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Local tunneling spectroscopy of a Nb/InAs/Nb superconducting proximity system with a scanning tunneling microscope

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Local tunneling spectroscopy for a Nb/InAs/Nb superconducting proximity system was demonstrated with a low-temperature scanning tunneling microscope. It is found that the local electron density of states in the InAs region is spatially modulated by the neighboring superconductor Nb.

The superconducting proximity effect has recently been studied in semiconductor-coupled superconducting junction systems from many points of view.[1-8] In particular, the transport properties of Nb/InAs/Nb proximity systems,[1,2] where the electron mean free path in InAs is as small as $\hbar v_F/2\pi k_B T$ (where v_F is the Fermi velocity and T is the temperature), have been explained by consideration of the normal coherence length[9] governed by a diffusion process.

However, the excitation spectrum of superconductor–normal-metal–superconductor ($S/N/S$) systems, including semiconductor-coupled systems, has not been well understood either experimentally or theoretically. The excitation spectrum in proximity systems has been investigated mainly in superconductor–normal-metal–insulator–normal-metal ($S/N/I/N$) structures by tunneling spectroscopy from the normal-metal side.[10] A recent experiment on a $Nb/In_{1-x}Ga_xAs/InP/In_{1-x}Ga_xAs$ system,[11] which is similar to the Nb/InAs systems, was made along this line. In this work, a gaplike structure in the tunneling density of states in the $In_{1-x}Ga_xAs$ region was shown. However, such tunneling spectroscopy does not give direct information on the spatial profile of the local density of states near the superconductor–normal-metal (S/N) boundary. Therefore, a more direct measurement method is required for the study of the energy spectrum in $S/N/S$ systems.

Recent development of scanning-tunneling-microscopy (STM) and scanning-tunneling-spectroscopy (STS) technologies can provide directly spatial variation of the local density of states. In practice, the local density of states is measured for a superconducting vortex on $NbSe_2$.[12] This system is similar to proximity systems in the sense that the pair potential is not spatially homogeneous.

We report here experimental data on local density of states for the superconducting proximity system Nb/InAs/Nb using a low-temperature scanning tunneling microscope.

The Nb/InAs/Nb sample is shown in Fig. 1. The sample consists of strip patterns with a 1.5-μm pitch (0.5-μm-wide InAs and 1-μm-wide Nb). Tip approach to the patterns is no problem because of the 3×3-mm^2 area of the patterns. Electron-beam lithography, shallow etching of the InAs surface, Nb electron-beam evaporation at an angle, and liftoff were used to fabricate this sample. The fabrication process is the same as for ordinary Nb/InAs/Nb junctions.[1] The carrier concentration and mobility of the n-type InAs used are about 2×10^{18} cm^{-3} and 1×10^4 cm^2/V s at 4.2 K. Assuming an electron effective mass of $0.024m_e$ and the free-electron model, the Fermi velocity and mean free path are estimated to be 1.9×10^6 m/s and 0.26 μm.

The STM instrument uses a tube scanner measuring 45 mm long, 12 mm in diameter, and 1 mm thick. An outside electrode is separated into two parts, one for lateral motion and the other for vertical motion. The tunneling tip is a mechanically sharpened $Pt_{0.8}Ir_{0.2}$ wire. The STM head attached to the insert is directly dipped into a liquid-helium storage Dewar which is suspended by a spring for vibration isolation. The maximum scan area at 4.2 K is 1.2×1.2 μm^2, which is about 20% compared to the area at room temperature. When the I-V curve is measured, the feedback loop is switched off and the distance between the tip and the sample is held constant. dI/dV-V curves are obtained by numerical differentiation of the measured I-V data about V.

Figure 2(a) is a topographic STM image of the Nb/InAs/Nb proximity system at 4.2 K. The bias voltage is 0.5 V and the tunneling current is 1 nA. The dI/dV-V curves at 4.2 K taken at the four positions indicated in Fig. 2(a) are shown in Fig. 2(b), where curves 2–4 are shifted. The derivatives were computed as differences with a step of about 0.1 mV. The tunneling resistance of the flat part of each curve is about 100 MΩ. The dI/dV-V curve in the Nb region (curve 1) is the same as the one for bulk Nb. Because of the low surface quality, the structure of the curve is smeared as compared to ideal tunnel junctions. Taking account of the thermal smearing, the value of the superconducting energy gap estimated from the voltage at which the dip structure begins almost corresponds to that of Nb ($\sim$1.5 meV). In the InAs region, each curve has a similar structure and becomes gradually smooth as the distance from the measurement

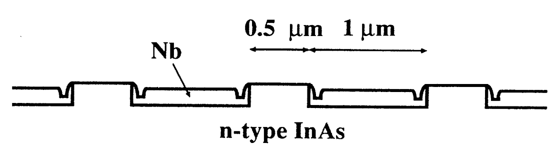

FIG. 1. Schematic cross-sectional view of the sample structure.

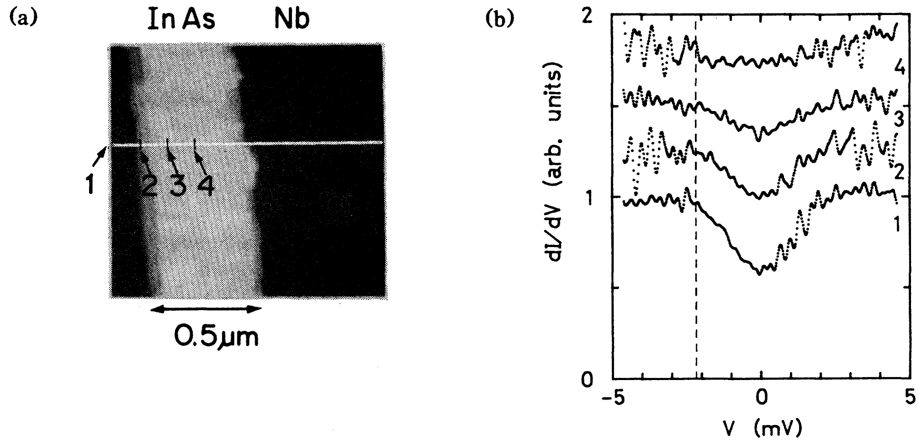

FIG. 2. (a) Topographic STM image of a Nb/InAs/Nb proximity system at 4.2 K. The bias voltage is 0.5 V and the tunneling current is 1 nA. (b) *dI/dV-V* curves at 4.2 K taken at the four positions indicated in (a). Curves 2–4 are shifted. The dashed line indicates the voltage at which the dip structure of each curve begins.

position to the Nb/InAs boundary increases. The *dI/dV-V* curve for bulk InAs, however, shows constant tunneling conductance in this energy range. The dip structure of the *dI/dV-V* curve in the InAs region shows that the local electron density of states is modulated by neighboring superconductor Nb.

It seems that this modulation indicates a decay of a proximity-induced pair potential in the InAs region. At present, the experimental results are rather crude to be analyzed quantitatively. However, it can be pointed out that the voltage at which the dip structure of each curve begins is almost the same as shown by the dashed line in Fig. 2(b). If the energy gap was varied spatially, this voltage would vary spatially, too. Therefore, the spatial dependence of the structure does not indicate the decay of the induced superconducting energy gap. Considering the fact that the mean free path in the InAs region is close to the width of this region, there is a possibility that bound states in a pair-potential well are related to the obtained tunneling conductance. In actuality, according to the theory of bound states in *S/N/S* junctions,[13,14] the number of bound states in our system is one and the eigenvalue is close to the Nb energy gap which corresponds to the depth of the pair potential well. The density of states for these bound states may explain the fact that each *dI/dV-V* curve starts to decrease at almost the same voltage. Further experimental improvement is needed to make a realistic comparison with this model.

In conclusion, we have demonstrated local tunneling spectroscopy for the Nb/InAs/Nb superconducting proximity system using a low-temperature tunneling microscope. The tunneling conductance in the InAs region indicates that the local electron density of states of the energy-gap region is modulated by the neighboring superconductor Nb.

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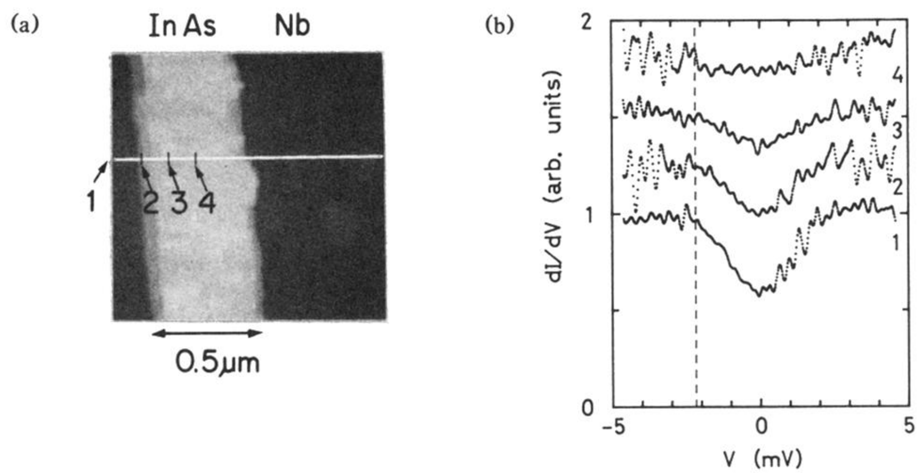

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