dominated by the nanorod itself, or by the small area nanorod-to-tip contact. Figure 2 shows the I-V curves and a SEM image for a particular nanorod. When the tip is initially brought into contact with the nanorod, the I-V characteristics are rectifying and well described by transport through a barrier; i.e., the I-V curve is exponential at forward bias; see inset of Fig. 2. This corresponds to the injection-limited regime, and the I-V is dominated by the behavior of the nanorod-to-tip contact. As the tip is pressed into the nanorod, the nature of the I-V characteristics changes, with the current increasing by a factor of 100, becoming symmetrical about the origin, and well described by a $I \propto V^2$ behavior. These measurements demonstrate unequivocally the transition between injection-limited and SCL transport; since there is only one relevant contact in these measurements, the symmetrical current-voltage characteristics must be due to the nanorod itself. (The reason for the improvement in the nanorod-to-tip contact quality is not entirely clear, but could be due to a combination of a thin native oxide being destroyed as the tip is pressed into the nanorod and the small radius of curvature of the tip leading to substantial field enhancement. It should be noted that in several nanorods the I-V characteristics changed gradually from rectifying to leaky diode and finally to SCL.)

The observations of quadratic I-V curves are consistent with a theory of SCL current in thin wires. For transport through a thin wire of radius R and length L, the drift component of the current density is

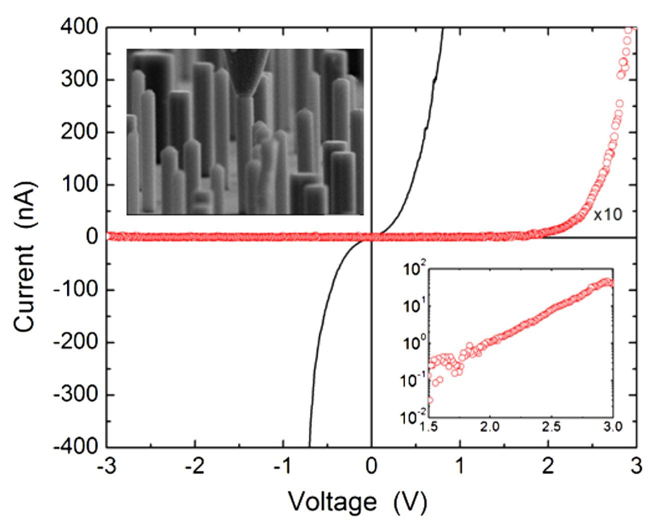

FIG. 2 (color online). Current-voltage characteristics before (symbols) and after (line) the tip is pressed into the nanowire. The bottom right inset shows the current before pressing on a log scale. The top left inset is a SEM image of the Au-coated W tip contacting a GaN nanowire.

$$J = \frac{2}{R^2}\int_0^R rj(r)dr = \frac{2e\mu}{R^2}\int_0^R rn(z,r)E_z(z,r)dr, \quad (1)$$

where $j(r) = e\mu n(z,r)E_z(z,r)$ is the current density at radial coordinate r, μ is the mobility, $n(z,r)$ the carrier concentration, and $E_z(z,r)$ the electric field in the transport direction z. (The diffusion component of the current is negligible for voltages $\gtrsim 10kT/e$ [10].) This equation is combined with Poisson's equation for the electrostatic potential *inside* the thin wire:

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} = \frac{en(z,r)}{\epsilon}, \quad (2)$$

where ϵ is the semiconductor dielectric constant, and where we assumed that the charge distribution is isotropic in the angular coordinate ϕ. [Note that outside the wire $r > R$, we have $n(z,r) = 0$.] The solution of Poisson's equation with the Green function $(4\pi)^{-1}|\mathbf{r} - \mathbf{r}'|^{-1}$ [19] gives the spatially dependent electric field *inside* the wire:

$$E_z(z,r) = \frac{e}{\epsilon}\int_0^L\int_0^R n(z',r')G(z-z';r,r')r'dr'dz', \quad (3)$$

where $G(z-z';r,r') = (4\pi)^{-1}\partial_z\int_0^{2\pi}(|\mathbf{r}-\mathbf{r}'|^{-1} - |\mathbf{r}-\mathbf{L}|^{-1})d\phi'$ with $\mathbf{L}$ a point on the electrode at $z = L$. When combined with Eq. (1), this expression for the electric field provides an integral equation [10] for the spatially dependent carrier concentration; with the scalings $\xi = z/L$, $\alpha = r/L$, and $\nu(\xi) = (2\epsilon J/e^2\mu L)^{-1/2}n(\xi)$, this equation is $(4L^2/R^2)\int_0^{R/L}\nu(\xi,\alpha)\alpha d\alpha[\int_0^{R/L}\int_0^1\nu(\xi',\alpha')G(\xi - \xi',\alpha,\alpha')\alpha' d\alpha' d\xi'] = 1$. The potential on the drain electrode can be obtained from $V = -\int_0^L E_z(z,r)dz$ and is given by

$$V = -\left(\frac{JL^3}{2\epsilon\mu}\right)^{1/2}\int_0^1\left[\frac{L^2}{2R^2}\int_0^{R/L}\alpha d\alpha\nu(\alpha,\xi)\right]^{-1}d\xi. \quad (4)$$

The integral in this last equation is simply a numerical factor, which we define as $(\zeta/2)^{-1/2}$; the total current density is then

$$J = \zeta(R/L)\frac{\epsilon\mu}{L^3}V^2. \quad (5)$$

Thus, we find that for a thin wire, the current density depends quadratically on the applied voltage, with a prefactor that depends on the ratio R/L. This can be compared with SCL current in a bulk material by using $n(z,r) = n(z)$ and taking the limit $R/L \gg 1$ in the above equations, giving $\zeta = 9/8$ and the current density [10,11] $J_{\text{bulk}} = (9\epsilon\mu/8L^3)V^2$. The important point is that the dimensionality does not change the dependence on voltage but affects the scaling with length. In any dimension where SCL current dominates, a plot of I/V vs V gives a straight line, as observed in our experimental data. (Velocity saturation would lead to $I \propto V$ at larger voltages, which we have not seen in our measurements; this is consistent with electric fields larger than 10 V/μm needed to reach the maximum carrier velocity in GaN [20].)

Additional evidence for SCL transport comes from a more detailed study of the experimental data in terms of a scaling analysis. Equation (5) can be rewritten as

$$\frac{L^3}{AV^2}I = \epsilon\mu\zeta(R/L), \quad (6)$$

where A is the nanowire cross-sectional area, and ζ is the scaling function. Figure 3 shows a plot of $(IL^3)/(AV^2)$ as a function of R/L for a number of nanorods contacted lithographically and with the STM tip. It is remarkable that both types of contacts, despite their very different geometry, lead to the same universal behavior, providing further evidence that the observed behavior is not due to contacts. Furthermore, the dependence of the data on R/L is entirely consistent with the theoretical analysis presented above. Indeed, for small R/L the carrier concentration is independent of r to a good approximation [21], and we can derive that $\zeta(R/L) = \zeta_0(L/R)^{-2}$; a similar situation holds for large R/L, and we have $\zeta(R/L) \sim$ const. The solid lines in the main figure and the inset show that a fit of the form $a(L/R)^{-2}$ represents well the data for $R/L < 0.2$; the crossover to the large R/L regime is also apparent. This explicit dependence of the current on the length of the nanorod L also indicates that the behavior is not due to contacts. In addition, from the relation $a = \zeta_0\epsilon\mu$ and the fit to the experimental data, the effective carrier mobility is calculated to be 386 cm^2/V s [22]. This value is consistent with values for bulk GaN material at room temperature

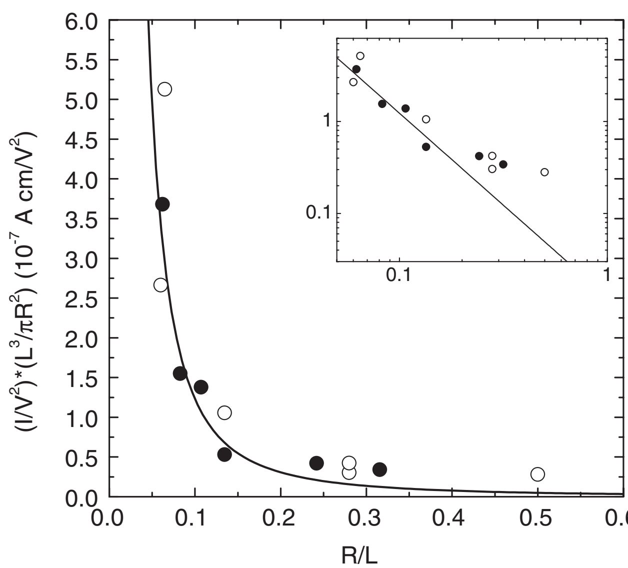

FIG. 3. Scaling behavior for several GaN nanowires with lithographically defined top contacts (solid circles) and with the STM tip as the contact (open circles). The inset is the same data plotted on a log-log scale. In both plots the solid line is a best fit to the data of the form $a(R/L)^{-2}$ for $R/L < 0.2$.

[23], again supporting the conclusion that the bulk of the nanorod itself determines the behavior.

In bulk materials, there exists a crossover voltage $V_c^{\rm bulk}$ between an initial Ohmic behavior and SCL transport. For small voltages, the current has an Ohmic behavior $J = e\mu n_0 V/L$, where n_0 is the effective carrier concentration. The transition to the SCL regime occurs when $J_{\rm bulk}^{\rm SCL} = (9\epsilon\mu/8L^3)V^2$ exceeds the Ohmic current, or $V_c^{\rm bulk} \sim en_0L^2/\epsilon$. A similar argument holds for thin wires, except that the crossover voltage is given by

$$V_c = \frac{1}{\zeta(R/L)}\frac{en_0L^2}{\epsilon} \sim \frac{1}{\zeta(R/L)}V_c^{\rm bulk}. \qquad (7)$$

The presence of the factor $\zeta^{-1}(R/L)$ has a significant impact on the magnitude of V_c. Indeed, for small R/L we have $V_c \sim (R/L)^2 V_c^{\rm bulk}$, and the crossover voltage is reduced by orders of magnitude for small values of R/L. The immediate implication is that the carrier concentration needed to obtain Ohmic behavior is much larger in thin wires, by a factor $(L/R)^2$. And more generally, it points to the conclusion that, as long as carrier injection is efficient, SCL transport should be prevalent in materials at reduced dimensionality. The origin of this behavior lies in the fact that in high-aspect ratio structures, the Coulomb interaction is poorly screened [13,24]. For SCL transport in thin wires, this means that the effective magnitude of the injected charge is significantly increased because it can only be screened up to a radius R.

In summary, we find that GaN nanorods show nonlinear *I-V* characteristics of the form $I \propto V^2$ which we ascribe to SCL transport. This electronic transport regime arises when conduction is mobility dominated, when the carrier injection is efficient, and the carrier concentration is low. This situation may be prevalent in thin wire materials for several reasons. First, because of the poor electrostatic screening in thin wires, SCL current is enhanced by orders of magnitude. Second, dopant incorporation during growth is often difficult to achieve, so doping levels may be inherently low, leading to long depletion widths and punchthrough, a situation that is exacerbated by the poor electrostatic screening. In addition, surface states and charge traps may deplete the carriers. Finally, because of the scaling of the SCL current with the aspect ratio, much larger effective carrier concentrations are needed to obtain Ohmic behavior. Taken together, these arguments suggest that future electronic devices based on nanorods and nanowires should carefully consider SCL behavior in their design.

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[1] X. Duan, Y. Huang, Y. Cui, J. Wang, and C. M. Lieber, Nature (London) **409**, 66 (2001).
[2] Y. Cui, X. Duan, J. Hu, and C. M. Lieber, J. Phys. Chem. B **104**, 5213 (2000).
[3] M.-H. Ham, J-H. Choi, W. Hwang, C. Park, W.-Y. Lee, and J.-M. Myoung, Nanotechnology **17**, 2203 (2006).
[4] Z. Y. Zhang, C. H. Jin, X. L. Liang, Q. Chen, and L.-M. Peng, Appl. Phys. Lett. **88**, 073102 (2006).
[5] E. Stern *et al.*, Nanotechnology **16**, 2941 (2005).
[6] D. Wang, Y.-L. Chang, Q. Wang, J. Cao, D. B. Farmer, R. G. Gordon, and H. Dai, J. Am. Chem. Soc. **126**, 11 602 (2004).
[7] J. Goldberger, D. J. Sirbuly, M. Law, and P. Yang, J. Phys. Chem. B **109**, 9 (2005).
[8] Y. Huang, X. F. Duan, Y. Cui, L. J. Lauhon, K. H. Kim, and C. M. Lieber, Science **294**, 1313 (2001).
[9] C. Fasth, A. Fuhrer, L. Samuelson, V. N. Golovach, and D. Loss, Phys. Rev. Lett. **98**, 266801 (2007).
[10] A. A. Grinberg, S. Luryi, M. R. Pinto, and N. L. Schryer, IEEE Trans. Electron Devices **36**, 1162 (1989).
[11] M. A. Lampert and P. Mark, *Charge Injection in Solids* (Academic Press, New York, 1970).
[12] R. W. Smith and A. Rose, Phys. Rev. **97**, 1531 (1955).
[13] F. Léonard and J. Tersoff, Phys. Rev. Lett. **83**, 5174 (1999).
[14] Y. Gu and L. J. Lauhon, Appl. Phys. Lett. **89**, 143102 (2006).
[15] A. D. Schriker, F. M. Davidson III, R. J. Wiacek, and B. A. Korgel, Nanotechnology **17**, 2681 (2006).
[16] S. D. Hersee, X. Sun, and X. Wang, Nano Lett. **6**, 1808 (2006).
[17] P. J. Hartlieb, R. F. Davis, and R. J. Nemanich, in *Nitride Semiconductors*, edited by P. Ruterana, M. Albrecht, and J. Neugebauer (Wiley-VCH, Weinheim, 2003), p. 491.
[18] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1980).
[19] The Green function depends on the boundary conditions on the electrodes, and the expression used here is appropriate for point contacts, with the compensating charge on the drain. Calculations for more complicated electrode geometries do not change the $I \propto V^2$ behavior, only the numerical prefactor. This is discussed in detail for thin films in Ref. [10].
[20] S. J. Pearton, F. Ren, A. P. Zhang, and K. P. Lee, Mater. Sci. Eng., R **30**, 55 (2000).
[21] This is supported by three-dimensional simulations of nanowires contacting electrodes of different geometries; see, for example, J. Hu, Y. Liu, C. Z. Ning, R. Dutton, and S.-M. Kang, Appl. Phys. Lett. **92**, 083503 (2008).
[22] To obtain this value of the mobility, we used $\zeta_0 = 1$. This is consistent with calculations in different thin film and bulk geometries [10], where ζ_0 is always close to 1.
[23] J. I. Pankove and T. D. Moustakas, *Gallium Nitride I* (Academic Press, San Diego, 1998).
[24] A. Achoyan, S. Petrosyan, W. Craig, H. E. Ruda, and A. Shik, J. Appl. Phys. **101**, 104308 (2007).