Electrical transport and optical properties of carbon nanotubes probed by in situ and cross-correlated experiments

M. Kobylko [a,1], M. Kociak [a], K. Suenaga [b], A. M. Bonnot [c], A. Débarre [d], L. Henrard [e], A. Kasumov [a], C. Colliex [a], Y. Sato [b], K. Urita [b], S. Iijima [b]

[a] Laboratoire de Physique des Solides (LPS), CNRS/UMR 8502, Université Paris-Sud, Bâtiment 510, F-91405 Orsay Cedex
[b] National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, 305-8565, Japan
[c] Laboratoire d'Etude des Propriétés Electroniques des Solides (LEPES), CNRS/UPR 11, BP166, F-38042 Grenoble Cedex 9
[d] Laboratoire Aimé Cotton, CNRS/UPR 3321, Bâtiment 505, F-91405 Orsay Cedex
[e] Laboratoire de Physique du Solide, University of Namur, Rue de Bruxelles 61, 5000 Namur, Belgium

Summary - Firstly, we will present the results of *ex situ* experiments supposed to probe the transport properties of individual carbon nanotubes which are in contradiction with elastic medium theory calculations. We will show that *in situ* experiments resolve this contradiction. Secondly, we will present the results of cross-correlated electron diffraction and Raman spectroscopy experiments. We will show that these experiments allow to conclude on electron-hole interactions in carbon nanotubes. Finally, we will briefly present recent development in *in situ* and nanomanipulation sample holders.

1. Introduction

It is widely known that the measurement of the electronic and structural properties of one and the same carbon nanotube (CNT) is a difficult experiment. However, the correlation between them is essential because it would provide experimental data to answer still open questions in fundamental and applied science, e.g. the influence of disorder on the transport properties of CNTs or the effect of electron-electron or electron-hole interactions.

2. Probing the electrical transport properties of the CNTs

We will first present a set of experiments where individual CNTs are dipped into mercury droplets. In principle, as described in a famous experiment [1], these experiments are supposed to give a precise idea of the transport properties of the CNTs (conductance quantification, ballisticity…). By using elastic medium theory, we will show that when CNTs with small radii or few walls are considered the probability that the CNT enters the drop of mercury is very small. This contradicts what can be measured in *ex situ* experiments, where appearance of conductance quantification can be observed (Fig.1).

We will demonstrate, based on *in situ* transport experiments in a TEM, that this contradiction can be overcome when considering the transport and mechanical properties of mercury itself [2].

3. Probing the optical properties of the CNTs

We will present a second set of experiments where the Raman spectra of individual single wall CNTs (SWCNTs) were recorded together with their parallel beam electron diffraction patterns (Fig.2). From the Raman spectra, the values of the Radial Breathing Mode (RBM) and the transition energies between the Van Hove singularities (VH) can be extracted. From the diffraction patterns, the values of the chiral indices are deduced. The comparison of the RBM values with the diameters deduced from the diffraction patterns will be discussed in the light of recent similar experiments [3]. More interestingly, we show that this cross-correlated technique may be a direct method of probing electron-hole interactions in SWCNTs and coupled CNTs.

4. *In situ* sample holders

Finally, we will briefly discuss recent development in *in situ* transport and nanomanipulation sample holders. The former is designed for transport measurements on *on chip* objects. The latter allows transport measurements and manipulation of nanoobjects placed on tips. The realization of the above-mentioned *in situ* transport measurements on individual carbon nanotubes dipped into mercury droplets requires a sample holder of this kind.

5. References

[1] S. Frank et al., Science 280 (1998) 1744
[2] M. Kobylko et al., in preparation
[3] J.C. Meyer et al., Phys. Rev. Lett. 95, (2005) 217401

[1] Corresponding author : kobylko@lps.u-psud.fr – Tel : +33 (0) 1 69 15 53 80

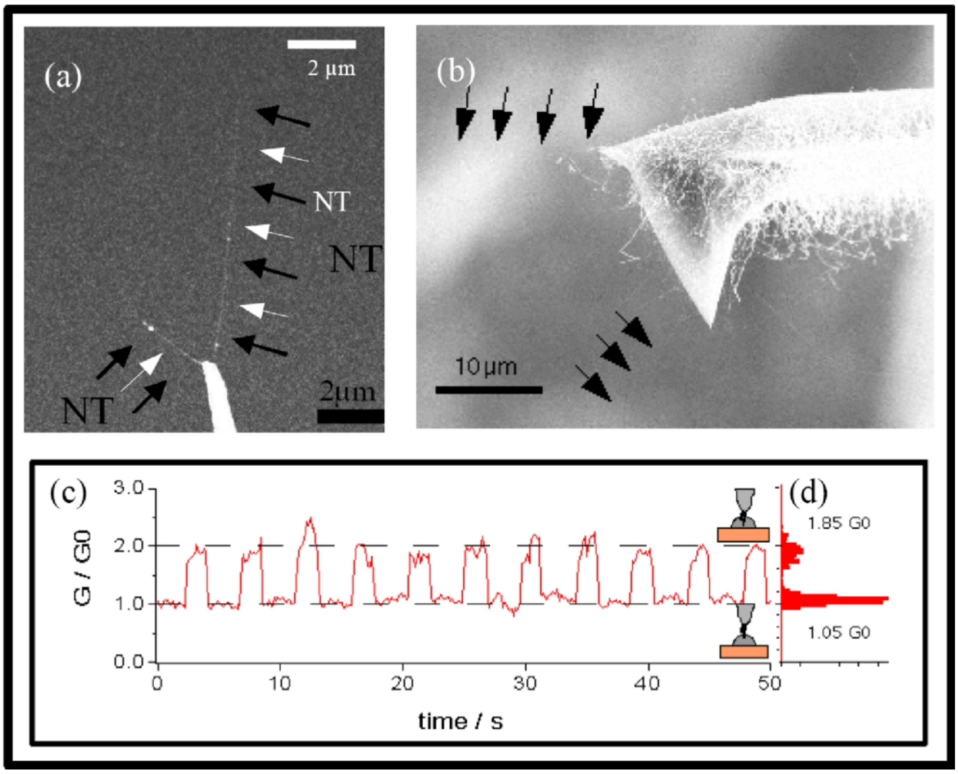

Figure 1 *– Adapted samples (metal tip (a) or metallized tip (b)) with CNTs on the apex (as indicated by the arrows). (c) Ex situ conductance measurement while the sample is repetitively approached and moved away from the Hg-surface. It shows conductance plateaux with no interim values. (d) Histogram of the conductance data showing two conductance values 1.05 G0 and 1.85 G0. The common interpretation would be to assume two ballistic CNTs on the apex, the first with a conductance of 1.05 G0 and the second with a conductance of 0.80 G0. However, in situ experiments can show that these results can be due to another effect.*

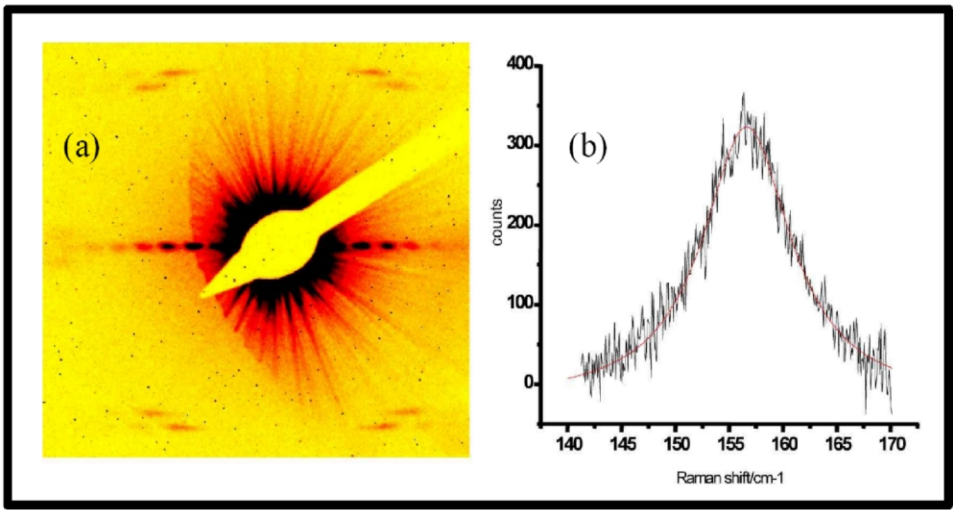

Figure 2 *– (a) Diffraction pattern and (b) Raman spectrum of the same SWCNT.*