Electronic Conduction Mechanisms in Thin Wires and Nanoscale Contacts

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Scientific Thrust Area: Nanoscale Electronics and Mechanics

Proposal Title: Characterization and Integration of Vertical GaN Nanorods (S. D. Hersee)

Research Achievement:

We report on the electrical transport characteristics of undoped, *n*-doped, and *pn*-junction GaN nanowires grown by selective epitaxy on GaN/sapphire substrates. The selective epitaxy is realized by a combination of a patterned Si_3N_4 mask, which defines the position and diameter of the nanowires, and appropriate growth conditions, which lead to a near one-dimensional growth along the *c*-direction. 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 nominally undoped GaN nanorods and demonstrate that the nonlinear behavior originates instead from space-charge-limited current (Fig. 1). A new 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. We extract an electron mobility of ~400 cm^2 /V s and a free-carrier concentration of ~10^{15}–10^{16} cm^{-3}. By controlling the nanowire doping, we observe Ohmic transport for *n*-doped nanowires and rectifying characteristics for *pn*-junction, light-emitting diode, nanowires. For light-emitting diodes consisting of approximately 300 nanowire *pn*-homojunctions, operating in parallel (Fig. 2), the electroluminescence intensity grows superlinearly with current. For individual nanowire light-emitting diodes the forward and reverse leakage current is ~1 pA. The low leakage current of individual light-emitting nanowire diodes indicates that surface effects do not dominate the electrical behavior of these LEDs.

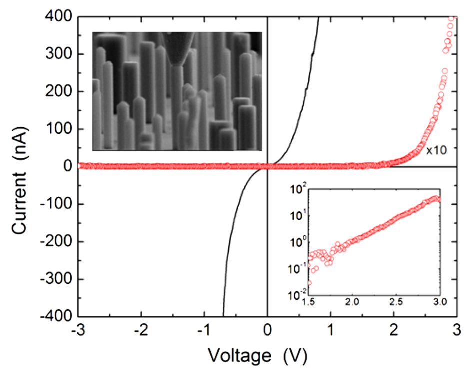

Fig. 1. Current-voltage characteristics before (symbols) and after (line) the tip is pressed into the nanowire. The bottom right inset shows the current before pressing on a log scale. The top left inset is a SEM image of the Au-coated W tip contacting a GaN nanowire.

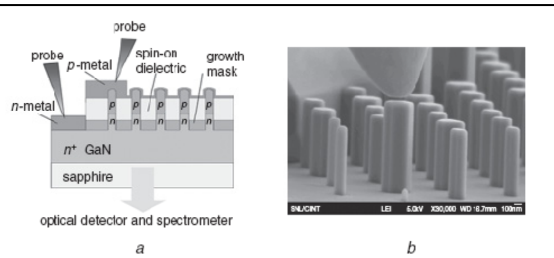

Fig. 2 (a) Schematic showing cross-section of nanowire array LED, and (b) SEM image showing electrical probing of individual pn-nanowire diode near edge of patterned growth template.

To study the electronic interface between Ge nanowires and the Au catalyst particles from which they are grown, we measured the transport by contacting the Au catalyst particles directly. We present electronic transport measurements of the individual Au-catalyst–Ge-nanowire interfaces that demonstrate the presence of a Schottky barrier (Fig. 3). Surprisingly, the small-bias conductance density increases with decreasing diameter. Theoretical calculations suggest that this effect arises because electron-hole recombination in the depletion region is the dominant charge transport mechanism, with a diameter dependence of both the depletion width and the electron-hole recombination time. The recombination time is dominated by surface contributions and is found to depend linearly on the nanowire diameter.

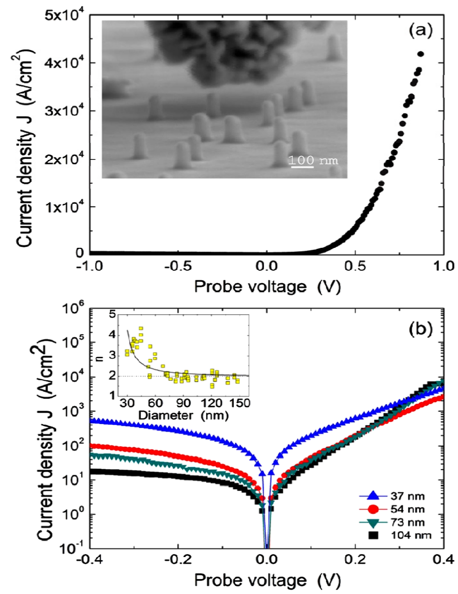

Fig. 3. (a) Current-voltage characteristics for a Ge nanowire of 54 nm diameter. The inset is a SEM image of the Au-coated W tip and several Ge nanowires. (b) Current-voltage curves on a log scale, for four nanowires of different diameters. The inset shows the ideality factor measured at forward bias as a function of nanowire diameter.

Future Work:

From the work on the Au/*n*-Ge NW/*n*-Ge substrate, above, we know that the Au/*n*-Ge NW interface has the Fermi level pinned near the valence band. Therefore, a *p*-type Ge nanowire should yield a relatively small Schottky barrier for hole injection at the Au contact, giving us a near-ohmic contact. We will probe the Au/*p*-Ge NW/*p*-Ge substrate configuration to test this. In addition, measuring the transport through a Au/*p*-Ge nanowire into an *n*-Ge substrate gives us the opportunity to study the transport properties of so-called "heterodimension" *pn*-junctions. That is, a *pn*-junction in which one side is a nanowire and the other side is the semi-infinite bulk substrate. This will enable us to measure how the transport scales as the dimensionality changes from ~1-d to ~3-d. Measuring the transport through Au dots directly on an *n*-Ge substrate should yield a barrier that is proportional to the Au dot diameter – opposite to the nanowire case. This should hold as long as the substrate is not too highly doped. A Ge substrate with a dopant concentration of 10^{17} cm^{-3} has a depletion width of about 100 nm. We expect to see a crossover from the nanocontact to the conventional contact regime by measuring Au dots with diameters from ~20 nm to ~150 nm.

Publications:

1. "Unusually Strong Space-Charge-Limited Current in Thin Wires", A. A. Talin, F. Léonard, B. S. Swartzentruber, X. Wang, and S. D. Hersee, Phys. Rev. Lett., **101**(7), 076802 (2008).
2. "GaN Nanowire Light Emitting Diodes Based on Templated and Scalable Nanowire Growth Process", S. D. Hersee, M. Fairchild, A. K. Rishinaramangalam, M. S. Ferdous, L. Zhang, P. M. Varangis, B. S. Swartzentruber, and A. A. Talin, Electronics Letters, **45**(1), 75 (2009).
3. "Diameter-Dependent Electronic Transport Properties of Au-Catalyst/Ge-Nanowire Schottky Diodes", F. Léonard, A. A. Talin, B. S. Swartzentruber, and S. T. Picraux, Phys. Rev. Lett., **102**(10), 106805 (2009).
4. "Electrical Transport in GaN Nanowires Grown by Selective Epitaxy", A. A. Talin, B. S. Swartzentruber, F. Léonard, X. Wang, and S. D. Hersee, J. Vac. Sci. Tech. B (in press).