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Impact Ionization in Semiconducting Single Wall Carbon Nanotubes

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We investigated the high field (~10 V/μm) behavior of single-wall carbon nanotubes (SWNTs) near electrical breakdown. Both semiconducting and metallic nanotubes were analyzed, having lengths in the 1–2 μm and diameters in the 2–3.5 nm range. Metallic nanotubes exhibit 20–25 μA current saturation at high-voltage as typically expected, but semiconducting nanotubes of large diameter show an "up-kick" to ~50% higher currents just before breakdown. We suggest this increase is a result of avalanche impact ionization for the diameter and electric field range surveyed. The experimental data is also supported with simulations which include the additional impact ionization current. The results shed new light on the ultimate current-carrying capacity of semiconducting nanotubes, which are remarkably higher than 25 μA.

Nanotube devices were grown by CVD from Fe catalyst on SiO_2, back-gated, and exposed to air from above, as shown in Fig. 1. Metallic and semiconducting nanotubes were separated by their on-off currents, and typical I_D–V_{GS} curves are shown in Fig. 2a. Only devices having single-tube connections were considered. All metallic SWNTs display current saturation near 20–25 μA due to self-heating and strong electron-phonon scattering [1,2], up to breakdown as shown in Fig. 2b. However, some semiconducting nanotubes are seen to exhibit an increasing current "tail" just before breakdown, as shown in Fig. 3(a,b).

A similar behavior has been observed in p-n diodes and MOSFETs near breakdown [3,4]. As shown in Fig. 4a, high-fields carriers (here, holes) gain energy comparable to the band gap (E_G) and can relax by creating new electron-hole pairs (EHPs). These EHPs gain energy and create other electron-hole pairs, causing an "avalanche" increase in current. More recently Perebeinos has theoretically shown that impact excitation (IE) and impact ionization (II) can both occur in SWNTs [5]. While EHPs from IE are quasi-bound and do not contribute to net current, the EHPs from II are not bound and can be swept by the high-field, resulting in a current increase. The probability of impact ionization scales as $P_{II} \sim \exp(-E_G/q\lambda F)$ where λ is the inelastic mean free path and F is electric field [3-5]. Thus, II is more likely in small-gap nanotubes, which is supported by our observation of high-current "tails" in large diameter (2.2–3.5 nm) SWNTs and rarely in small diameter (1.5–2 nm) tubes. Nanotube diameter and energy gap are inversely proportional, $E_G \approx 0.84/d$ eV/nm [6]. In addition, band separations are much higher in metallic SWNTs [6], agreeing with the fact that we do not see a current up-kick in our metallic nanotube devices.

An increase in current may also be caused by multi-band transport initiated by band-to-band (BB) tunneling [7]. As shown in Fig. 4b, carriers could tunnel through the band separation (ΔE) into other subbands, opening new channels for transport. We estimate $P_{BB} \sim \exp(-\Delta E^2/q\hbar v_F F)$, where v_F is the nanotube Fermi velocity [8]. Fig. 4c plots the estimated BB and II probabilities for the nanotube diameters (2–3.5 nm), lengths (1–2 μm), and fields ($F \leq 10$ V/μm) in this study. II appears more likely than BB here, as our SWNTs break down by Joule heating before reaching a field high enough for band-to-band tunneling. Finally, we modified an existing nanotube model [1] to include the additional II current as an additional current path through a parallel resistor. We write $R_{II} = R\exp(E_G/q\lambda F)$, where λ is the electron-optical phonon (inelastic) mean free path, and R for single-band transport is computed consistently with the SWNT temperature. The results are shown in Fig. 3(c,d) in good agreement with the experimental data, with the only adjustable parameter being the inelastic mean free path, $\lambda = 25$ nm here.

In conclusion, we have experimentally observed and modeled a second-order transport mechanism near breakdown in large-diameter (small-gap) semiconducting SWNTs. We determine impact ionization to be the primary cause of the up-kick in current. Subsequent simulations taking impact ionization into account provide a theoretical match to our experimentally observed current tail.

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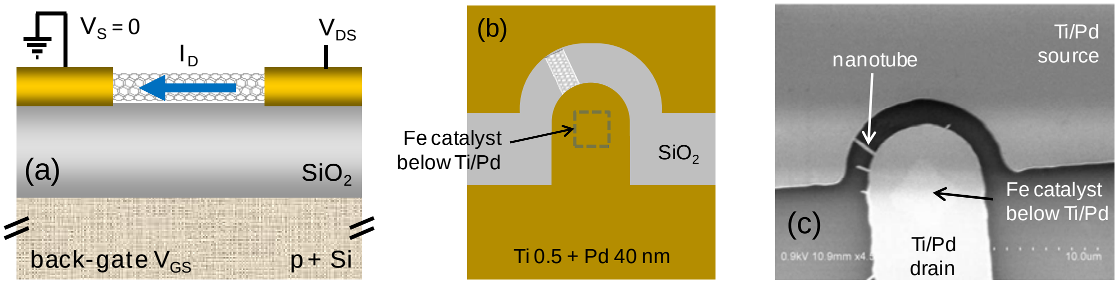

Fig. 1. (a) Side view schematic of typical nanotube device. Metal pads are Ti/Pd (0.5/40 nm). The nanotube is grown on top of ~300 nm of SiO_2, and exposed to air from above. The devices are back-gated with the highly doped (p++) Si wafer beneath. **(b)** Top view schematic and **(c)** top view SEM image of a typical device, with one active connection. Nanotubes were grown by CVD using Fe catalyst. Semi-circular electrodes are used for tighter control of nanotube device length.

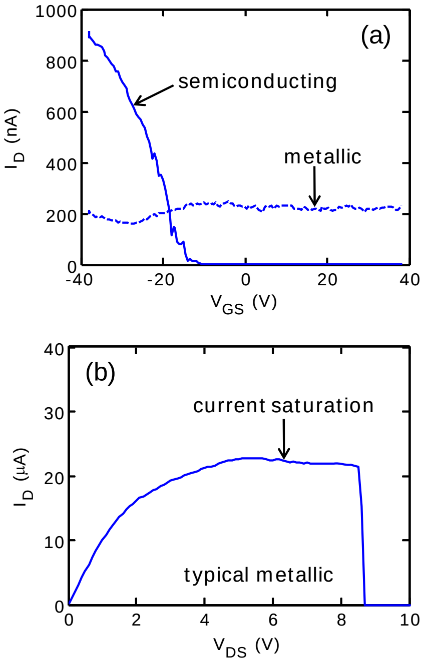

Fig. 2. (a) $I_D - V_{GS}$ curves for semiconducting and metallic nanotubes at $V_{DS} = 0.05$ V. **(b)** Typical $I_D - V_{DS}$ experimental curve for a metallic nanotube, $L \sim 1.5$ μm. All metallic nanotubes exhibited near-constant current saturation (20-25 μA), as expected, up to breakdown in air.

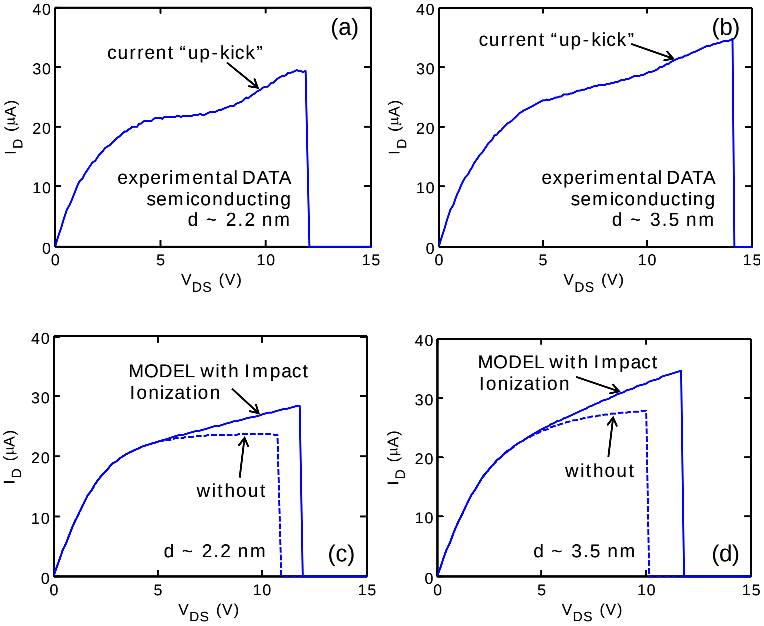

Fig. 3. (a,b) Experimental breakdown $I_D - V_{DS}$ curves for two semiconducting SWNTs with diameter 2.2 nm (a) and 3.5 nm (b). The length is $L \sim 1.3$ μm, and $V_{GS} = -40$ V in both cases. Note the current increase ("up-kick") near breakdown, and higher breakdown voltage (V_{BD}) vs. the metallic nanotube of comparable length (Fig. 2b). **(c,d)** Model including and excluding additional current from avalanche impact ionization, reproducing the behavior observed experimentally. Semiconducting nanotubes appear to break down at higher voltages because part of Joule energy is spent in creating electron-hole pairs.

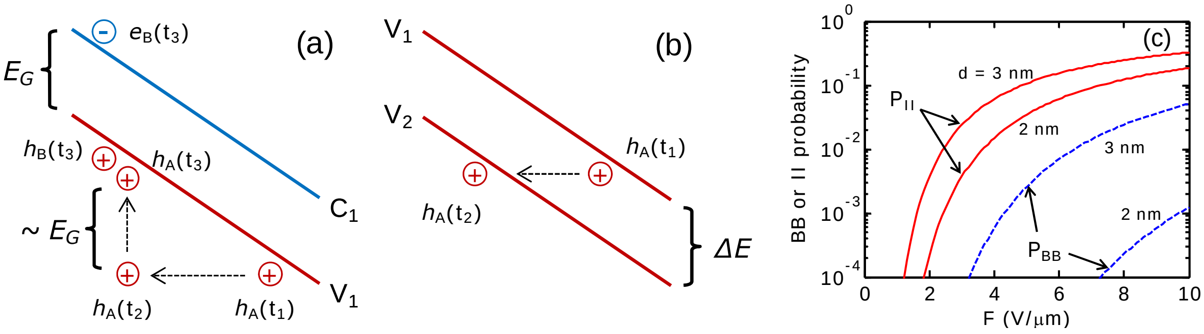

Fig. 4. (a) Schematic of hole-driven impact ionization (II), with highly energetic hole creating a new electron-hole pair. **(b)** Schematic of multi-band transport by hole (valence) band-to-band (BB) tunneling. **(c)** Estimate of impact ionization probability (solid red) and band-to-band tunneling (dashed blue) vs. electric field for 2–3 nm diameter nanotube, up to 10 V/μm electric field.