# Role of Electrical and Thermal Contact Resistance in the High-Bias Joule Breakdown of Single-Wall Carbon Nanotube Devices

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Several data sets of electrical breakdown *in air* of single-wall carbon nanotubes (SWNTs) on insulating substrates are collected and analyzed. These are data taken in different labs across the world on a wide range of SWNTs, spanning lengths 10 nm – 8 μm, diameters 0.8 – 3.2 nm and electrical contact resistance between 9 – 830 kΩ. A *universal* scaling of the Joule breakdown power with nanotube length is found, essentially independent of the insulating substrates used (here, $SiO_2$, $Si_3N_4$, $Al_2O_3$). The electrical *and* thermal resistance at the nanotube-electrode contacts regulate the breakdown behavior for short ($L < 0.6$ μm) SWNTs, whereas the breakdown power scales linearly with length for longer tubes.

Fig. 1 shows cross-sections of the typical two-terminal SWNT device considered here [1]. During *I-V* testing the voltage applied across the nanotube is raised until the power dissipated causes significant self-heating. The peak temperature occurs in the middle of the tube (Fig. 2b), and once this reaches the breakdown temperature the nanotube oxidizes (burns) irreversibly. This yields a sharp drop to zero in the *I-V* curve, and a physical "cut" in the nanotube itself (Figs. 2a and 2c). The breakdown temperature of SWNTs is approximately $T_{BD} \approx 600$ °C from thermogravimetric (TGA) analysis of bulk samples [2].

Published breakdown data from Refs. [1,3], [4] and [5] are collected and displayed in Figs. 3 and 4. These are labeled the "Stanford," "Caltech" and "Infineon" data sets, respectively. Only data for whom the complete *I-V* curve and the nanotube length are available are chosen. The electrical contact resistance ($R_C$) is estimated from the linear region of the *I-V* curve at low bias, and data sets for which this has significant bias dependence are eliminated. The aggregate data are shown both as breakdown voltage $V_{BD}$ vs. length (Fig. 3), and breakdown power $P_{BD}$ vs. length (Fig. 4). Figs. 3b and 4b present a "zoom-in" of the data for the shortest tubes. Note the effect of removing $R_C$ from the breakdown data, i.e. subtracting $IR_C$ and $I^2R_C$ from $V_{BD}$ and $P_{BD}$ respectively. This accounts for the amount of voltage dropped and power dissipated at the contacts. The trends of $V_{BD}$ and $P_{BD}$ scaling appear more clearly once these are removed.

Solving the heat conduction along the nanotube, the breakdown power for lengths longer than about 0.6 μm can be approximated $P_{BD} \approx I(V_{BD}-IR_C) = g(T_{BD}-T_0)L$ [1]. This scales linearly with the length of SWNTs, as the dashed trend line in Figs. 3 and 4. The slope of this line gives a thermal conductance from nanotube to substrate $g \approx 0.16 \pm 0.03$ W/K/m across the aggregate data surveyed. This is significantly lower than the thermal conductance owed to any of the insulating substrates here ($SiO_2$, $Si_3N_4$ or $Al_2O_3$), and indicates that the heat flow is limited by the nanotube-substrate interface [1]. At the other extreme, the simple formula above does not work for very short nanotubes (Figs. 3b and 4b). In this range, the solution of the heat equation is better approximated by $P_{BD} \approx (T_{BD}-T_0)/(L/8kA)$ which predicts a $1/L$ dependence of the breakdown power (dash-dot line in Fig 4b). However, this implies an infinitely large breakdown power as the length approaches zero, which is *not* observed experimentally. The key is to realize there is a finite thermal resistance ($R_T$) associated with the two nanotube-electrode contacts. The breakdown power becomes $P_{BD} \approx (T_{BD}-T_0)/(L/8kA+R_T/2)$ which is shown with the solid line in Fig. 4b, where $R_T = 1.2 \times 10^7$ K/W (consistent with typical metal-dielectric interface thermal resistance for the small contact area here). This gives a finite $P_{BD} \approx 0.1$ mW for the shortest tubes. The competing effect of heat sinking through the contacts vs. the substrate also yields a minimum in $P_{BD}$ for tubes with length around 0.6 μm ≈ $3L_H$, where $L_H = (kA/g)^{1/2} \approx 0.2$ μm is the thermal healing length along the SWNT [1].

In conclusion, this study analyzes *in-air* breakdown of single-wall nanotubes. The importance of the electrical and thermal nanotube-electrode resistance is shown, and simple scaling rules are given for breakdown power in the "short" and "long" length limits. The results are relevant for SWNT reliability, and the bottom-up approach to building SWNT circuits through controlled electrical breakdown [5].

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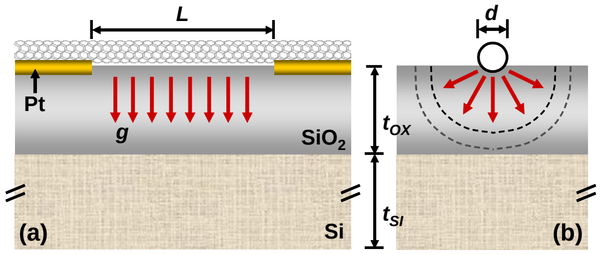


Fig. 1. (a) Longitudinal and (b) transverse cross-sections of the typical two-terminal single-wall nanotube (SWNT) device considered in this work. The arrows represent the direction of heat loss into the substrate ($g$ term). Other symbols used in this work are $T_0$ = ambient temperature, $k$ = nanotube thermal conductivity and $A$ = transverse area.

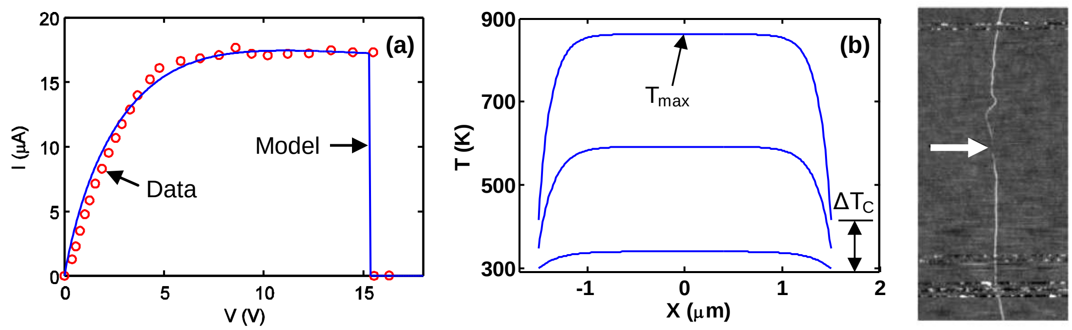


Fig. 2. (a) Typical *I-V* breakdown curve (here $L$=3 μm, $d$=2 nm). Data from [3] and model from [1]. (b) Calculated temperature profile at 3, 9 and 15 V bias (bottom to top). Note peak temperature at middle of tube and $\Delta T_C$ at the contacts. (c) AFM image of a similar tube after breakdown [1], showing the "cut" at the point of highest $T$.

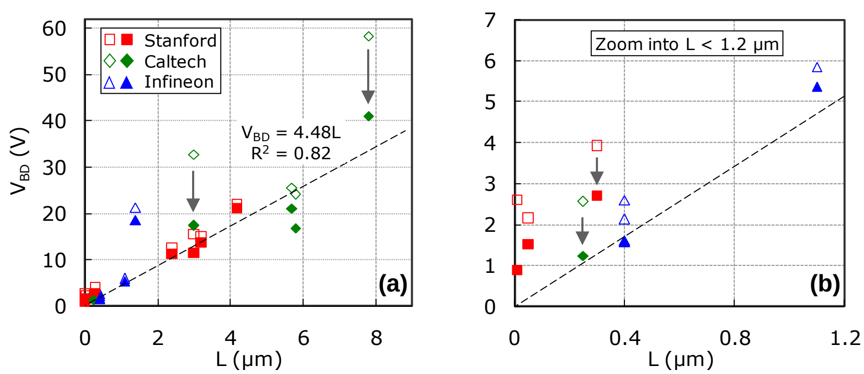


Fig. 3. (a) Breakdown voltage vs. SWNT length from the Stanford, Caltech and Infineon data sets. Empty symbols are before, and solid symbols are after removing the electrical contact resistance drop $IR_C$ (arrows highlight some of the changes). (b) Same data, zoomed into the shorter nanotube range.

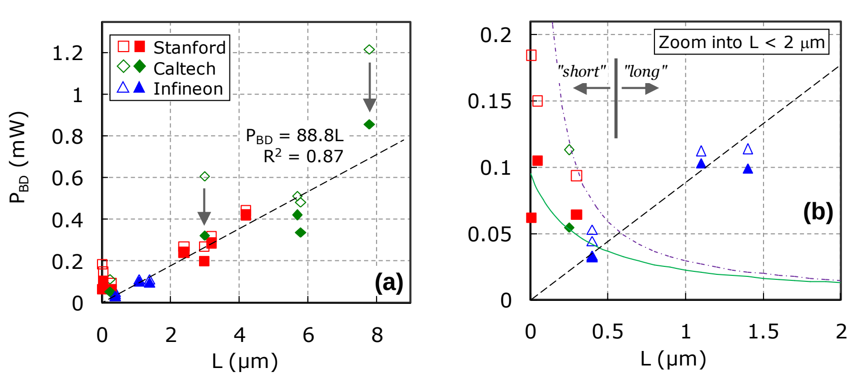


Fig. 4. (a) Breakdown power vs. SWNT length from the Stanford, Caltech and Infineon data sets. Empty symbols are before, and solid symbols are after removing the contact power dissipation $I^2R_C$ (arrows highlight some of the changes). (b) Short nanotube range, and simple model without (dash-dot line) and with (solid line) the nanotube-electrode thermal resistance $R_T$. The latter correctly reproduces the finite breakdown power at near-zero length.