Oscillations of Josephson Supercurrent in Pb/Al/AlO_x/Pb Junctions

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Oscillations of the Josephson supercurrent have been observed in Pb/Al/AlO_x/Pb junctions. The oscillations only occur in the temperature dependence of the supercurrent in a constant magnetic field. Causes for these oscillations are discussed in terms of the change of the London penetration depth and the Josephson penetration depth with temperature.

1. INTRODUCTION

There has been extensive studies [1-3] in the temperature and magnetic field dependence of the Josephson junctions with SNS structures. The magnetic field dependence of the Josephson supercurrent for a uniform current distribution follows a simple Fraunhofer diffraction. However, for a nonuniform current distribution, the I_c versus T can deviate from a Fraunhofer behavior. Indeed for a step-like current distribution, one found [4]

$$I_c\left(\frac{\Phi}{\Phi_0}\right) = I_c(0) \left(\frac{2s}{\xi\ell + 2s}\right) \left| \frac{\xi\ell}{2s} \frac{\sin\left(\pi \frac{\ell}{L} \frac{\Phi}{\Phi_0}\right)}{\pi \frac{\ell}{L} \frac{\Phi}{\Phi_0}} + \frac{\sin\left(\pi \frac{s}{L} \frac{\Phi}{\Phi_0}\right)}{\pi \frac{s}{L} \frac{\Phi}{\Phi_0}} \cos\left[\pi \left(\frac{\ell+s}{L}\right) \frac{\Phi}{\Phi_0}\right] \right| \quad (1)$$

where $\Phi = H_y L d$, $d = d_n + 2\lambda_s$ and $\ell = L - 2s$.

By examining the $I_c(B, T)$ surface in some earlier works [3]. It was found that the relative phase of the Cooper pair passing through the junction can be changed either by changing the temperature, that is, quantum oscillations have been observed in the I_c versus T curve. Oscillation with temperature arise from the field penetration depth and Josephson penetration depth. The previous work was placed on the changes which occur because λ_L arises. In this work, emphasis is placed on changes in J_c versus T curves which occur because λ_s changes.

2. EXPERIMENTALS

The samples were Josephson junctions with Pb/Al/AlO_x/Pb structures. The bottom Pb-strip was first evaporated onto a glass substrate in a 10^{-6} torr vacuum system. A second square-layer of aluminum was next depositing on the top of the Pb-strip. The sample was exposed to air for about 10 minutes. The junction was completed by evaporating a third layer of Pb-strip across the sample. The thickness of Al is about 110 nm. The external fields were shielded by layers of Mu-metals. The magnetic field and temperature dependence of the sample were measured.

3. CURRENT-VOLTAGE CHARACTERISTICS

The junctions show well-defined supercurrent up to some critical value, I_c , above I_c , the I-V curve rises sharply. There was hysteresis in the I-V curve. Typical values of I_c are about 5 mA for a square junction with width 0.6 mm at 4.2 K.

4. TEMPERATURE DEPENDENCE OF J_c

The critical current of SNIS^C junctions increases monotonically as temperature decreases. This I_c versus T behavior is similar to those observed in reference [5]. In Fig. 1 the temperature dependence of J_c is indicated for T close to T_c . J_c follows a behavior which can be expressed as

$$J_c = 9.62 (1 - T/T_c)^{3/2} \text{ (A/cm}^2\text{)}, \quad (2)$$

Near T_c , good agreement is found between theory [6] and experiment for the temperature dependence of the Josephson supercurrent.

Figure 1. Temperature dependence of J_c for sample A near T_c .

5. MAGNETIC FIELD DEPENDENCE OF I_c

A number of factors can distort the I_c versus H behavior from a single Fraunhofer pattern. In a nonuniform current distribution, the I_c versus B curve can be completely different from a uniform current distribution. In Fig. 2 the J_c versus T curve is indicated for a sample at 5.72 K. The solid curve is the theoretical calculation based on Eq. (1). In the fitting we have assumed $\xi = 0.007$, $s/L = 0.022$. The I_c versus H curve shows similar behavior at high temperatures. However the magnetic field period is larger at lower temperatures compared to that observed at higher temperatures. Fig. 3 shows the temperature dependence of Josephson supercurrent at $H = 4.4$ G and 4.7 G for sample A. Oscillations of J_c have been observed in the J_c versus T curves and small changes in H modulate

Figure 2. Magnetic field dependence of J_c at 5.72 K for sample A. The solid curve is based on Eqs.(1),(2) and (3); $\xi = 0.007$, $s/L = 0.022$.

radially the curves. To understand the oscillatory J_c versus T curves, it's helpful to recall several the characteristic lengths that control the flow of currents. The regime $W < \lambda_J$, the effective area of the junction for the magnetic field penetration is $(d_n + 2\lambda_s(T))$, where λ_s is the penetration depth in the S-layer, d_n is the normal layer thickness, because λ_s changes with temperature, the effective area of the junction changes in a predictable way [1]. One observes an oscillation J_c versus T as successive vortices enter the junction as the area changes. For the junction reported here W/λ_J is small for T near T_c . The oscillatory J_c versus T behavior can be explained by considering a three-dimensional $I_c(H,T)$ surface. Assuming the I_c varies with magnetic field according to Eq.(1) and the variation of $\lambda_s(T)$ according to the following equation:

$$\lambda_s(T) = 390(1 - (T/T_c)^4)^{-1/2}, \quad (3)$$

in units of Å. Using Eqs. (1), (2) and (3), we

Figure 3. Oscillatory J_c versus T at $H=4.4$ G and $H=4.7$ G near T_c . Small changes in H modulate radially the curves.

should obtain a series of $I_c(H,T)$ surfaces at various temperatures. As one moves from low temperature toward higher temperature at a constant magnetic field, one will encounter a series of current minima and oscillatory J_c versus T behavior will be obtained as shown in Fig.3. The agreement between theory and experiment is not quite good. However the basic oscillatory J_c versus T behavior is clearly demonstrated. Fig.4 shows the J_c versus T in constant magnetic field for sample B at $H=5.4$ G and 5.2 G. Small changes of magnetic field also modulate the J_c versus T curves.

Figure 4. J_c versus T curve at $H=5.4$ G and 5.2 G for sample B. Oscillatory behavior was also observed.

6. CONCLUSIONS

Oscillatory J_c -versus- T curves were observed in constant magnetic fields in Pb/Al/AIO_x/Pb junctions, and small changes in H will modulate radially the shape of the curves. As one increases the temperature toward T_c , successive flux quanta will enter the junction through the variation of $\lambda_s(T)$ and results an oscillatory J_c behavior. Quantum interference in SNIS junction agrees qualitatively well with the present theory, and the experiment shows that either H or T can control the interference of the Josephson supercurrent.

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