Proximity Effect-Induced Superconducting Networks

S Tsuchiya and S Tanda
Department of Applied Physics, Hokkaido University, Sapporo, kita-ku kita13 nishi8, Japan
E-mail: tuchiya@eng.hokudai.ac.jp

Abstract. We have studied proximity effect-induced superconductivity of micro wire networks in a magnetic field for investigating topological effects of the superconducting order parameter through Little-Parks oscillation. We prepared a regular honeycomb network, which has Pb-Au bilayer structure, by standard electron beam lithography and measured variation of superconducting transition temperature ($T_c$) in a magnetic field. We also fabricated a honeycomb network made of Pb monolayer and measured it in the same way. In the experimental results of the monolayer network, 2.06 $\pm$ 0.02 Gauss of periodic variation of $T_c$ in a magnetic field was observed at around 7.2 K. The area estimated from this period is 10.04 $\mu$m$^2$ and correspond to unit honeycomb enclosed by center of the wire. While, in the results of the bilayer network, 2.66 $\pm$ 0.04 Gauss of periodic variation of $T_c$ in a magnetic field was observed at around 4.3 K because of the proximity effect. The area estimated from this period is 7.78 $\mu$m$^2$ and correspond to unit honeycomb enclosed by edge of the wire. In the latter case, the superconducting current flows through edge of the wire since the order parameter can be considered to be more developed and inhomogeneous on the wire cross-section at around 4.3 K less than 7.2 K. Consequently, a novel network of paths flowing through the superconducting current, which consists of loops enclosed by edge of the wire, can be realized by controlling the proximity effect.

1. Introduction
The interesting properties of various kinds of superconducting networks in a magnetic field have been extensively studied in recent years [1, 2, 3, 4, 5]. This system is extremely sensitive to the phase coherence of the superconducting order parameter over the network, so their properties are affected to the network topology. Consequently, characteristic vortex entry and configuration, which is observed as cups or dips in the magnetic field response, are appeared in the structure resulting from the topological effect. However, when a network consists of a superconductor and a normal metal with good electrical contact, network effects remains unclear. In this case, superconductivity is weakened in the superconductor and induced in the normal metal known as the proximity effect [6]. Accordingly, novel kinds of vortex entry and configuration are expected to occur because the property of the order parameter in superconductors can be modified by the proximity effect. In this letter, we report the study of the proximity effect-induced superconductivity of micro wire networks in a magnetic field for investigating topological effects of the superconducting order parameter through Little-Parks oscillation. Power spectrum analysis is also performed to search for periodicity in detail.

2. Experimental
We prepared two types of honeycomb network by standard electron beam lithography. One consists of Pb monolayer wire, the other Pb-Au bilayer wire. The gold layer is first thermally
evaporated on the substrate. And the lead layer is second evaporated over the Au layer. These samples are the same designed honeycomb network where about 2500 unit hexagons is spreaded uniformly, and its side length is 2 \( \mu \text{m} \) with linewidth of 0.2 \( \mu \text{m} \), thickness of Pb of 0.1 \( \mu \text{m} \) and Au of 0.01 \( \mu \text{m} \).

Then we investigated Little-Parks oscillation \cite{7} of these samples by using 12.5 \( Hz \) four terminal ac Resistance Bridge with excitation voltage 100 \( \mu V \). Little-Parks oscillation is a periodic variation of superconducting transition temperature (\( T_c \)) with a magnetic field by the superconducting fluxoid quantization. Experimentally Little-Parks oscillation of \( T_c \) can be observed as a periodic variation of resistance with a magnetic field at fixed temperature, which was taken near the midpoint of normal-to-superconducting transition.

3. Results and Discussion

In the case of the monolayer network, the superconducting transition temperature (\( T_c \)) was measured to be around 7.2 \( K \) at half of normal resistance. This value good agree with \( T_c \) of bulk lead 7.2 \( K \). Figure 1 (a) shows the magnetic flux dependence of the sample resistance from \(-10\) to 0 and 0 to 10 \( \text{Gauss} \). We observe 2.06 \( \pm \) 0.02 \( \text{Gauss} \) period of oscillation for each downward cusp. The area estimated from the period is 9.85 \( \mu m^2 \) and correspond to a hexagonal unit cell enclosed by center of the wire. This value compares well to the value 10.04 \( \mu m^2 \) obtained from SEM observation with 2 \% accuracy. Thus the period correspond to one-flux quantum \( \Phi_0 = \hbar/2e \) per unit cell.

The spectral analysis was performed by maximum entropy method (MEM) to investigate other periods with small amplitude. Figure 1 (b) presents the power spectrum of the data from \(-10\) to 0 \( \text{Gauss} \). Fundamental peak labeled as \( A_1 \) correspond to period of 2.12 \( \text{Gauss} \) and is almost coincident with the previous results of 2.06 \( \text{Gauss} \) period. The second strongest peak labeled as \( A_2 \) and the third strongest peak as \( A_3 \) correspond to period of 0.67 \( \text{Gauss} \) and 0.45 \( \text{Gauss} \) which are about 1/3 and 1/4.7 the period of \( A_1 \). This result is reminiscent of the recent report \cite{8} and indicates the feature of the honeycomb network when \( A_3 \) peak can be considered to be almost 1/5 the period of \( A_1 \). Thus, at the \( A_2 \) peak, the state of the system become stable energetically since configuration of vortex is commensurate with its base of honeycomb structure.

![Figure 1.](image)

Figure 1. (a) The magnetic flux dependence of the sample resistance from \(-10\) to 0 and 0 to 10 \( \text{Gauss} \) in the case of the monolayer network. We observe 2.06 \( \pm \) 0.02 \( \text{Gauss} \) period of oscillation for each downward cusp. (b) The power spectrum of the data from \(-10\) to 0 \( \text{Gauss} \). Fundamental peak labeled as \( A_1 \) correspond to period of 2.12 \( \text{Gauss} \). The second strongest peak labeled as \( A_2 \) and the third strongest peak as \( A_3 \) correspond to period of 0.67 \( \text{Gauss} \) and 0.45 \( \text{Gauss} \) which are about 1/3 and 1/4.7 the period of \( A_1 \).

Next we investigated the bilayer network in the same way. \( T_c \) was observed at around 4.3
This reduction of \( T_c \) is assumed to be due to the proximity effect of gold [9]. Figure 2 (a) shows the magnetic flux dependence of the sample resistance from \(-10\) to \(10\) Gauss. We observe \(2.66 \pm 0.04\) Gauss period of oscillation for each downward cusp. The area estimated from the period is \(7.78 \mu m^2\) and correspond to a hexagonal unit cell enclosed by edge of the wire. This value compares well to the value \(7.56 \mu m^2\) obtained from SEM observation with \(3\%\) accuracy. In this case, the superconducting order parameter is assumed to be more developed and inhomogeneous on the wire cross-section at around \(4.3\) \(K\) less than \(7.2\) \(K\). Consequently, superconducting current flows along edge of the wire since the magnetic penetration depth can become short.

![Figure 2](image-url)

**Figure 2.** (a) The magnetic flux dependence of the sample resistance from \(-10\) to \(10\) Gauss in the case of the bilayer network. We observe \(2.66 \pm 0.04\) Gauss period of oscillation for each downward cusp. (b) The power spectrum of the data from \(-10\) to \(10\) Gauss. Fundamental peak labeled as \(B_1\) correspond to period of \(2.68\) Gauss. The second strongest peak labeled as \(B_2\) and the third strongest peak as \(B_3\) correspond to period of \(0.70\) Gauss and \(0.36\) Gauss which are about \(1/3.8\) and \(1/7.5\) the period of \(B_1\).

Furthermore, power spectrum analysis was performed in figure 2 (b). Fundamental peak labeled as \(B_1\) correspond to period of \(2.68\) Gauss and don’t conflict with the previous results of \(2.66\) Gauss. In addition, the second and the third strongest peak labeled as \(B_2\) and \(B_3\) which correspond to \(0.70\) Gauss and \(0.36\) Gauss, are also observed. \(B_2\) and \(B_3\) are \(1/3.8\) and \(1/7.5\) the period of \(B_1\). These results are obviously different from the case of the monolayer network and reflect new phenomenon attributed to the proximity effect.

We discuss vortex configuration in the both networks. In the case of the monolayer network, the superconducting current flows through the paths enclosed by center of the wire. For example, at \(f = 1/3\), that is, the magnetic flux corresponding to \(A_2\) peak, one vortex is stably allocated in every three unit cells. Figure 3 (a) shows vortex configuration in the monolayer network at \(A_2\) peak. The plaquettes occupied by vortices are shown shaded. And the dashed line represent path through which superconducting current flow. While, in the case of the bilayer network, the superconducting current flows through the paths enclosed by edge of the wire. Now we try to refer the relation of the periodicity between the case of the monolayer network and bilayer network. A magnetic flux ratio between \(A_1\) and \(B_1\) or, area enclosed by center of the wire and edge of the wire, is around \(4/5\). The coefficient of \(1/3\) between \(A_1\) and \(A_2\) times \(4/5\) is almost \(1/3.8\) and coincident with the coefficient between \(B_1\) and \(B_2\). Moreover the coefficient of \(1/1.5\) between \(A_2\) and \(A_3\) times \(4/5\) and well agree with the coefficient between \(B_2\) and \(B_3\) of \(1/1.96\). This result may indicate the same vortex configuration at \(A_1\) peak and \(B_1\) peak. Therefore, values of these peaks in the case of the monolayer network are different.
Figure 3. Configuration of vortices. The plaquettes occupied by vortices are shown shaded. The dashed line represent paths through which superconducting current flow. (a) is for the monolayer honeycomb network with the magnetic flux corresponding to $A_2$ peak. Vortices consist of loops enclosed by center of the wire. (b) is for the bilayer honeycomb network with the magnetic flux corresponding to $B_2$ peak. Vortices consist of loops enclosed by edge of the wire.

from the case of the bilayer network, but implication of these peaks are identical each other from the view point of vortex configuration. Figure 3 (b) exhibits vortex configuration in the bilayer network at the magnetic flux corresponding to $B_2$ peak. New network of paths consisting of loops enclosed by edge of the wire is realized in the bilayer network as a result of the proximity effect.

4. Summary
We studied proximity effect-induced superconductivity of micro wire networks in a magnetic field. We prepared Pb monolayer honeycomb network and Pb-Au bilayer network by standard electron beam lithography. From the results of Little-Parks oscillation, vortices is found to consist of loops enclosed by center of the wire in the monolayer network and enclosed by edge of the wire in the bilayer network. Furthermore, in the power spectrum analysis performed by MEM, we obtained not only fundamental peak but also the second and the third strongest peak. Values of these peaks in the case of the monolayer network are different from the case of the bilayer network, but implication of these peaks are found to be identical from the view point of vortex configuration. Accordingly, a novel network of paths flowing through the superconducting current, which consists of loops enclosed by edge of the wire, can be realized by controlling the proximity effect.

5. Acknowledgment
This work has been supported by Grant-in-Aid for the 21st Century COE program Topological Science and Technology.

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