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Optoelectronic Properties and Electromechanical Resonance Behavior in Individual Suspended Carbon Nanotube pn-Junctions and Devices

STEPHEN CRONIN, University of Southern California

In carbon nanotubes *pn*-junctions, we observe Zener tunneling behavior and photocurrent generation in quasi-metallic nanotubes [1], which have smaller band gaps than most known bulk semiconductors. These carbon nanotube-based devices deviate from conventional bulk semiconductor device behavior due to their low dimensional nature. We observe rectifying behavior based on Zener tunneling of ballistic carriers instead of ideal diode behavior, as limited by the diffusive transport of carriers. We observe substantial photocurrents at room temperature, suggesting that these quasi-metallic pn-devices may have a broader impact in optoelectronic devices. We also explore the role of weak clamping forces, typically assumed to be infinite, in the electromechanical resonance behavior of these suspended carbon nanotubes [2]. Due to these forces, we observe a hysteretic clamping and unclamping of the nanotube device that results in a discrete drop in the mechanical resonance frequency on the order of 5−20 MHz, when the temperature is cycled between 340 and 375 K. This instability in the resonant frequency results from the nanotube unpinning from the electrode/trench sidewall where it is bound weakly by van der Waals forces. Interestingly, this unpinning does not affect the Q-factor of the resonance, since the clamping is still governed by van der Waals forces above and below the unpinning. For a 1 μm device, the drop observed in resonance frequency corresponds to a change in nanotube length of approximately 50−65 nm. On the basis of these findings, we introduce a new model, which includes a finite tension around zero gate voltage due to van der Waals forces and shows better agreement with the experimental data than the perfect clamping model. From the gate dependence of the mechanical resonance frequency, we extract the van der Waals clamping force to be 1.8 pN. The mechanical resonance frequency exhibits a striking temperature dependence below 200 K attributed to a temperature-dependent slack arising from the competition between the van der Waals force and the thermal fluctuations in the suspended nanotube.

[1] Amer, M.R., S.-W. Chang, R. Dhall, J. Qiu and S. Cronin, "Zener Tunneling and Photocurrent Generation in Quasi-Metallic Carbon Nanotube pn-Devices" Nano Letters, 13, 5129 (2013).
[2] Mehmet Aykol, Bingya Hou, Rohan Dhall, Shun-Wen Chang, William Branham, Jing Qiu, and Stephen Cronin, "Clamping Instability and van der Waals Forces in Carbon Nanotube Mechanical Resonators" Nano Letters, 14, 2426-2430 (2014).
[3] Shun-Wen Chang, Kevin Bergemann, Rohan Dhall, Jeramy Zimmerman, Stephen Forrest, Stephen Cronin, "Non-ideal Diode Behavior and Band Gap Renormalization in Carbon Nanotube P-N Junctions" IEEE Transactions on Nanotechnology, 13, 41 (2014).