Local and nonlocal conductance enhancement due to Cooper pair splitting

Jian Wei$^1$ and V. Chandrasekhar
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA
E-mail: weijian6791@pku.edu.cn

Abstract. Enhanced local conductance due to Andreev reflection is well known for high transparency Normal metal-Superconductor (NS) interface. For low transparency NS junctions, observation of two-electron tunneling contribution (enhanced Andreev reflection) to current was also reported previously. In our recent work [J. Wei and V. Chandrasekhar, Nat. Phys. 6, 494 (2010)], for a three-terminal Cooper pair splitter geometry, i.e., with two closely placed NS junctions sharing the same S terminal, we were able do a 2D scan of both local and nonlocal differential resistance, since for our ideal tunneling junctions there is little current redistribution (flow from one normal-metal lead to the other via the superconducting lead). In contrast to previous 1D nonlocal resistance measurements, 2D scans clearly show regime with pronounced contribution of the nonlocal processes to both local and nonlocal conductance enhancement. The enhanced local conductance and negative nonlocal resistance are consistent with enhanced Cooper pair splitting, and dynamical Coulomb blockade could be the origin of this enhancement.

The transparency property of the NS junctions is critical for understanding the Coulomb blockade effect [1, 2, 3, 4, 5], e.g., a large subgap conductance was found for devices in Ref. [1] and enhanced Andreev reflection due to pin-holes or inhomogeneities of the oxide barrier was suspected. At finite temperature, for homogeneous resistive NS junctions the current voltage characteristics (CVC) are determined by quasiparticle tunneling and can be fitted by the simple semiconductor model [6].

Figure 1 shows the fits near zero bias current at different temperatures for our NS junctions in Ref.[7]. The estimate current due to quasiparticle tunneling without considering Andreev reflection is [6]:

\[
I_{NS} = \frac{1}{eR_{NN}} \int_{\Delta}^{\infty} \frac{E}{\sqrt{E^2 - \Delta^2}} \left[ f_n(E - eV) - f_n(E + eV) \right] dE,
\]

where \( R_{NN} \) is the junction resistance in the normal state, and \( f_n \) is Fermi function of electrons in the normal state. Here in For Fig. 1, the junction resistance is 19 k\( \Omega \). For numerical calculation the divergence at \( E = \Delta \) can be eliminated by the substitution \( E/\Delta = \cosh \theta \) following the treatment in Ref [8]. The equation after substitution becomes

\[
I_{NS} = \frac{1}{eR_{NN}} \int_{0}^{\infty} \left[ f_n(\cosh \theta - \frac{eV}{\Delta}, \frac{k_B T}{\Delta}) - f_n(\cosh \theta + \frac{eV}{\Delta}, \frac{k_B T}{\Delta}) \right] \cosh \theta d\theta.
\]

1 Present address: International Center for Quantum Materials, School of Physics, Peking University, Beijing 100871, China

Published under licence by IOP Publishing Ltd
Figure 1. NIS junction characterized by current voltage characteristics. **a**, CVC at bath temperatures: 0.05 K (magenta), 0.1 K (cyan), 0.2 K (red), 0.3 K (green), and 0.4 K (blue). The solid lines are fits using the semiconductor model, with slightly elevated electron temperatures: 0.075 K, 0.125 K, 0.23 K, 0.34 K, and 0.45 K. **b**, the same data replotted with log scale of absolute value of current. **c** (**d**), differential resistance (conductance) by numerically differentiating data in **a**, for clarity only data at 0.1 K and 0.2 K are shown.

The excellent fitting with the semiconductor model confirms that the junction has no pin holes, which is also justified by shot noise measurements [7]. The fitting parameters in the equation are the superconducting gap energy $\Delta$ and the electron temperature $T$. Here $\Delta$ is 212 $\mu$V, which is consistent with the measured $T_c$ close to 1.44 K. The fitted electronic temperatures are slightly higher than the bath temperature (as listed in the caption of Fig. 1), probably due to heating of electrons by noise.

In Fig. 1b the CVC are replotted with the absolute value of current in log scale, and a noise background of approximate 0.2 pA is clearly visible. When the data are smoothed and numerically differentiated, a leakage conductance about $10^{-8}$ S (or 100 MΩ leakage resistance) is obtained as shown in Fig. 1d. This leakage resistance is probably due to our electronics set-up. The differential resistance numerically calculated from the CVC is shown in Fig. 1c, which does not show saturation near zero current bias, in contrast to the AC differential resistance measurements (see Fig. 2) where the capacitance in parallel shunts the junction. However, the scatter of the data prevents any meaningful comparison with theory. To find the contribution of Andreev reflection, the AC differential resistance is still preferred.

For resistive tunneling junctions with no leakage, classical current redistribution (flow from one normal-metal lead to the other via the superconducting lead) may be neglected, which enables us to do a 2D scan of both local and nonlocal differential resistance, different from the
Figure 2. Differential local ($dv_A/di_A$) and nonlocal resistance ($dv_B/di_A$) measurements at 0.3 K. **a**, local differential resistance with nonlocal bias $I_B = 0$ pA (blue), -100 pA (green), -200 pA (red), -300 pA (cyan), -400 pA (magenta), and -500 pA (yellow). The arrows indicate the reduction of resistance. The black solid line is fit using the semiconductor model, with $T = 0.3$ K. Due to capacitance shunting of the junction, the measured differential resistance peak near zero bias is flattened. **b**, nonlocal differential resistance at the same $I_B$ values as in **a**. For clarity, data below $I_A = -100$ pA when $I_B = -500$ pA are not shown. **c**, the reduction of the local resistance ($\Delta dv_A/di_A$) calculated by subtracting data at $I_B = -500$ pA. **d**, the same data in **b** plotted in log scale. In both **c** and **d** the resistance values are multiplied by -1 to plot in log scale. The black solid lines in **c** and **d** are the same fit in **a** divided 4.

The measured local differential resistance is compared with the semiconductor model in Fig. 2a. By subtracting the curve measured at high $I_B$, a clear reduction of the local resistance near zero bias ($I_A = I_B = 0$ pA) can be obtained, consistent with the reduction at other finite values of $I_A(I_B = I_A)$. The reduction of the local resistance ($\Delta dv_A/di_A$) resembles the negative nonlocal resistance ($dv_B/di_A$), as shown by Fig. 2c and Fig. 2d. The magnitude of the peaks at various DC bias values ($I_B \sim I_A$, indicated by arrows) for both of them is approximately a quarter of the fitted local resistance, which indicates an increase of conductance by a factor of 1/3 for the local junction.

For NISIN three terminal devices in the subgap regime ($e|V|, k_B T \ll \Delta$), the contributions to local and nonlocal conductance enhancement are characterized by the following conductance matrix: [12, 13]

$$
\begin{pmatrix}
I_A \\
I_B
\end{pmatrix} = 
\begin{pmatrix}
G_{2A} + G_{CAR} + G_{EC} & G_{CAR} - G_{EC} \\
G_{CAR} - G_{EC} & G_{2B} + G_{CAR} + G_{EC}
\end{pmatrix} 
\begin{pmatrix}
V_A \\
V_B
\end{pmatrix}
$$

(3)
where $G_{2A}$ and $G_{2B}$ are the contributions due to direct Andreev reflection, $G_{CAR} = G_Q A^{CAR}$ and $G_{EC} = G_Q A^{EC}$ are the nonlocal contributions. It is clear that the CAR term contributes the same to the local conductance and the nonlocal conductance. And when $V_A = V_B$ the contribution due to the EC term vanishes.

Since differential resistance is usually measured, the resistance matrix is derived by inverting the conductance matrix [9, 10, 11, 2, 14]. At finite temperature when the quasiparticle tunneling dominates, we assume $G_{2A} = G_{2B} = G$ for simplicity and lump in $G$ with an extra term $G_{NS}$. The observation of a negative nonlocal resistance is consistent with $G_{CAR}$ dominating over $G_{EC}$, i.e., Cooper pair splitting process is favored.

At 0.3 K, when $I_A = I_B$ we have $\Delta v_I/\Delta I_A \sim -1/(4G)$ and $\Delta v_B/\Delta I_A \sim -1/(4G)$, which leads to $G_{CAR} = G/2$ and $G_{EC} = 0$. Although the above argument can explain the reduction of the local resistance and the negative nonlocal resistance at zero bias, it can not explain the observation at finite $I_B$ since there is no explicit $I_B$ dependence in the equations of the local and nonlocal resistance. This suggests that the amplitudes of the nonlocal processes, $A^{CAR}$ and $A^{EC}$, are bias dependent, consistent with previous results [5, 2, 1].

The observed local conductance enhancement due to nonlocal processes is rather different from enhanced conductance for simple NS interface [15], and for low transparency NS junctions where enhanced Andreev reflection is resulted from special geometry [16, 17, 18]. At 0.4 K and 0.25 K, the reduction of the local resistance and the negative nonlocal resistance are about 1/18 and 1/4 respectively, showing that the nonlocal processes change abruptly between 0.4 K and 0.3 K. This is in the ballpark of the charging energy $E_C = e^2/2C \sim 0.15$ K estimated from the junction geometry (assuming the thickness of the oxide layer is 1 nm, dielectric constant is 9.1, area 0.15 $\mu$m$^2$, $E_C$ is about 13 $\mu$eV), which suggests local conductance enhancement may share the same origin as the negative nonlocal resistance [4, 5, 19], i.e., both related to Dynamical Coulomb blockade.

This research was conducted with support from the National Science Foundation under grant No. DMR-0604601.

1. Beckmann D and v Löhneysen H 2007 Applied Physics A: Materials Science & Processing 89 603–607
2. Kleine A, Baumgartner A, Trbovic J and Schönenberger C 2009 Europhys. Lett. 87 27011
3. Brauer J, Hübler F, Smetanin M, Beckmann D and v Löhneysen H 2010 Phys. Rev. B 81 024515
4. Recher P and Loss D 2003 Phys. Rev. Lett. 91 267003
5. Levy Yeyati A, Bergeret F S, Martin-Rodero A and Klapwijk T M 2007 Nature Physics 3 455–459
6. Tinkham M 1996 Introduction to Superconductivity 2nd ed (McGraw Hill)
7. Wei J and Chandrasekhar V 2010 Nature Physics 6 494–498
8. Fisher P A 1999 Development of an On-Chip Electric Refrigerator Based on a Normal-Conductor/Insulator/Superconductor Tunnel Junction Ph.D. thesis Harvard University
9. Beckmann D, Weber H B and v Löhneysen H 2004 Phys. Rev. Lett. 93 197003
10. Russo S, Kroug M, Klapwijk T M and Morpurgo A F 2005 Phys. Rev. Lett. 95 027002
11. Cadden-Zimansky P and Chandrasekhar V 2006 Phys. Rev. Lett. 97 237003
12. Falci G, Feinberg D and Hekking F W J 2001 Europhys. Lett. 54 255–261
13. Bignon G, Houzet M, Pistolesi F and Hekking F W J 2004 Europhys. Lett. 67 110–116
14. Golubev D S, Kalenkov M S and Zaikin A D 2009 Phys. Rev. Lett. 103 067006
15. Blonder G E, Tinkham M and Klapwijk T M 1982 Phys. Rev. B 25 4515–4532
16. Hekking F W J and Nazarov Y V 1994 Phys. Rev. B 49 6847–6852
17. Pothier H, Guéron S, Esteve D and Devoret M H 1994 Phys. Rev. Lett. 73 2488–2491
18. Quirion D, Hoffmann C, Lefloch F and Sanquer M 2002 Phys. Rev. B 65 100508
19. Mélin R, Benjamin C and Martin T 2008 Phys. Rev. B 77 094512