Controlling the Conductance of Single-walled Carbon Nanotubes: Anderson Localization

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Carbon nanotubes are a good realization of one dimensional crystals where basic science and potential nanodevice applications merge. For the case of electronic circuits based on carbon nanotubes, the influence of disorder and defects is of fundamental relevance in the performance of the device (e.g. the density of defects can change the transport regime from ballistic regime to either weak or strong localization). Defects can be present in as-grown carbon nanotubes therefore, it is crucial to understand the properties of these defects in order to conquer their detrimental effects, but also because controlled defect introduction may be used to tune nanotube properties in a desired direction.

Observation of Anderson localisation at room temperature in irradiated carbon nanotubes

Quantum theory dictates that for a one dimensional conductor with defects weak localization effects emerge when the "phase coherence length" is larger than the localization length, L_0. For very long wires ($L>>>L_0$), the electron transport is a diffusive process controlled by localization, with the electrons hopping between neighbouring localized states. However, if L is not too large (for L about 3-10 L_0) and the inelastic interaction is weak, the wire resistance is controlled by the phase-coherent electron propagation, falling into the strong localization regime in which the resistance increases exponentially with the length of the wire. This regime is the one addressed here as in nanotubes the dephasing length can easily be longer than the localization length, which is the basic requirement for achieving Anderson localization.

Experimentally, a metallic AFM tip was used to measure the current vs. voltage characteristics of the nanotubes as a function of the distance between the metallic AFM tip, used as mobile electrode, and a fixed macroscopic gold electrode (see figure). By measuring the electrical resistance of the same metallic nanotube after successive irradiations we were able to map the resistance as a function of the nanotube length. Our data shows that the resistance increases exponentially with length at scales $L \geq 500$ nm (see inset in the figure). The length scale at which this exponential behavior is observed could be reduced substantially by irradiation with Ar^+ ions, indicating that it is caused by Anderson localization. Simulations demonstrated that mainly di-vacancies contributed to the exponential conductance drop induced by irradiation (di-vacancies appear in about 30-40% of the Ar^+ impacts).

We used a first-principles Local Orbital Density Functional method to calculate the relaxation around the defects and transport characteristics. The advantage of this approach is that it provides a means of calculating the conductance using standard Green-function techniques derived for tight-binding Hamiltonians but now with first-principles accuracy allowing the calculation of the electronic properties of very long nanotubes (up to several microns long) with an arbitrary distribution of defects immersed on them providing a quantitative comparison between theory and experiments. In the figure we show the calculated mean value of the room T resistance (as a result of an average over 15 random cases) as a function of the carbon nanotube length for different d's.

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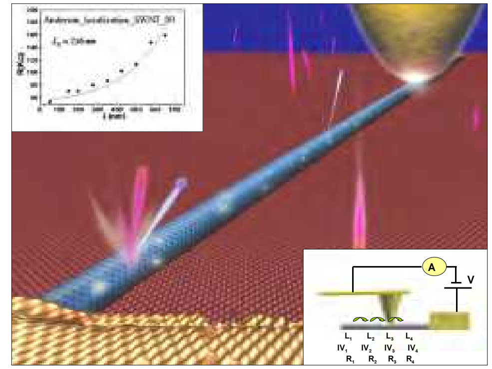

Scheme of the experimental set-up showing a gold covered AFM tip, the macroscopic gold electrode, the SWNT, the irradiation with Ar atoms and the used circuit.

The top inset shows one low-voltage-resistance vs. length, clearly exhibiting Anderson localisation.

The calculated resistance fits a universal curve once it is plotted in terms of the number of defects (N) instead of the total length (L). The inset shows that calculated room T localization length, L_0 exhibit two distinct regimes: i) for lower defect density (i.e., large values of *d*, *d*>5 nm), L_0 depends linearly with *d*, ii) For higher defect density (small values of *d*), L_0 saturates. In all our measurements the defect density is below 0.15% corresponding to case (i).

To highlight our findings, we have shown the extreme importance of defects (in particular di-vacancies) on the low-bias conducting properties of single-walled carbon nanotubes irradiated with an Ar^+ ion beam: only a 0.03% of di-vacancies produce an increment of three orders of magnitude in the resistance of a 400 nm carbon nanotube segment. Our theoretical calculations support this conclusion, indeed for a (10,10) carbon nanotube we have found: (i) the transition between the ballistic and the localization regimes appears for a small number of di-vacancies (about 3–5). (ii) For a higher number of defects the system shows localization, reducing the number of effective channels from two (ballistic) to one. (iii) At zero T, the nanotube conductance shows strong fluctuations. The net effect of a finite T is to wash out those strong fluctuations. We remark that, in spite of the disappearance of the fluctuations, the exponential behavior is still preserved at room T. Besides its fundamental relevance, this work opens new paths to tailor the electrical properties of future nanotube devices using ion irradiation. It also suggests the possibility of using these devices as radiation detectors and points out the limits of performance of carbon nanotubes in the presence of radiation. Whether interaction effects — that is, Tomanaga–Luttinger-liquid type of correlations — play a role has to be resolved by future investigation. ■

Temperature washed out the quantum fluctioatins in the conductance but not the localisation phenomena.

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