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Electronic transport of single-wall carbon nanotubes with superconducting contacts

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1. Introduction

Single-wall carbon nanotubes (SWCNTs) have ideal one-dimensional structures with a diameter of the order of 1nm. Pd contacts are known to show the Ohmic behavior even at low temperature. The SWCNT connected with superconducting materials may give an interesting possibility as the unique Josephson junction [1-4], in terms of the extremely small junction area and the ballistic nature of the junction. The transport properties of the unique SNS (S; superconducting material, N: normal material which is the SWCNT in this case) have been studied, recently. The structure could be a possible candidate for the Andreev quantum bit (qubit) [5], where the SNS junction is embedded in a superconducting loop with the one-dimensional S region. To understand how the superconducting properties appear in the system, we have studied electronic transport properties of the SWCNT with Al contacts. In the report, we show properties of two different samples with different coupling strength to the leads. The main observation is as follows. In the sample A, the zero-voltage conductance peak due to the effect of the superconducting leads was observed as well as the multi-Andreev scattering peaks. In contrast, the zero-voltage conductance peak was not observed in the device B, but the multi-Andreev peaks were observed when the contacts were in the superconducting states. Moreover, the conductance peak due to the Kondo effect was observed when the contacts were in the normal state.

2. Sample preparation and measurement procedure

To study the superconducting properties of the Al/SWCNT/Al system, the thin Pd (3.5nm) was deposited below the Al layer (60nm). This was because the Pd gives low contact resistance, and the Al is not able to be deposited directly on the SWCNT. They were deposited consecutively in the high vacuum chamber of an electron beam evaporator. The distance between the two contacts was about 200nm. Unfortunately, it is difficult to control the contact resistance in our process, and the value roughly varied in a range of 10kΩ~100kΩ in our fabrication process.

In this report, we show the result of the two samples. One sample (sample A) had a contact resistance of 11kΩ, and the other sample (sample B) had that of 60KΩ at room temperature. Samples were set in the special holder the in the dilution refrigerator, where the all the wiring were heavily filtered at the lowest temperature to reduce the high frequency noise that would increase the electron temperature. The DC current-voltage characteristics and the differential conductance were simultaneously measured by superimposing the small AC signal to the sample in the mixing temperature range from 20mK to 1K. The gate voltage was applied using a highly doped substrate as a gate.

The contact leads were driven from the superconducting state to the normal state by applying small magnetic fields that destroyed the superconductivity of the Al.

3. Results and discussions

(a) Strong coupling regime (Sample A)

Figure 1(a) shows a gray scale plot of the differential conductance as function of the source drain voltage (V_{sd}) and the gate voltage (V_g), taken at the lowest temperature. It should be noted the conductance is too high for the Coulomb blockade to occur, and the observed pattern originate from the Fabry-Perrot interference that occurs outside the superconducting gap. Figure 1(b) shows the blow-up of the region near the zero voltage. The black color indicates the high conductance, while the white color indicates the low conductance. The origin of the black color region is the indication of the effect of the superconducting leads, which occurs when the broadened resonant level is in the source-drain bias window (on resonance). In contrast, the conductance is low in the off-resonance condition. The on and off resonance is tuned by the gate voltage [1]. There are patterns in the finite voltage regions, which is more clearly seen in Fig.2 (a) for the on-resonance and (b) for the off-resonance. In the on-resonance condition, the large

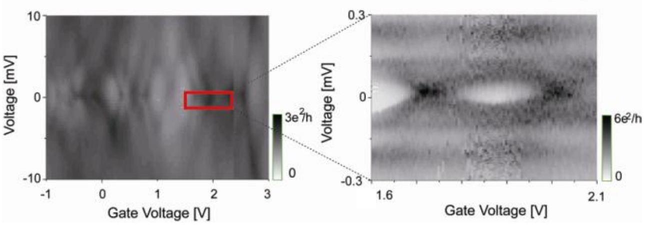

Fig.1:(a) Gray scale plot of the differential conductance as functions of Vsd and Vg in the large Vsd range. (b) Blow-up region of Fig 1(a) near the zero-voltage

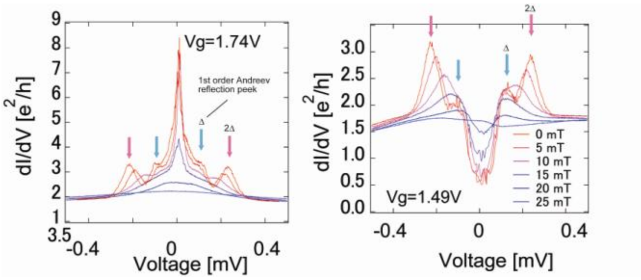

Fig.2: Conductance as a function of source drain voltage (a) at the on-resonance condition and (b) at the off-resonance condition with different magnetic fields

conductance peak is observed at the zero-voltage, followed by the two small peaks. The peak indicated by Δ is due to the 1st order multi-Andreev process, while the peak indicated by 2Δ is due to the quasi-particle tunneling. The height of the peaks decreases as the magnetic field is increased, which is due to the diminishing superconducting effect in the leads. In the off-resonant region, the conductance dip is observed at the zero-voltage, while the peaks due to the 1st order multi-Andreev process and the quasi-particle tunneling are still observable. These features are reduced as the magnetic field is increases, as is the case for the on-resonance condition.

(b) Less strong coupling regime (Sample B)

The gray scale plot of the differential conductance as function of V_{sd} and V_g is shown in Fig.3, where the superconductivity in the leads is broken by the small magnetic field. It should be noted that the conductance is low enough for the Coulomb blockade effect to be important. The distorted diamond-like pattern is observed. The parallel lines to the V_g axis in the Coulomb diamonds originate from the cotunneling process, indicating the relatively strong coupling to the leads. The line indicated by the arrow, which appears at V_{sd}=0 in one diamond is possibly due to the Kondo effect. The estimated Kondo temperature from the temperature dependence of the conductance peak is ~1.2K. It is not clear why the Kondo ridge is observed only in the diamond. Figure 4(a) shows the zoom-up plot near the small V_{sd} for the diamond where the Kondo ridge is observed. In the top panel, the Kondo ridge is observed when the leads are in the normal state, while the 1st order Andreev peaks are observable when the leads are in the superconducting state, as shown in the lower panel. The behavior is more clearly observed in Fig,4(b), where the differential conductance is plotted as a

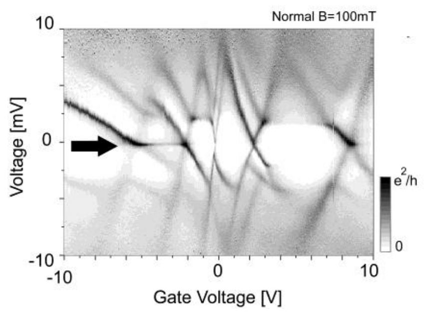

Fig.3: Coulomb diamond measurement when the leads are in the normal state. The arrow indicates the Kondo ridge.

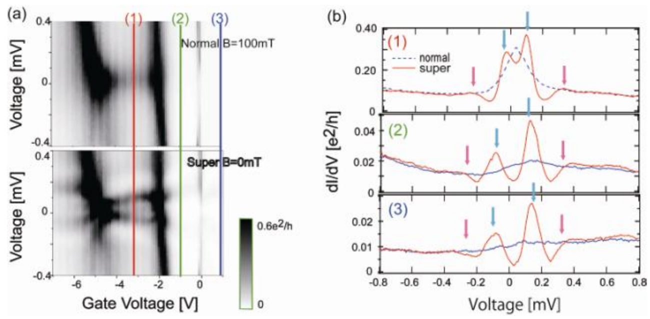

Fig.4: (a) Zoom-up plot of Fig.3 near Vsd=0 (b) Differential conductance as a function of Vsd measured along lines (1), (2), (3) for different diamonds. The Kondo peak is observable along the line (1).

function of the source-drain voltage for the normal and superconducting electrodes. The numbers (1), (2), (3) indicates the voltage line, along which the source-drain voltage was swept for the different diamonds. The cross-section along (1) is taken in the diamond where the Kondo ridge is observed. It is interesting to note that the conductance peak height of the 1st order Andreev process is much higher in the diamond where the Kondo effect is observed, than in the diamonds where no Kondo effect is observed. It seems that the Kondo effect may enhance the multi-Andreev process. The reason for this is not known yet.

4. Summary

Electrical transport properties of the SWCNT with superconducting leads has been studied in the two different coupling regime between the SWCNT and the leads. In the strong coupling regime, the zero-voltage conductance peaks as well as the peaks due to the multi-Andreev process were observed. In the less coupling regime, the Kondo ridge was observed when the leads were in the normal state. The multi-Andreev peaks had much higher peak in the Kondo diamond than in the diamonds without the Kondo ridge.

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References

[1] P.Herrero-Jarillo, J.A.van Dam, and L.P.Kouwenhoven, ," *Nature*,**439**, (2006)953-1-4,

[2] H. I. Jørgensen, K. Grove-Rasmussen, K. Flensberg, and P. E. Lindelof, *Phys.Rev B*, **79** , (2009),155441-1-6,

[3] A.Eichler., M.Weiss, S.Oberholzer, C.Schönenberger A.Levy Yeyati, J.C.Cuevas and A.Martín-Rodero, *Phys.Rev.lett*, **99**, (2007),126602-1-4

[4] T.Sand-Jespersen, J.Paaske, B.M.Andersen K.Grove -Rasmussen, H.I.Jorgensen, M.Aagesen, C.B.Sorgensen, P.E.Lindelof, K.Flensberg J.Nygard *Phys.Rev.lett*, **99** , (2007) ,126603-1-4

[5] A. Zazunov , V. S. Shumeiko,1 E. N. Bratus',2 J. Lantz,1 and G.Wendin1 , *Phys.Rev.lett*, **90** , (2003),087003-1-4