Role of the Metal in Contacting Single-Walled Carbon Nanotubes

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Abstract. Electrodes have been defined by e-beam lithography on top of Carbon Nanotubes in order to reduce the contact resistance between metal and Nanotube. Individual Single-Walled Carbon Nanotubes or individual thin bundles were contacted with different metals (Au, AuPd, Al, and Co). The electrode material has been varied in order to investigate the Nanotube/metal - contact. The adhesion properties of the metals and the Carbon Nanotubes on the substrates turned out to be crucial.

INTRODUCTION

Electrodes have been deposited on top of Carbon Nanotubes (CNTs) by several groups in order to minimize the contact resistance $R_{contact}$ between CNT and metal. Theoretical studies [1, 2] predict that the metal should have a minor influence on the contact properties, including $R_{contact}$. In contrast, a strong effect is expected from the extraordinary fast decay of the Fermi-level states of the CNTs perpendicular (z-direction) to its symmetry axis: $\psi \propto \exp\{-[2m_e/\hbar^2(V - E_F) + k^2]^{1/2} \cdot z\}$, with potential in space V between CNT and metal, Fermi-level wave vector k and electron mass m_e [1].

In the present work, electrode arrays of different metals (Au, AuPd, Al and Co) have been defined by e-beam lithography on top of Single-Walled Carbon Nanotubes (SWNTs). Electronic transport was investigated in order to reveal the dependence of the contact properties on the metal.

EXPERIMENTAL

SWNTs are dispersed in aqueous surfactant solution and then purified by centrifugation [3]. As substrates Si wafers with a ~ 300 nm thick thermally grown oxide layer were used. To promote adsorption of the SWNTs, the wafer was treated with 3-(aminopropyl)-triethoxy-silane [3].

The electrode arrays were produced by covering the substrate by a two-layer poly(methyl methacrylate) resist system and using electron beam lithography to define the electrode arrays. Afterwards the desired metal was evaporated on the substrate and

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finally the lift-off process was performed during which undesired metal is removed by mechanical stress. Electrical transport was measured under helium atmosphere.

RESULTS AND DISCUSSION

Gold-Palladium (AuPd)

In Fig. 1 a SFM-image of a AuPd electrode array on top of SWNTs and thin SWNT bundles is shown. The current/voltage (I/V) characteristics at room temperature (RT) and 4.2 K of the contacted CNTs (electrode pair (I)/(II)) are depicted in Fig. 2a) and 2b), respectively.

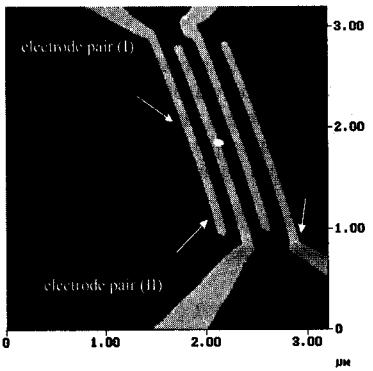

Figure 1. 15 nm AuPd on top of SWNTs. Arrows mark individual SWNTs and a thin bundle.

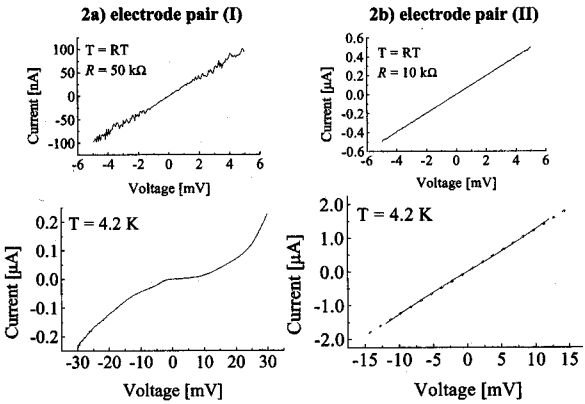

Figure 2. I/V-curves at RT and 4.2 K of pair (I) and (II). Dots are guide for the eye.

The contour of SWNTs and the SWNT bundle can be detected in the metal profile, indicating that their structural integrity is preserved during the evaporation process. Electrode pair (I) shows a RT resistance of about 50 kΩ > h/e^2. At 4.2 K step-like features are observed, characteristic of Coulomb-Blockade dominated transport. Pair (II) exhibits at RT only ≈ 10 kΩ < h/e^2, suggestive of ballistic transport. Compared to the I/V-curve of pair (I), no conductance fluctuations occur at higher voltages which are attributed to thermal instabilities of the contact region. At 4.2 K a power-law dependence $I \propto V^{\gamma}$ is observed ($\gamma \approx 0.9$) which could originate from, e.g., a non-constant density of states or Luttinger Liquid behaviour.

Gold (Au)

Fig. 3 shows a SFM-image of a Au electrode array contacting thin SWNT bundles. The RT I/V-characteristics are displayed in Fig. 4. Similar to AuPd, resistances smaller than h/e^2 are observed. However, the measured data yield $R^{(I)} \approx R^{(II)}$, $R^{(I)} + R^{(II)} \geq R^{(III)}$ and $\{R^{(I)}, R^{(II)}\} < R^{(III)}$. This indicates that ballistic transport is impeded along the SWNT bundle. Good contacts, even though not biased (as electrode Φ when measuring pair (III)), provide a finite probability for the travelling electron to propagate into. Therefore they represent a scattering centre perturbing ballistic transport.

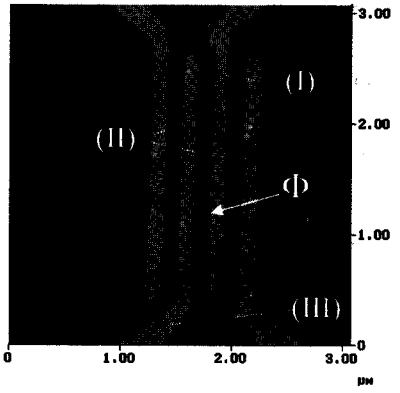

Figure 3. 20 nm Au on top of SWNTs.

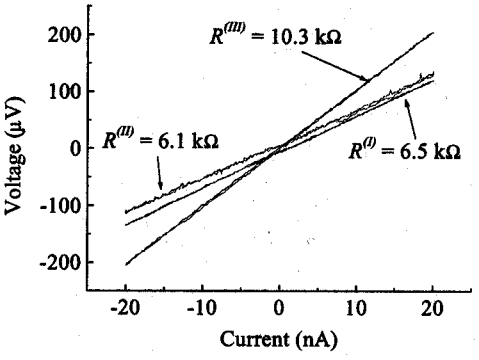

Figure 4. I/V-curves of different electrode pairs at RT.

Occasionally, partially detached electrode lines are observed after lift-off, indicating that the adhesion of SWNTs to the surface-treated SiO_2 is of similar strength or stronger than the adhesion of the Au to this surfaces. It is noteworthy, that similar adhesion properties are observed for AuPd electrodes.

Aluminium (Al)

Despite the removal of residual H_2O by Ar-ion sputtering before Al evaporation at $p < 10^{-8}$ mbar and sample storage under Ar-atmosphere, no measurable current ($I > 0.5$ pA) could be observed for up to a few volts in any of the prepared samples. Interestingly, difficulties in contacting have been reported also for Al evaporated on Langmuir-Blodgett films consisting of aromatic molecules [4]. Moreover, the observed Al adhesion to the surface-treated substrate was much weaker compared to Au and AuPd.

Cobalt (Co)

Fig. 5 shows a SFM-image of a Co-electrode array. The resistance of both pairs (3 /16) and (3/4) exceeds 10 GΩ, whereas pair (15/16) shows ≈ 130 kΩ (corresponding to ~ 390 kΩ per bundle, as also found for other samples). The RT I/V-curve of pair (15/16) is depicted in Fig. 6a). The adhesion of Co to the substrate turned out to be weaker compared to Au and AuPd, but stronger than for Al.

Magnetoresistance of pair (15/16) (Fig. 6b)) changes significantly depending on the orientation of the magnetic field ***B*** relative to the substrate. This change could be due to weak-localization effects within the contacted SWNT bundles and or individual SWNTs. Aharanov-Bohm and weak-localization effects involving the electrodes are excluded, since the tunneling barriers between metal and SWNT are expected to randomize the phase of the electron wave-function. Further, no significant hysteresis could be observed in the up and down sweep of ***B***, which would be characteristic of coherent spin transport [5].

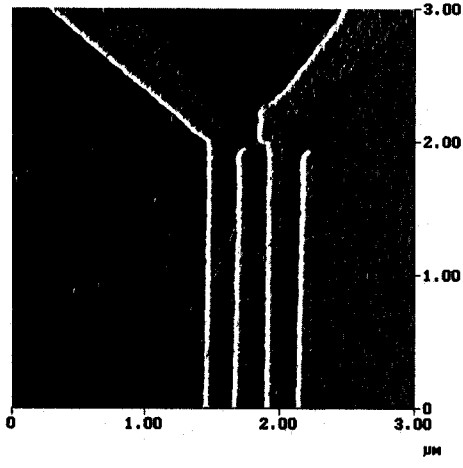

Figure 5. SFM amplitude image of Co (50 nm) on top of SWNTs.

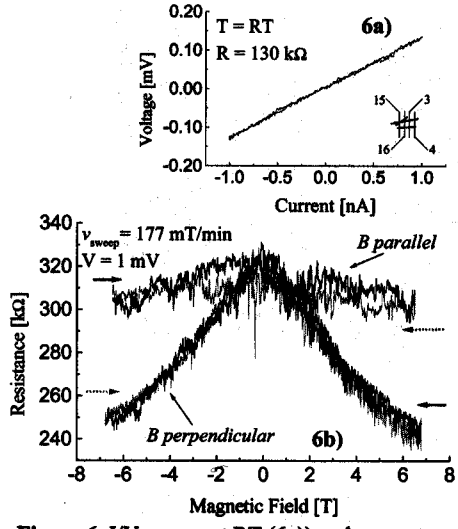

Figure 6. I/V-curves at RT (6a)) and magneto-resistance at 4.2 K (6b)) of electrode pair (15/16). Arrows mark the sweep direction.

CONCLUSION

In contrast to SWNTs on top of electrodes [6], the resistance could be reduced below h/e^2 for Au and AuPd on top of tubes. As a consequence, non-biased electrodes may act as scattering centre and impede ballistic transport. The observed adhesion problems may lead to a mechanical increase of the SWNT/metal distance, $d_{SWNT/metal}$, during the lift-off process. Since the operator V of the potential in space V [1] is expected to be proportional to $d_{SWNT/metal}$, the transmission probability, which is proportional to $|< \psi | V | \psi_{metal} >|^2$, of an electron decreases, and hence $R_{contact}$ increases. For the larger resistances found for Co compared to Au and AuPd, this is a plausible explanation. The results obtained with Al demonstrate that metals can have a significant influence on the contact properties and the local electronic structure of SWNTs.

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