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High-Field Resistance Surge in a Carbon Nanotube Ballistic Resistor

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Abstract:

A newfangled paradigm through deployment of the nonequilibrium Arora's distribution function (NEADF) for resistance surge in a carbonnanotube (CNT) ballistic conductor is presented. The experimental nonlinear I-V characteristics, when voltage across the length of aresistor is higher than its critical value, defy ohmic and ballistic transmission through a CNT. The scattering-limited lowfield restance Rois shown not to be valid when voltage is higher than its critical value Vc=IsatRo where Isat is the saturation current. Both Ro and Vc areneeded to characterize a nano resistive channel with default infinite value of Vc for an ohmic resistor. The finite value of Vc necessitates differentiation of incremental signal resistance from the direct one, bringing to focus the surge with the applied voltage. Isat is shown to be limited by the intrinsic velocity which is the Fermi velocity in a metallic CNT.

Keywords: NEADF, High-Field Transport, Ballistic Transport, Resistance Surge, Intrinsic Velocity, Critical Voltage, Saturation Current, Nanowire, Carbon Nanotube

In its introspective presentation, Yang, Yan and Fardy1 took a critical look at the research progress within the nanowire (NW) community for the past decade. A carbon nanotube (CNT), just like a nanowire, has one-dimensional (1D) nanostructure except that energy-momentum relation is linear in a CNT and parabolic in a nanowire. Therefore, issues on the discovery of fundamentally new phenomena versus performance benchmarking are the same both in a NW and CNT. Consistent with findings of Yang et. al,1 both the bottom-up and top-down approaches have played important roles in advancing the fundamental understanding of NW and CNT. This communication elucidates fundamental understanding of nonohmic and ballistic conduction.

Purewal et. al2 present an experimental investigation on the scaling of resistance in individual single-walled CNT devices with channel lengths that vary 4 orders of magnitude on the same sample. The electron mean free path (mfp) is obtained from the linear scaling of resistance and its dependence on both the impurity scattering and acoustic phonon scattering determined. An unusually long mean free path at room temperature has been experimentally confirmed, consistent with the work of Riyadi et. al3, 4 who found exponential increase in resistance as arising from the degradation of mobility even when the mfp was enhanced due to ballistic injection from the contacts. The mfp is central to nonequilibrium Arora's distribution function (NEADF),5 where reduced electrochemical potential is linearly declining function of electric field, with as the unilateral chemical potential as stochastic velocity vectors become unidirectional. The reduced Fermi energy is connected to the Fermi energy separation from the conduction band edge in terms of thermal energy .

NEADF's transformation of equilibrium stochastic velocity vectors into a streamlined mode in extreme nonequilibrium leads tovelocity saturation in a towering electric field. In a metallic CNT, the randomly oriented velocity vectors in equilibrium are of uniform Fermi velocity as elucidated in detail in Ref. 6.6 The saturation current arises naturally from this saturation, where is the linear carrier concentration along the length of the tube consistent with experimentally observed5 . q is the electronic charge. The carrier statistics6 gives 67.5 meV which is larger than the thermal energy for all temperatures considered (T=4, 100, and 200 K), making statistics strongly degenerate applicable. The transition from ohmic to nonohmic saturated behavior initiates at the critical voltage for nondegenerate statistics with energy and for degenerate statistics with energy . The mfp extracted from is that gives mobility7 . The possibility of ballistic transport is miniscule given . The ballistic transport in 2D systems is extensivelydiscussed by Arora and co-workers,8, 9 where it is shown that the ballistic conduction degrades substantially the mobility in a 2D ballistic conductor with length smaller than the ballistic mfp. It may be tempting to apply the same formalism to 1D nanowire or nano CNT. However, the surge in resistance in a 1D

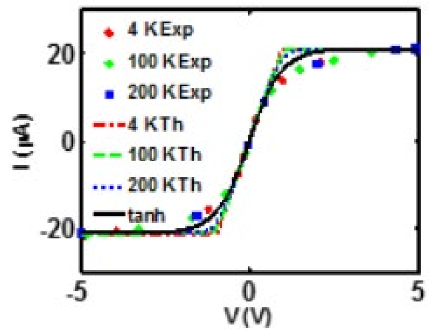

Fig. 1. I-V characteristics of a CNT of length 1 m. Th stands for theoretical curves derived from degenerate statistics. Tanh curves are display of Eq. (1).

The distinction between direct and differential mode of resistance is crucial when I-V relation is nonlinear. and are given by

R/Ro = (V/Vc) / tanh(V/Vc) = (2)

r/Ro = cosh2 (V/Vc) = (3)

This relationship is in direct contrast to with used by Yao et. al,5 which can be obtained from Eq. (2) by using approximation . of Yao et. al is the same as . As shown in Fig. 2, the rise in is exponential compared to linear rise in . The potential divider rule between channel and contacts will make the lower-length resistor more resistive.13 Hence great care is needed to ascertain the critical voltage of the contact and channel regions.

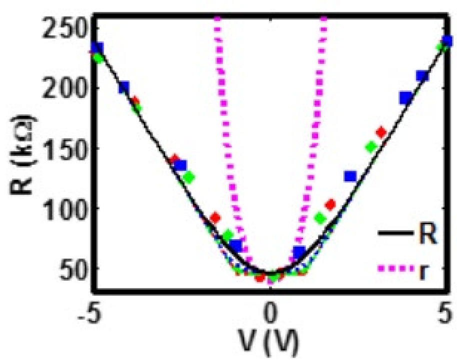

Fig. 2. R-V characteristics of a CNT of length 1 m. Markers and lines have same legend as in Fig. 1. The differential resistance r (Eq. 3) rises sharply than the direct resistance R (Eq. 2). The Letter presents a comprehensive paradigm supporting the experimental findings of highly quoted paper of Yao et. al.5 The following observations are made consistent with the experimental data:

1.Ohmic transport is valid so far the applied voltage across the length of the channel is below its critical value ( ).

2.The transition to nonlinear regime at the onset of critical electric field corresponding to energy gained in a mean free path is comparable to the thermal energy for nondegenerate statistics and Fermi energy for degenerate statistics.13, 14

3.Resistance surge effect in ballistic channels corroborate well with that observed by Yao et. al5 preceded by what was pointed out by Greenberg and Del Alamo15 in 1994. The surge in contact region will change the distribution of voltage between contacts and the channel. In this light, Yao et. al5 correctly conjectured that the measured resistance to be a combination of the resistance due to the contacts and the scattering-limited resistance of the CNT channel. The application of NEADF in CNT6 gives not only the comprehensive overview of metallic and semiconducting band structure of CNT, but also elucidates the rise of resistance due to the limit imposed on the drift velocity by the Fermi velocity.

4.Onset of quantum emission lowers the saturation velocity. However, if quantum is larger than the thermal energy, its effect on transport is negligible.14 It is important to employ Bose-Einstein statistics7 to phase-in the possible presence of acoustic phonon emissions in addition to optical phonons or for that matter photons as transitions are induced by transfer to higher quantum level induced by an electric field. The phonon emission, generalized to quantum emission with Bose-Einstein statistics, is effective in lowering the saturation velocity only if the energy of the quantum is higher than the thermal energy. Quantum emission does not affect the ohmic mobility or for that matter ohmic resistance.

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