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Thin Film dc SQUID with Quasiparticle-Injected Superconducting Weak Links

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Quasiparticle-injected superconducting weak links of lead alloy were fabricated under various conditions. The resistance of the weak links did not depend on the width of the injector but on the indium concentration; a larger indium concentration gave a larger normal resistance. Applying the weak links of this large normal resistance to dc Superconducting Quantum Interference Devices(SQUID), a larger output voltage(∿30 μV) was attained, which is comparable to that of a conventional, resistively shunted dc SQUID.

I. INTRODUCTION

A large output voltage(∿30μV) was obtained for a new type of dc SQUID (Superconducting Quantum Interference Devices) having quasiparticle-injected superconducting weak links.

Up to now, there are many reports on the application of weak links for digital and analogue devices, the types of which are, for example, tunnel junction, bridge, point contact, etc.. Generally speaking, weak links mean a partition between two superconducting electrodes by depressing the order parameter in a local region. The size of the locally weak region should be comparable with or smaller than the characteristic length of the superconductor, generally supposed to be the temperature-dependent coherence length $\xi(T)$. This condition imposes rather severe constraints on the fabrication and operation of weak links. The link dimensions should be under the micron level. Moreover, the critical current varies depending on the temperature. In particular, if we want to operate SQUID in a wide temperature range, the relation $LI_0 \sim \phi_0$ should always be satisfied, where L is the loop inductance of SQUID, I_0 the critical current of the weak link, and ϕ_0 the flux quantum. However, the critical current varies depending on the temperature. Therefore this relation is no longer satisfied in a wide temperature range.

On the other hand the injection of electronic excitations into a narrow superconducting strip line through a superconducting tunnel junction was shown by Wong, Yeh and Langenberg to result in a region of weakened superconductivity which gives rise to a Josephson device having controllable characteristics,[2] so that it is attractive to apply these quasiparticle-injected superconducting weak links to dc SQUID in order to overcome the difficulty mentioned above.

Nonequilibrium superconductors have been attracting the considerable attention of many workers.[3-5] The injection of a quasiparticle creates the nonequilibrium state in superconductors, and the diffusion of the quasiparticle takes place. From the theoretical viewpoint, two important simple models were discussed. Owen and Scalapino proposed the u* model in which the excess number of quasiparticles is characterized by chemical potential u*.[6] On the other hand, Parker proposed a T* model in which an effectively elevated temperature, T*, describes the number of quasiparticles and their energy distribution.[7] The diffusion process of quasiparticles has been discussed; for instance, Wong et al. worked on the basis of the phenomenological theory of the Rothwarf-Taylor equation.[8,9]

We fabricated quasiparticle-injected weak links in lead alloy under various indium concentrations and found that a larger indium concentration gave a larger normal resistance.

II. EXPERIMENT

For the fabrication of quasiparticle-injected superconducting weak links and their application to dc SQUID, Nb/oxide/Pb-alloy junctions on the silicon wafers were used in the lift off method. Niobium films of 50 nm were deposited under the pressure of 5×10^{-6}Pa in an oil free, high quality vacuum chamber with the background pressure of 5×10^{-7}Pa, followed by exposing the films to rf O_2 plasma before depositing the lead alloy of 100 nm. Finally the samples were covered by a KMER[12] photoresist of 500 nm. In order to observe the dependence of the characteristic on the mean free path, we varied the concentration of indium in lead from 0%(pure lead) to 30% in thickness. The configuration of the weak links is shown in Fig.1(a). The width of the strip line is 5 µm, the length L_{strip} is 125 µm; the width of the injector was varied from 5 to 20 µm. The measurement was performed at 4.2K. A quasiparticle was injected through the tunnel junction to the strip line of lead alloy. This injection weakened the superconductivity of the strip line near the injected area, causing the characteristic of the strip line to indicate a weak link one. By connecting these weak links as a superconducting loop, dc SQUID were formed, as shown in Fig.1(b).

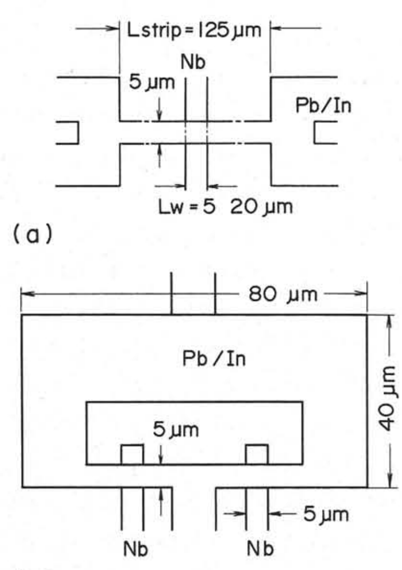
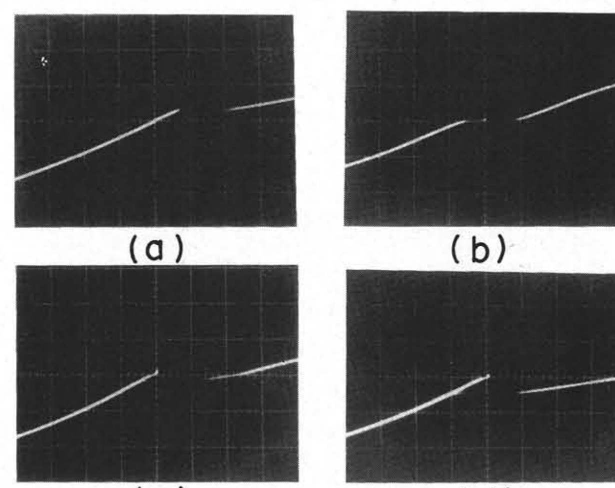


FIG. 1 (a) The configuration of quasiparticle-injected superconducting weak links. The length of the strip line is sufficiently larger than the diffusion length of the quasiparticle. The width of the injector was varied from 5 to 20 µm.
(b) The configuration of the dc SQUID with quasiparticle-injected superconducting weak links. Two injectors of 5µm square were placed under the superconducting loop of the Pb/In film.

III. RESULTS and DISCUSSION

The total thickness of the lead alloy film was 100 nm and the indium concentration was varied from 0%(pure Pb) to 30% in thickness. The width ofthe injected area was varied from 5 µm to 20 µm. In the quasiparticle-injected weak links, the excess quasiparticles depress the superconducting order parameter over some distance, Λ , and create a weak link if Λ is comparable to the coherence length and the depression is sufficiently strong. The characteristics of this weak link, e.g. the critical current, depend both on Λ and on the suppressed gap energy. The size of the depressed region, Λ , in this type of weak link cannot be defined clearly, in contrast with the usual bridge type weak link where "the banks" and "the span" are separated distinctly. However, we can make the experimental order estimation of Λ by measuring the value of $\Lambda_{exp}=L_{strip}(r/R)$, where L_{strip} is the length of the strip line, r the normal resistance of the weak link at just $I_c=0$, and R the total residual resistance of the strip line at just above the transition temperature. The value of Λ_{exp} does not depend on the widths of the injected area, as shown in Fig.2, where the

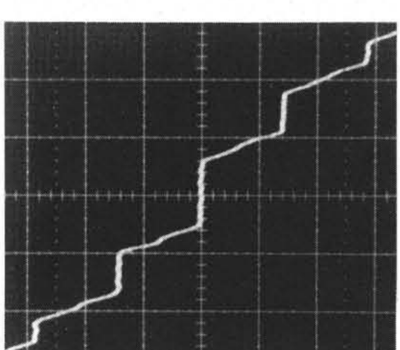


X: 0.05mV/div., Y: 0.05mA/div.

FIG. 2 Current-voltage characteristics for various width of the injector; (a)5 µm, (b)10 µm, (c)15 µm, (d)20 µm. The injection current was adjusted so that $I_c=0$

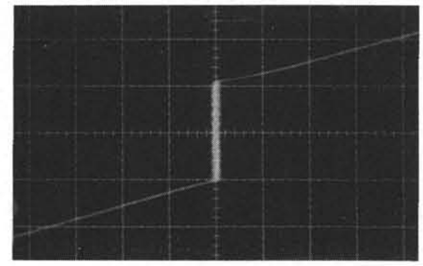
current-voltage characteristics are shown for various width of the injector at just $I_c=0$. On the other hand, the value of Λ_{exp} depends on the indium concentration; Λ_{exp} decreases as the indium concentration increases. This dependence is due to the variation of the mean free path of the quasiparticle. The size of the depressed region is estimated by $\sim\sqrt{\xi l_0}$.

The response to the irradiation of microwave(13GHz) was investigated. In Fig.3, the usual harmonic current steps were observed as well as the subharmonic current steps at voltages $V_n=n(h\omega/2e)$ where $n=1/2,1,3/2,2....$ The occurrence of the subharmonic current steps is interpreted as the deviation of the current-phase relation from the sinusoidal form. Generally speaking, there are two types of the weak link structure, depending on whether the weakened part consists of a normal metal(S-N-S) or a superconducting material(S-S'-S). Concerning the structure of the weak link, the theoretical analyses of the characteristics for both cases were made and reviewed by Likharev, especially on the current-phase relation. The deviation from the sinusoidal relation was predicted for S-S'-S structure, while the sinusoidal form was kept for S-N-S weak links. On the other hand, the deviation from the sinusoidal relation in the current-phase relation causes the subharmonic steps in the current-voltage characteristics under microwave radiation. Thus our experimental results suggest that the quasiparticle-injected superconducting weak links have the S-S'-S structure.



X: 0.02mV/div., Y: 0.2mA/div.

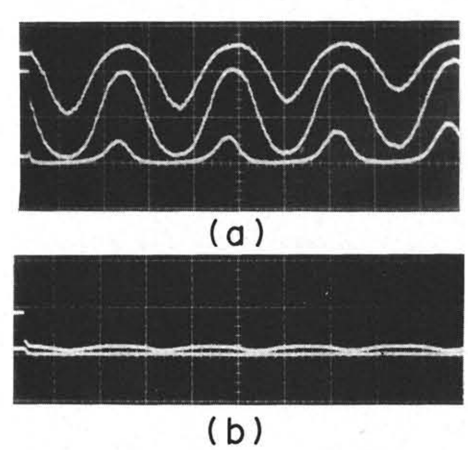
FIG. 3 Current-Voltage characteristics of the quasiparticle-injected superconducting weak links under the irradiation of microwave(13GHz). The indium concentration was 20% in thickness. The subharmonic current steps are shown.



X: 0.02mV/div., Y: 0.2mA/div

FIG. 4 Current voltage characteristics of the dc SQUID with 30% indium concentration.

Figure 4 shows the current-voltage characteristics of the dc SQUID for the sample with 30% of indium concentration. Owing to the low capacitance of the weak links, there is no fine structure due to the resonance, which is usually observed in conventional dc SQUID.[15,17] Both of the weak links of the dc SQUID were adjusted to have the same critical current. The normal resistance of the one junction was 0.5 ohm. This value is larger than that of a previous report[10] because of the higher indium concentration in the lead alloy. This large normal resistance made it possible to indicate the larger output voltage in the periodic Φ-V characteristics, which is shown in Fig.5(a) for various bias points. This output voltage($\sim$ 30 μV) is comparable to the value of the conventional resistively shunted dc SQUID.[15] Figure 5(b) shows the Φ-V characteristics for the SQUID with pure Pb. The output voltage is very low because of its low resistance. The depressed region, Λ, is large



X: arbitrary, Y: 0.02mV/div.

FIG. 5 Φ-V characteristics of the dc SQUID for various bias points. (a)In case of 30% indium concentration, the output voltage is comparable to that of conventional dc SQUID. (b)The output voltage is small for the pure lead sample.

in this pure Pb sample because of the large mean free path. However, the coherence length is also large. Thus the coherency of the phase is kept between both sides of the injected area even for the large , and the weak link characteristics are shown.

V. CONCLUSIONS

The characteristics of the quasiparticle-injected weak links were observed under various indium concentrations and injector sizes. We observed that the size of the depressed region in the strip line does not depend on the size of the injected area; however it does depend on the indium concentration, and a larger normal resistance was achieved for the samples with the larger indium concentration. Finally, based on these observations of the basic properties, we applied the weak links with large normal resistance to dc SQUID and obtained a large output voltage.

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REFERENCES

1. L. Solymar, Superconductive Tunnelling and Applications (Chapman and Hall Ltd., London, 1972).
2. Ting-wah Wong, J.T.C. Yeh, and D.N. Langenberg, Phys. Rev. Lett. **37**, 150(1976).
3. I. Iguchi, J. Appl. Phys. **59**, 533(1986).
4. R.C. Dynes, V. Narayanamurti, and J.P. Garno, Phys. Rev. Lett. **39**, 229(1977).
5. K.E. Gray and H.W. Willemsen, Phys. Rev. Lett**41**, 812(1978).
6. C.S. Owen and D.J. Scalapino, Phys. Rev. Lett. **24**, 1559(1972).
7. W.H. Parker, Phys. Rev.**B12**, 3667(1975).
8. Ting-wah Wong, J.T.C. Yeh, and D.N. Langenberg, IEEE. Trans. Mag.**MAG-13**, 743(1977).
9. A. Rothwarf and B.N. Taylor, Phys. Rev. Lett. **19**, 27(1967).
10. K. Kojima, S. Nara and K. Hamanaka, Appl. Phys. Lett.**47**, 327(1985).
11. P.K. Hansma, Phys. Rep.**30**, 145(1977).
12. KMER is a registered trademark of the Eastman Kodak Company, Rochester, N.Y.
13. M. Tinkham, Introduction to Superconductivity (McGraw-Hill, Inc., New York, 1975).
14. K.K. Likharev, Rev. Mod. Phys.**51**, 101(1979).
15. M.B. Ketchen and J.M. Jaycox, Appl. Phys. Lett. **40**, 736(1982).
16. S.B. Kaplan, J. Low. Temp. Phys.**37**, 343(1979).
17. N. Ohkawa, T. Noguchi and K. Hamanaka, Jpn. J. Appl. Phys.**24**, L798(1985).