MAGNETICALLY-INDUCED CARBON NANOTUBE FIELD-EFFECT TRANSITORS

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The exceptional low-dimensionality and symmetry of carbon nanotubes (CNT) are at the origin of their spectacular physical properties governed by quantum effects. Ajiki and Ando [1, 2] predicted that an axial magnetic feld would tune the band structure of a CNT between a metal and a semiconductor one, owing to the modulation of the Aharonov-Bohm (AB) phase of the electronic wavefunctions. This remarkable effect leads to a class of new physical phenomena. In this work we report on magnetotransport measurements of devices made in the configuration of a standard CNT field-effect transistor (CNFET) with a metallic or quasi-metallic CNT [3]. The sample geometry is shown in Fig. 1. An exponential decrease of the device off-state conductance is observed under high axial magnetic felds up to room temperature (Fig. 2). It is consistently described by the opening of an energy gap in the CNT electronic spectrum and modulation of the Schottky barriers at the CNT/metal interfaces. Remarkably, intrinsic properties of a quasi-metallic CNT, such as the helical symmetry, as well as the characteristics of the Schottky barriers formed at the metal-nanotube contacts, can be obtained by using temperature-dependent magnetoconductance measurements (Figs. 2-3).

References:

[1] Ajiki, H. & Ando, T. Electronic states of carbon nanotubes. J. Phys. Soc. Jpn. 62, 1255 (1993).
[2] Ajiki, H. & Ando, T. Aharonov-Bohm effect in carbon nanotubes. Physica B 201, 349 (1994).
[3] Fedorov, G.; Tselev, A.; Jiménez, D.; Latil, S.; Kalugin, N.G.; Barbara, P.; Smirnov, D & Roche, S. Magnetically-induced field-effect transistors. Submitted to Nano Letters.

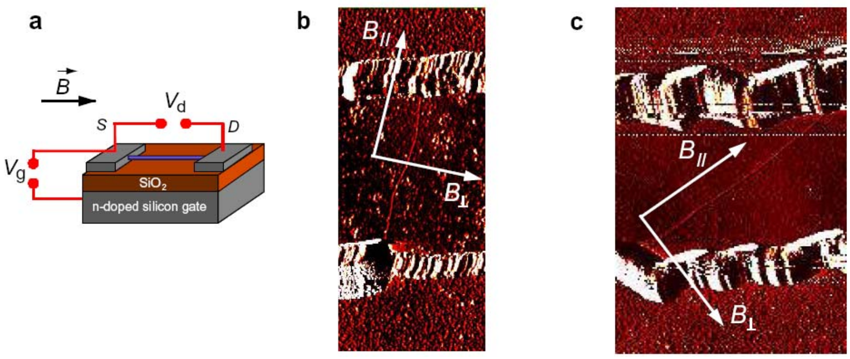

Figure 1. Schematic of a CNFET-type device. Single-walled nanotubes were grown on highly conductive n-doped Si substrates, capped with 400 nm of thermally grown SiO_2 and used as a back gate. Each nanotube was contacted with two 50 nm-thick Pd electrodes labelled S (source) and D (drain). b, c, AFM images of the CNT in samples 1 and 2 respectively. White arrows indicate direction of the magnetic field. Accuracy of the alignment was about ±3º. Length of the nanotubes between the contacts determined by FESEM was 2.8 μm (sample 1) and 5.1 μm (sample 2).

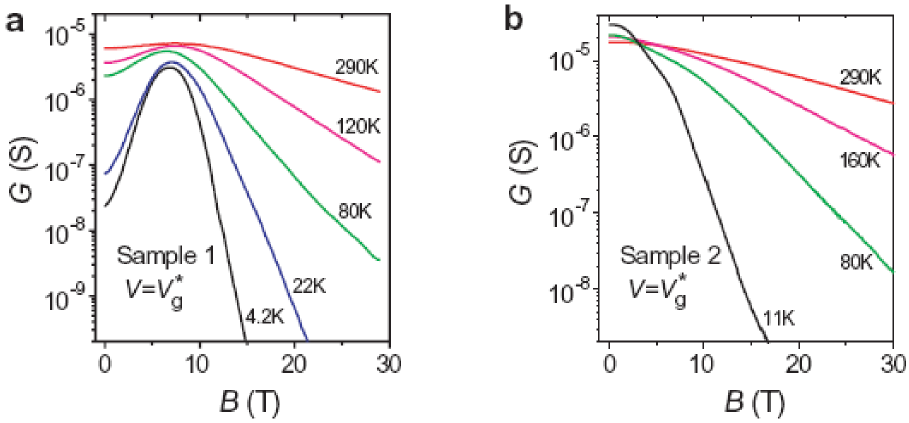

Figure 2. Off-state magnetoconductance of the CNT-based devices. a,b, Magnetoconductance curves G(B) of sample 1 and sample 2 measured at the ambipolar conduction point at different temperatures. At B > 10 T the G(B) curves of both samples appear as straight lines in the log-vs.-linear scale. A quasi-metallic CNT (sample 1), with a small band gap at zero magnetic field, closes its gap after the application of a magnetic field along the axial direction, hence evolving towards a metallic behavior. Further increase of the magnetic field opens the gap and the CNT behaves as a semiconductor. The magnetic field value that closes the gap (B_0) is a hallmark of the helical symmetry. By comparing the experimental B_0 value (6 T) with theoretical B_0 values (from tight-binding calculations) of a large family of helical symmetries, we have been able to identify sample 1 with a (19,10) CNT. Following a similar procedure, sample 2 has been identified with a (19,19) CNT.

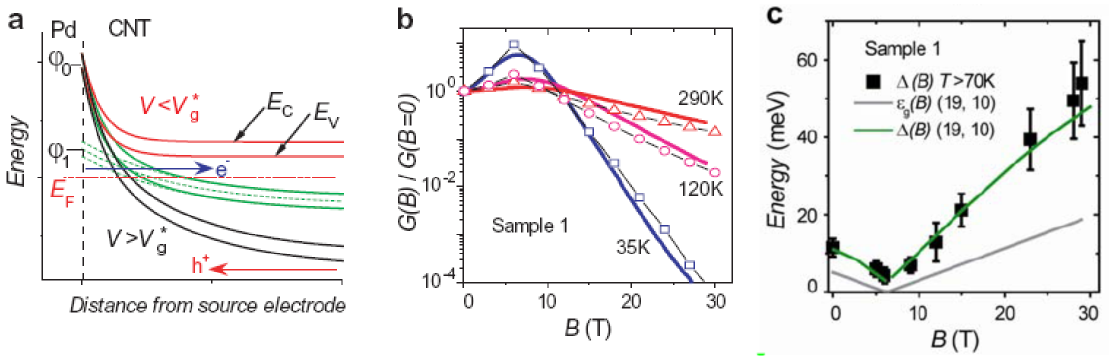

Figure 3. Magnetoconductance of CNT-based devices: intrinsic versus contact phenomena. a, Band profiles at different gate voltages. To describe the electric transport in our devices under magnetic fields, we consider a CNT energy band diagram with *B*-dependent Schottky barriers that form at the nanotube/metal interface. The height of the Schottky barrier for electrons equals $\varphi_0+\varepsilon_g/2$, where φ_0 is approximated as the difference in the work-functions of Pd and CNT (400 meV). We assume that the band profiles have two characteristic length scales along the CNT axis. The length scale of the band bending away from the electrodes, y_0, is determined by the electrostatic influence of the gate and is of the order of the SiO_2-layer thickness. Close to the electrodes, the midgap energy is shifted from φ_0 down to φ_1 on the short length scale $y_1 << y_0$, thus inducing the formation of a thin tunnelling barrier for electrons. The existence of such an additional short-scale interface barrier can be attributed to doping-induced effects. Both parameters φ_0 and y_1 depend on the chemical environment and/or the particular geometry of the electrodes. b, Conductance of sample 1 (solid lines), normalized to its value at zero magnetic field compared to simulations for the (19,10) CNT (hollow symbols). c, The effective activation energies Δ(B) were determined from the linear parts, T > 70 K, of the conductance Arrhenius plots for sample 1 (symbols) and (19,10) CNT (green line). Grey line: calculated dependence of the band gap of a (19,10) CNT on magnetic field.