SCREENING EFFECTS IN NORMAL STATES OF HIGH-\(T_c\) SUPERCONDUCTOR

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ABSTRACT

The capacitance-voltage (C-V) characteristics were measured at various temperatures by using the Ag-MgO-high-\(T_c\) superconductor (\(\text{Ba}_2\text{YCu}_3\text{O}_x\) and \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x\)) MIS diode structure. With decreasing temperature, the capacitance of \(\text{Ba}_2\text{YCu}_3\text{O}_x\) films decreases. This temperature dependence of the capacitance will be discussed based on a marginal Fermi liquid theory.

Key words: High-\(T_c\) superconductor, Normal states, Screening effects, Marginal Fermi liquid, C-V characteristics, MIS diode

1. INTRODUCTION

Recently, the metal-insulator-superconductor (MIS) diode structures have been fabricated using high-\(T_c\) superconducting materials and the electric field effect measurements have been performed.\(^1\)\(^2\) However, the capacitance-voltage characteristics are analyzed by a conventional (unjustified) semiconductor model on a normal state of high-\(T_c\) superconductor.

In this work, we report the fabrication of Ag-MgO-high-\(T_c\) superconductor MIS diode (\(\text{Ba}_2\text{YCu}_3\text{O}_x\) and \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x\)) and C-V characteristics measured at various temperatures. Temperature dependence of capacitance will be discussed based on a marginal Fermi liquid theory.

2. EXPERIMENTAL

\(\text{Ba}_2\text{YCu}_3\text{O}_x\) and \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x\) thin films deposited by rf magnetron sputtering on MgO(100) substrates. As-grown films showed superconducting transition at \(\sim 84\text{K}\) for \(\text{Ba}_2\text{YCu}_3\text{O}_x\) and \(\sim 70\text{K}\) for \(\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x\). MgO insulating layer was deposited by electron beam evaporation at 200~300°C. Ag gate and ohmic electrodes were formed by using the vacuum evaporation with metal mask. The C-V characteristics were measured at various temperatures under the probe signal with 100kHz and 10mV. The dc bias was swept at rates of 10~20V/min between -15 and 15V.

3. RESULTS

Most of C-V characteristics showed constant capacitance of MgO films independent of bias voltage. However, some of C-V characteristics showed that the MIS diode worked like a p-type or intrinsic semiconductor MIS diode. For Ag-MgO-Ba\(_2\)YCu\(_3\)O\(_x\) MIS diode, C-V characteristics were symmetrical with a maximum capacitance at \(V=0\), as shown in Fig. 1. In positive bias region, small hysteresis were observed at larger temperatures (300K and 250K). This symmetrical C-V curve suggests that a very thin intrinsic semiconductor-like layer exists at the interface between Ba\(_2\)YCu\(_3\)O\(_x\) and MgO. With decreasing temperature, the capacitance at zero bias decreases due
Fig. 1. Symmetrical C-V characteristics of Ag-MgO-BYCO MIS diode at different temperatures.

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to the decrease of the capacitance of Ba$_2$YCu$_3$O$_x$ film. These characteristics seem to reflect the screening effects in the normal state of high-$T_c$ superconductors, which will be discussed theoretically.

4. DISCUSSION

We shall discuss the experimental temperature dependence of capacitance. This temperature dependence can be described phenomenologically by the model that the screening distance of the high-$T_c$ normal film is about 10nm and the screening distance increases as temperature increases. The normal Fermi liquid shows this behavior for the abnormal case that $E_F$ (Fermi energy) $\propto kT$ ($T$: temperature).

We try to explain the experimental temperature dependence of capacitance based on a marginal Fermi liquid theory. This theory assumes a single hypothesis: There exist charge- and spin-density excitations in normal states of high-$T_c$ superconductors. And the absorptive part of the polarizability due to these excitation is proportional to $\omega / T$ at low frequencies and constant otherwise. This theory could explain successfully the abnormal properties of normal state of high-$T_c$ superconductors, that is, Raman scattering has the large featureless, nearly frequency- and temperature-independent background, the temperature dependence of resistivity is proportional to $T$, and the tunnel conductance $g(V)$ ($V$: bias voltage) is given by the form

$$g(V) \sim g_0 + g_1|V|.$$  

(1)

Assuming that the wave-number dependent static dielectric function $\varepsilon(q, 0)$ is given by

$$\varepsilon(q, 0) = \varepsilon_0 \left(1 + \frac{q^2}{q^2_c}\right),$$  

(2)

the capacitance $C_e$ per unit area due to electrons is expressed by the equation

$$C_e = \frac{2\varepsilon_0 \varepsilon_0}{1 - \varepsilon^{-\omega L}},$$  

(3)

where $L$ is the thickness of the films. Then, the total capacitance $C$ per unit area becomes that

$$C = \varepsilon_1 - \frac{1}{L} + C_e,$$  

(4)

where $\varepsilon_1$ is the ionic dielectric constant.
The marginal Fermi liquid theory yields that
\[ \varepsilon_0 \sim \left( 1 - c \ln \frac{\hbar \omega_c}{k_B T} \right)^{-1} \]
and
\[ \varepsilon_0 \xi_0^2 \sim \left( 1 - 2g^2 N^2(0) \ln \frac{k_B T}{\hbar \omega_c} \right)^{-1}, \]
where \( \omega_c \) is the cut-off frequency of charge- and spin-excitations, \( g \) is a coupling constant appeared in ref.3, and \( N(0) \) is the unrenormalized one-particle density of states. Experimentally, \( \omega_c \sim 1200 \text{cm}^{-1} \) and \( c \sim 0.1 \). Equations (5) and (6) are derived in Appendix. The experimental temperature dependence of the capacitance of Ba\(_2\)YCu\(_3\)O\(_x\) films can be explained qualitatively assuming the conditions that
\[ q_0 L \gg 1 \]
\[ \varepsilon/ L \ll \varepsilon_0 q_0 \text{ and } g^2 N^2(0) \sim 3.5 \gg c \sim 0.1. \]
Under these conditions, total capacitance \( C \) per unit area of Ba\(_2\)YCu\(_3\)O\(_x\) films becomes that
\[ C \approx 2\varepsilon_0 \xi_0 \propto \left( 1 - 2g^2 N^2(0) \ln \frac{k_B T}{\hbar \omega_c} \right)^{-\frac{1}{2}}. \]
The value (~10nm) of screening distance suggests that the electronic coupling between CuO\(_2\) plane is very weak.

Figure 2 shows the temperature dependence of the capacitance of Ba\(_2\)YCu\(_3\)O\(_x\) film obtained experimentally and that calculated using Eq.(8). Calculated values coincide semiqualitatively with the experimental results. This means that the temperature dependence of the capacitance of Ba\(_2\)YCu\(_3\)O\(_x\) film can be explained qualitatively based on a marginal Fermi liquid theory.

5. CONCLUSIONS

The capacitance-voltage (C-V) characteristics were measured at various temperatures by using the Ag–MgO–high-\( T_c \) superconductor (Ba\(_2\)YCu\(_3\)O\(_x\) and Bi\(_2\)Sr\(_2\)CaCu\(_2\)O\(_x\)) MIS diode structure. The capacitance of Ba\(_2\)YCu\(_3\)O\(_x\) film decreases as temperature decreases. This temperature dependence of the capacitance can be explained qualitatively based on a marginal Fermi liquid theory.

REFERENCES

APPENDIX

Kramers-Kronig relation for a dielectric function gives the equation

\[ \frac{1}{\varepsilon_0} = 1 - \frac{1}{4\pi^2} \int_{0}^{\infty} \frac{\sigma_2(\omega)}{\omega^2} d\omega, \]  
(A.1)

where \( \sigma_2(\omega) \) is the imaginary part of ac conductivity with an angular frequency \( \omega \). The theoretical fitting of the experimental value of \( \sigma_2(\omega) \) in \( \text{Ba}_2\text{YCu}_3\text{O}_x \) was done in ref. (3), which leads to

\[ \varepsilon_0 = 1.13 \left( 1 - 0.077 \ln \frac{\hbar \omega_c}{k_B T} \right)^{-1}. \]  
(A.2)

This can be approximated by eq. (5).

Random phase approximation (RPA) on a density correlation function \( g_q(\tau) \) can be written by

\[ g_q(\tau) \equiv -(T\rho_q(\tau)\rho_{-q}(0)) \]

\[ = \sum_k \langle T\sigma_k^{\dagger}(\tau)\sigma_{-k}(0)\rangle\langle T\sigma_k^{\dagger}(0)\sigma_k(\tau) \rangle, \] 
(A.3)

where \( \rho_q \) is the electron density operator with the wave number \( q \), and \( a_k^{\dagger} \) and \( a_k \) are the ordinary creation and annihilation operator, and \( T_\tau \) is a time ordering operator and symbol \( \langle A \rangle \) denotes a thermal average of operator \( A \).

Using a one-electron spectral function given by

\[ S(k, \omega) = \frac{1}{\pi} \frac{\text{Im} \Sigma(\omega)}{(\omega - \xi_k - \text{Re} \Sigma(\omega))^2 + \text{Im}^2 \Sigma(\omega)} \]  
(A.4)

(\( \Sigma(e) \) is the self-energy part of an electron green function and \( \xi_k \) is the energy of a free electron measured from a Fermi energy), we have that

\[ \varepsilon_0 g_0^2 = 4\pi e^2 N(0) P(T), \]  
(A.5)

(\( e \) is charge of electron)

where

\[ P(T) \simeq \frac{2}{\pi} \int_{0}^{\infty} \frac{2\text{Im} \Sigma(e)}{(e - 2\text{Re} \Sigma(e))^2 + (2\text{Im} \Sigma(e))^2} \text{d}e \]  
(A.6)

Substituting the explicit form of \( \Sigma(\omega) \) given by ref. (3) in eq. (A.5), we obtain that

\[ P(T) \simeq \frac{2}{\pi} \int_{0}^{\infty} \pi k_B T g^2 N^2(0) \left( \frac{\pi k_B T g^2 N^2(0)}{\frac{\hbar \omega_c}{k_B T}} \right)^{2\tau - 1} \text{d}\omega' \]

\[ \simeq \left( 1 - 2g^2 N^2(0) \ln \frac{k_B T}{\hbar \omega_c} \right)^{-1}. \]  
(A.7)
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