Measuring Diode Characteristics of Individual Semiconductor Nanowires

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Motivation—Nanowires made from a variety of semiconducting materials are showing great promise as active elements in electronics and are being extensively characterized electrically. However, transport properties of nanoscale contacts can differ significantly from their bulk counterparts. Our goal is to understand the origin of diode characteristics at nanoscale metal-semiconductor contacts and the performance of engineered junction diodes in nanowires so that individual nanowires can be predictably and reliably integrated into unique device structures.

Accomplishment—We measured the electrical transport characteristics of two fundamentally different nanoscale diodes: the intrinsic diode formed at the metal-semiconductor interface of gold catalyst particles on Ge nanorods; and pn-diodes grown at the midpoint of GaN nanorods by switching growth conditions (doping) midway through the processing.

Using the nanomanipulator in the scanning electron microscope (SEM), we measured the diode characteristics of individual Ge nanorods as a function of diameter by contacting the gold-catalyst particle directly. A SEM image of the probe in contact with the gold particle is shown in Figure 1a. Figure 1b shows several current-voltage (I-V) spectra taken on rods with various diameters. By analyzing the slope of the forward-bias I-V curves, we find that the current is dominated by carrier recombination in the depletion region of the nanorod. Furthermore, we find that the small-bias conductance *increases* with smaller diameter, which is contrary to most models of nanowire transport. Through comparison with theoretical calculations we find that this increase in conduction is due to an increase in the depletion length with smaller diameter, which increases the total recombination current.

We also measured the diode characteristics of fabricated pn-junction diodes grown in GaN nanorods. Figure 2a shows an SEM image of the nanomanipulator probe over a GaN pn-diode nanorod. We measured the transport both through individual rods and through ensembles of ~300 rods top-contacted over a spin-on insulating layer. The light output of the ensemble LED system is shown in Figure 2b. The peak electroluminescent wavelength (not shown) was 372 nm at 30 mA, which slightly red-shifted at higher currents due to sample heating. The intrinsic diode character of the nanorods is very good, as evidenced by I-V measurements on the individual nanorods (Figure 2b inset), which exhibited very little (< 1pA) leakage current, in contrast to the rather high leakage of the ensembles. The comparison reveals that the top metallization layer on the p-side of some of the rods in the ensemble was most likely contacting the n-side leading to a parallel conductance channel.

Significance—The ability to measure transport through intrinsic diodes formed at metal-semiconductor contacts on individual nanorods and through engineered pn junctions in combination with a theoretical treatment at the nanoscale is critical to understand the transport mechanisms that prevail in nanostructures. These capabilities will enable the development of devices that integrate active nanostructures.

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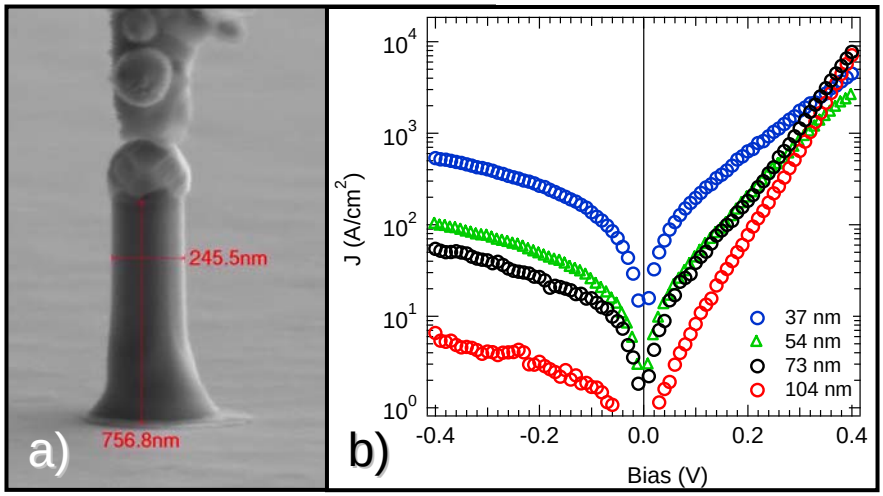

Figure 1. Conductivity of Ge nanorods. a) SEM image of tungsten probe contacting a gold catalyst particle. The nanorods grow from the bottom of the gold particle at high temperature as Ge from the vapor phase gets incorporated into the liquid gold drop and subsequently solidifies at the top of the Ge-crystal nanorod – so-called vapor-liquid-solid (VLS) growth. b) I-V spectra through Ge nanorods of various diameters showing diameter dependent electrical characteristics.

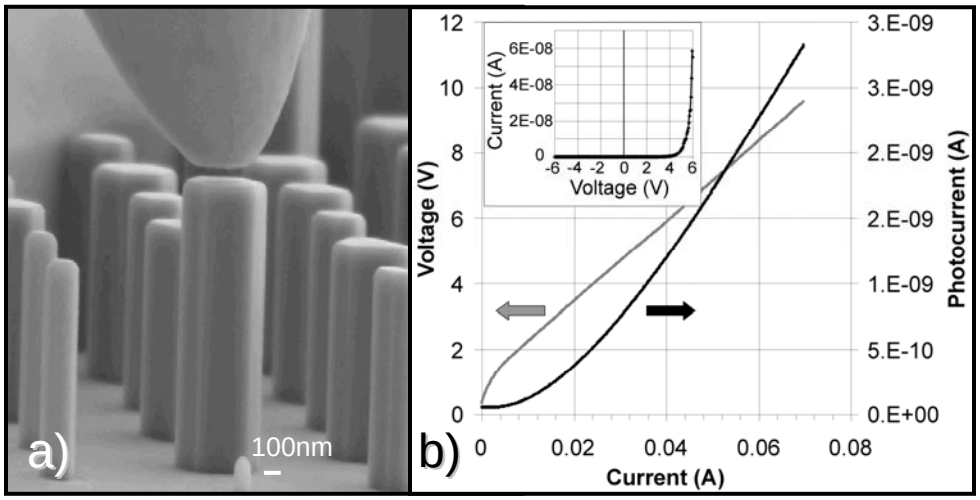

Figure 2. Electrical measurements of GaN pn-nanowire diodes. a) SEM image of a tungsten probe over a pn-nanowire diode. b) A typical L-I-V curve for a 300-nanowire LED. The electroluminescence intensity grows superlinearly over this current range. (inset: I-V curve for a single pn-nanowire diode.)