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Controlling supercurrents using single-walled carbon nanotube weak links

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Abstract. We have investigated proximity-induced supercurrents in single-walled carbon nanotubes. Phase diffusion is found to be present in the maximum measured supercurrent of 4.8 nA, which results in a minimum of 100Ω zero bias resistance in superconducting state. We also observe that the supercurrent is very sensitive to the measurement bandwidth and large phase fluctuations can even destroy the supercurrents. Our results shed light on the methods of how to improve the performance of high frequency superconducting single-walled nanotube devices.

1. Introduction

Single-walled carbon nanotubes (SWNTs) are considered as promising candidates for highly sensitive electrometers due to their small intrinsic capacitance C and large charging energy E_C. Single-electron transistors (SETs) [1, 2, 3] and radio-frequency single-electron transistors (rf-SETs) [4] made of SWNTs have already been reported. Rf-SETs have the advantage of high sensitivity by overcoming the low frequency $1/f$ noise with radio-frequency working band, while normal SETs are limited in a few kHz bandwidth due to their large resistance and a lead capacitance of $\sim$ 1nF. However, a matching tank-circuit is always needed for rf-SETs to convert the device resistance down to 50 Ohms, which indicates that good matching can be obtained only over a narrow frequency range of $f_0 \pm f_0/Q$, where $f_0 = 1/(2\pi\sqrt{LC})$ is the resonant frequency of the LC circuit, and quality factor $Q = \sqrt{L/C}/Z_0$ under perfect matching.

Another way to avoid the problem of large device resistance and obtain a high operating bandwidth is to connect the SWNT to superconducting electrodes. Gate-controlled, proximity-induced supercurrent can pass through SWNTs [5, 6, 7, 8] as well as multi-walled carbon nanotubes [9], which results in very small zero-bias resistance together with clear gate modulation. Although Josephson junction weak link theories and multiple Andreev reflections (MARs) work very well in explaining such a system, these theories are not very informative concerning actual microwave circuit design.

Here we report a study of gate-tunable proximity-induced supercurrents in an individual SWNT. We have measured the temperature dependence of the supercurrent, and achieved a minimum of 100 Ω zero bias resistance which is small enough for microwave usage. We have also investigated the reduction of supercurrents when the operating bandwidth is increased, i.e., the filtering scheme is changed. Good agreement is found in the comparison between observed supercurrents and the theory.

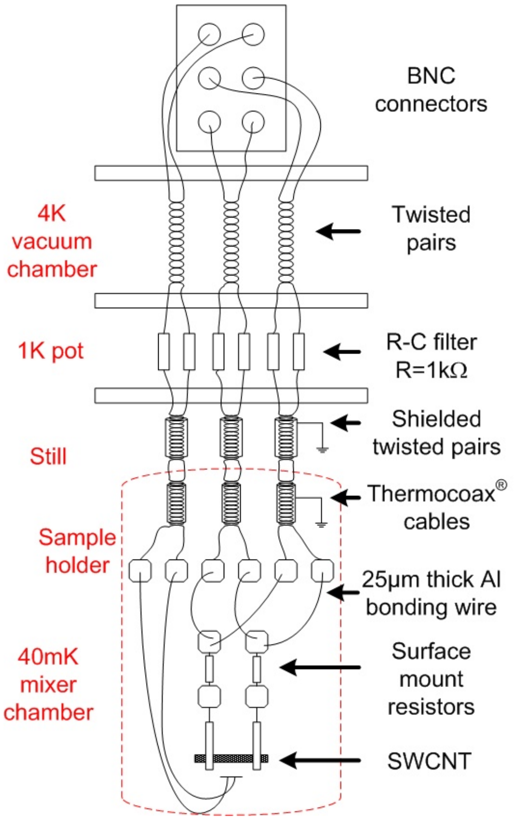

Figure 1. (Color online) Measurement scheme of the SWNT sample.

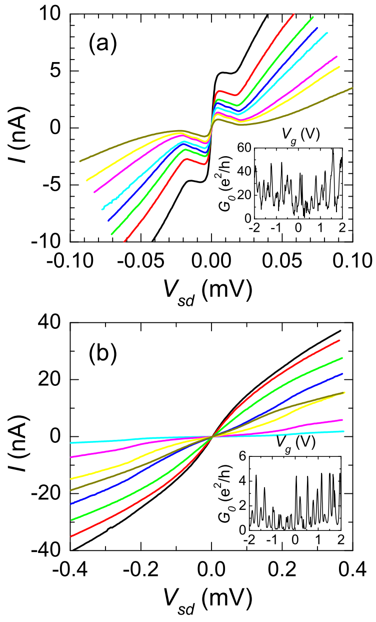

Figure 2. (Color online) (a) IV-curves measured on our SWNT device in the Fabry-Pérot regime using a measurement band width of BW = 100 kHz and voltage bias at $T = 65$ mK. (b) IV-curves measured on the same sample with BW = 100 MHz at $T = 60$ mK. Insets of the two figures present the superconducting state zero bias conductance G_0 versus gate voltage V_g, respectively.

2. Sample fabrication and experimental setup

Our nanotube samples were made using surface CVD growth with Fe catalyst directly on oxidized, heavily-doped SiO_2/Si wafer. The electrically conducting substrate works as a back gate, separated from the sample by 150 nm of SiO_2. A sample with $L = 0.7$ μm length and $\phi = 2$ nm diameter was located via the atomic force microscope and the contacts on the SWNT were made using standard e-beam overlay lithography. For the contacts, 10 nm of Ti was first evaporated, followed by 70 nm of Al, in order to facilitate proximity-induced superconductivity in Ti. Last, 5 nm of Ti was deposited to prevent the Al layer from oxidation. The width of the two contacts was 200 nm and the separation between them was 0.3 μm.

The samples were mounted inside a tight copper enclosure on our "dipstick" dilution refrigerator (Nanoway PDR50). The measurement leads were filtered using an RC filter with 100 kHz frequency band at 1 K, followed by twisted pairs with tight, grounded electrical shields for filtering with a bandwidth of 100MHz between the still and the mixing chamber, while the final section was provided by a 0.7-m long Thermocoax cable on the sample holder. The electrical environment was defined by 2 × 22 Ohm surface mount resistors that were positioned as close to the sample chip as possible. Four-lead measurement scheme was employed down to the bonding pads on the sample-holder, in order to avoid the impedance of the filters and Thermocoax cables.

In the measurements, differential conductance $G_d = dI/dV$ was recorded using standard lock-in techniques, and voltage bias was imposed via a room-temperature voltage divider. The normal state data were obtained by applying a magnetic field of $B \sim 70$ mT perpendicular to the nanotube.

3. Results and discussions

In the first cool down to 4K, the sample showed a strongly asymmetric Fabry-Pérot pattern with one low-transmission (spin-degenerate) channel and one with high transmission; the zero-bias conductance was limited to $2e^2/h$ as a consequence [10]. From the IV curves at $T = 60 - 65$ mK we observed a clear supercurrent (Fig. 2(a)) which was modulated by the gate voltage, and reached a maximum of 4.8 nA. The measured zero bias resistance R_0 of our SWNT samples as a function of temperature is shown in Fig. 3(a). As we can see, the resistance of the device decreases together with temperature, and gets below 100 Ω at the lowest temperature, and thus these devices do hold promise for high frequency operation without any matching circuits. According to the phase diffusion theory, the zero bias resistance should display T^2 temperature dependence, which is valid in our case at relatively high temperature, but some deviation occurs below 100 mK.

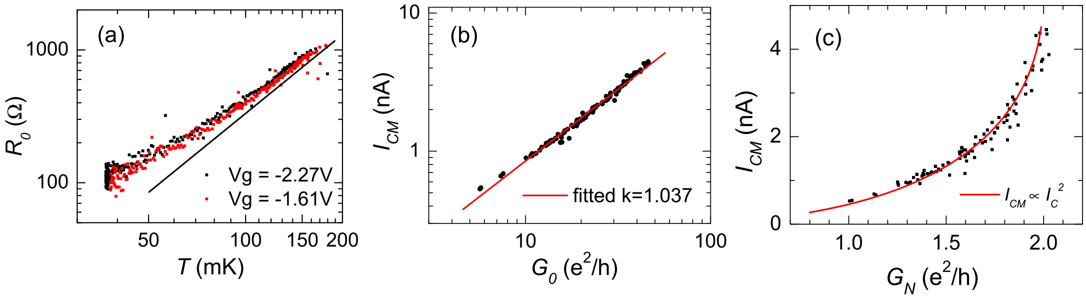

Figure 3. (Color online) (a) Temperature dependence of zero bias resistance R_0 of the superconducting SWNT sample in the Fabry-Pérot regime using voltage bias. Data at two different gate voltage values are displayed. The black line displays the theoretical asymptotic behavior of $R_0 \propto T^2$. (b) Measured critical current I_{CM} versus zero bias conductance G_0 at different gate voltages; the data are taken at 60 mK. The red line fits the power law between I_{CM} and G_0 which is theoretically expected to be 1 for voltage biasing at small junction limit. (c) I_{CM} measured in (b) versus normal state zero bias conductance G_N at different gate voltages. The red line is a theoretical fit using Breit-Wigner model.

We have investigated the influence of the measurement bandwidth on the zero bias impedance of superconducting SWNT device. We removed RC-filtering from our measurement setup, thereby increasing the measurement bandwidth from BW = 100 kHz to BW = 100 MHz. Consequently, the noise over this bandwidth is only marginally thermalized to the still/pot temperature in our setup. As seen in the conductance of Fig. 2, the zero bias resistance of the sample decreases by a factor of 10, indicating that the noise with BW = 100 MHz emerging from temperature of ~ 1 K causes strong phase diffusion. The phase diffusion results in impedance levels of over 5 kOhms that are too far from 50 Ohms and make such junction devices unusable for high frequency operation. For numerical estimation, 5 kOhm zero bias resistance corresponds to ~ 0.4 K temperature on the SWNT sample from Fig. 3(a). The results here emphasize the fact that, when the bandwidth is increased, it is crucial to have the extra noise to be thermalized at the lowest possible temperature. For example, one possible solution is provided by attenuation of

20 dB in the fridge at the mixing chamber temperature, which is a common scheme in microwave measurements [11].

To compare our measurement data to theories of superconductivity, the measured critical current I_{CM} versus zero bias conductance in superconducting state G_0 and normal state G_N are plotted in Fig. 3(b) and (c), respectively. The nanotube together with the superconducting leads can be considered as a short, ballistic SNS junction with bad interfaces and thus the two-barrier Breit-Wigner model is applicable to fit its behavior [6]. Classical phase diffusion theory predicts that in small junction limit of $E_J << k_BT$, zero bias resistance $R_0 = 2Z_{env}(k_BT/E_J)^2$ is proportional to temperature squared [12], which agrees well to our data at relatively high temperature. However, the measured I_{CM} is nearly one order of magnitude smaller than the ideally theoretical prediction $I_0 = (2e\Delta_g/\hbar)\tau \sim 30$ nA with transmission $\tau = 0.5$. Taking into account the phase diffusion in an underdamped, voltage-biased Josephson junction, the $I_{CM} - G_N$ relation can be written as $I_{CM} = I_{0M}[1 - (1 - \frac{1}{2}G_N)^{\frac{1}{2}}]^2$, where I_{0M} refers to the maximum measurable critical current. The exponent 2 in the formula arises according to the theory that in a voltage-biased Josephson junction the measured supercurrent $I_{CM} \propto {E_J}^2 \sim {I_C}^2$ [12] (which leads to $I_{CM} \propto G_0$ as shown in Fig. 3(b)), while in a current-biased junction $I_{CM} \propto {I_C}^{3/2}$ [13] (which is experimentally measured in Ref. [6]). This equation is written for one spin degenerate channel where the transmission coefficient is obtained from $\frac{1}{2}G_N$; in our case it applies approximately to the asymmetric FP conduction as well as seen from the transmission values from the shot noise measurements [10]. The theoretical fitting to our data is displayed in Fig. 3 (c), with $I_{0M} = 5.3$ nA.

4. Conclusions

In summary, we have shown that proximity-induced supercurrents can be controlled in a SWNT weak link. Although external noise can significantly change the behavior of such a device and precise thermalization and filtering is needed, the remarkably low resistance of the system enables the possibility of using SWNT devices with supercurrent in microwave regime.

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