Carbon Nanotubes in the Coulomb-Blockade Regime connected to Superconducting Leads

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Abstract. Single-Walled Carbon Nanotubes are connected to superconducting electrodes with a contact resistance considerably higher than the quantum resistance of $h/2e^2$. For the charge transport this excludes proximity effects and/or Andreev reflections but single-charging effects should be observable. The output characteristics of these devices are different from those observed in Single-Walled Carbon Nanotubes contacted by noble metal leads within the Coulomb-Blockade regime.

INTRODUCTION

The Coulomb-Blockade (CB) was one of the first observed and investigated phenomena in charge transport in Single-Walled Carbon Nanotubes (SWNTs) [2]. The charging of a SWNT by a single electron was interpreted in the frame of the theory of quantum dots (QDs) [1],[2]. During the studies, the excitation spectrum of the SWNTs was found to be much more complicated than that in inorganic, e.g. GaAs, quantum dots. The strong 1-dimensional character of the SWNTs [3] was assumed to be the reason for these observations. However, this discrepancy is not yet fully understood.
Here, SWNTs have been connected to superconducting leads with low transmission coefficients, a necessary condition to work in the Coulomb-Blockade regime and to suppress Andreev-reflection and/or the proximity-effect. The properties of the quasi-particles in the superconductor could be used to investigate the excitation-spectrum of the SWNT electron-system at low temperatures.

EXPERIMENTAL

SWNT raw material was first purified via centrifugation and then dispersed [4] on a thermally grown SiO_2-layer (about 100 nm thick) on a doped Si-Wafer which can be used as a backgate. Rhenium (Re) was chosen as superconducting material. If the substrate is cooled during evaporation, thin Re-films of about 50 nm thickness have a critical temperature T_c of approximately 6.7 K (in bulk: $T_c \approx 1.2$ K). In order to contact SWNTs, electron-beam lithography (EBL) was used, similar to Ref. [4]. The Re was evaporated on top of the SWNTs to avoid bending defects. Fig. 1 shows a thin SWCNT-bundle (≤ 3nm in height) connected to Re-electrodes. The room temperature resistances of the various contact pairs were $R_{5/7}$ = 4.7MΩ, $R_{7/18}$ = 5.5MΩ and

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$R_{5/18}$ = 1.7 MΩ. One continuous electrode line was generated, too, in order to proof that the lines, which are strongly reduced in their geometric dimensions, are still superconducting. The temperature dependence on the resistance is shown in the inset of Fig 1. Clearly at 6.1K a drop in the resistance is found indicating the superconducting transition.

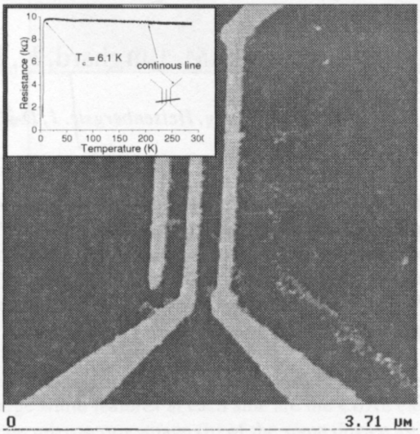

FIGURE 1. Re-electrode structure connecting a thin SWNT bundle. The inner electrode-lines are 2 µm long, about 23 nm thick and 120 nm in width. The lines are separated by about 200 nm. Re is more ductile than Au or AuPd. Therefore the Lift-Off process is not clean which is the reason for the left-overs of Re on the electrode lines. Inset: superconducting transition of the Re-electrodes.

RESULTS

In order to characterize the transport properties, the sample was cooled down to 25 mK in a He^3-dilution refrigerator. In this case the superconducting gap, which depends on the temperature according to the BCS theory close to T_c as $\Delta(T)=1.75\Delta_0(1-T/T_c)^{1/2}$ with $\Delta_0 \equiv \Delta(T=0)$, should be almost fully developed. The I/V-characteristics of the device are shown in Fig. 2.

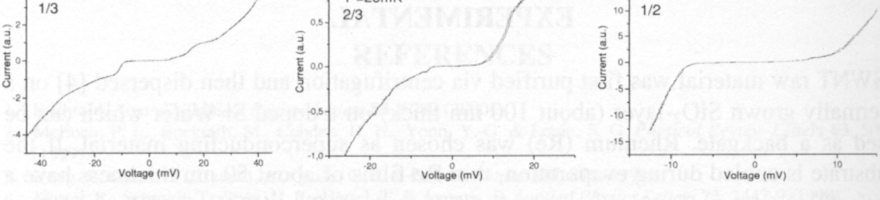

FIGURE 2. I/V-characteristics at 25mK. No peaks are apparent at the onset of the Coulomb-Blockade steps.

As expected from the high contact resistances, steps are apparent indicating that the charge transport is dominated by CB. In contrast to quasi-0-dimensional QD systems no peaks at the onset of the steps are observable [5],[6]. These directly reflect the high density of states of the quasi-particles at the edge of the superconducting gap and manifest themselves in the theoretical expression of the tunneling rate Γ for a quasi-particle from a lead into the QD [7]

$$\Gamma \sim \int D_{QP}(E)\cdot D_{QD}(E)\cdot f(E-\mu_{QP})\cdot(1-f(E-\mu_{QD}))dE$$

where $D_{QP}(E) \sim |E|/(E^2-\Delta^2)^{1/2}$ and $D_{QD}(E)$ are the density of states of the quasi-particles and of the single-electrons in the QD, respectively. The corresponding chemical potentials are μ_{QP} and μ_{QD} and f(E) is the Fermi distribution. Obviously, as E tends to Δ, $D_{QP}(E)$ and therefore Γ becomes infinite. Note, that this expression for Γ is only valid if a single quasi-particle tunnels into a single-particle state of the QD.
Since the transport through a SWNT in the Coulomb-Blockade regime was interpreted and understood in the frame of the quantum-dot theory, the observed I/V-characteristic in Fig. 2 are unexpected.
In the measurement discussed above, the back-gate (V_G) was at zero voltage. In contrast to the curves in Fig. 2 shallow peaks at the inset of the Coulomb-Blockade steps are apparent if V_G is varied and at higher source-drain voltage (V_{SD}) the peaks seem to vanish. Exemplary, in Fig. 3 the I/V-curves of the contact pair (2/3) are depicted in the range from +3V to -3V back-gate voltage.

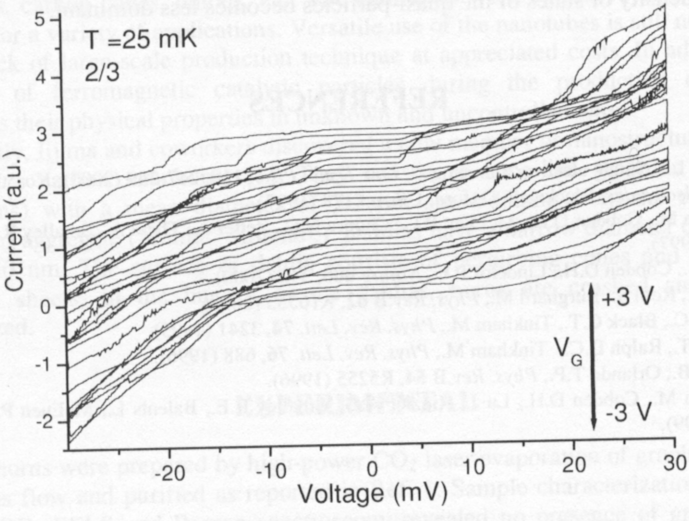

FIGURE 3. I/V-characteristics (shifted for clarity) at 25mK at different back-gate voltages. In contrast to the curves in Fig. 2 shallow peaks are apparent. The occurrence of the peaks seems to depend on both, V_G and V_{SD}.

CONCLUSION

In the present study SWNTs have been contacted with superconducting Re-electrodes in the Coulomb-Blockade regime. In contrast to the experimental observations on inorganic QDs [5], peaks at step-onset of the Coulomb-Blockade staircase appear only weakly and depend on both, V_G and V_{SD}.

At smaller V_{SD} the shallow peaks are apparent but not at every V_G. Since V_G shifts the spectrum of electronic states of the SWNT through the applied V_{SD}-window, the absence of the peaks indicates the presence of processes impeding the tunneling of the quasi-particles in the SWNT. Experimental observations [8] showed that the electron system in SWNTs is correlated at low temperatures and behaves as a Luttinger Liquid. From this point of view a quasi-particle from the superconductor would have to tunnel in a collective state and create a new one, i.e. giving rise to a collective excitations. Alternatively, the quasi-particle could tunnel into an excited single-particle state of the correlated electron system. Both processes would impede the tunneling from superconductor to SWNT and could suppress the peak at the onset of each CB step which is originating from the divergence of the quasi-particle density of states $D_{QP}(E) \sim |E|/(E^2-\Delta^2)^{1/2}$ at $E = \Delta$.

At higher V_{SD} the peaks seem to vanish independent of V_G. Within these relatively large V_{SD} windows a multitude of conducting channels is contributing to the charge transport through the device. The rise in the difference in the chemical potentials bears an increased tunneling in which quasi-particle states are involved with considerably lower density of states than at the edge of the superconducting gap Δ. Therefore the divergent density of states of the quasi-particles becomes less dominant.

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