Retention of the pairing mechanism by coupled surface-plasmon-polariton waves in the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattices

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The real part of the effective dielectric constant is drastically depressed by taking into account the coupling of surface-plasmon-polariton waves excited between neighboring superconducting layers. It is depressed to as low as −20 000 in the infrared region from 20 to 100 meV as the thickness ratio of the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattice changes from 1.2:9.6 to 4.8:1.2. This large negative dielectric constant causes Cooper pairs to be mediated by a boson-type plasmon. The superconducting state can be retained along the film-growth direction even when the thickness of the interposing insulating layer is larger than the coherence length.

The obstacle preventing the high-T_c superconductors from being successful Josephson devices may be the intrinsically short coherent length[1,2] that precludes tunneling by the paired electrons through the insulating bridge. Recent developments in the growth of Y-Ba-Cu-O/Dy(Pr)-Ba-Cu-O superlattices[3,4] indicate that the alloy can retain its superconducting state even when the interposing insulating $PrBa_2Cu_3O_7$ layers have a thickness greater than the coherence length in the growth direction (i.e., in the c axis). This leads us to believe that the coherence length might be increased in the superlattice structure. Several models of the superconductivity mechanism have been proposed for the high-T_c superconductors. The conventional phonon-mediated BCS theory is suspected to yield a critical temperature as high as 90 K, and the other mechanisms such as magnon-, exciton-, and bipolaron-mediated Cooper pairings are still unjustified. The survival of high-T_c in the superlattice structure implies a strong coupling of the plasmon-mediated pairing. In this work, we find that the surface-plasmon excited in each superconducting layer can interfere with those in neighboring layers to form coupled surface-plasmon-polariton waves (CSPPW) if the interposing insulating layer is thin enough. A prerequisite to the formation of CSPPW's is a negative dielectric constant in one of the interface media. The experimental reflectivity[5–7] $R(\omega)$ and conductivity[7–9] $\sigma(\omega)$ measured in the infrared region shows that the dielectric constant of the $YBa_2Cu_3O_7$ is negative. This infrared radiation may be generated by the Josephson tunneling between grains even with a dc bias applied. The CSPPW can largely increase the negative value of the effective dynamic dielectric constant $\epsilon'(\omega,q)$ of the superlattice.

The periodic structure of the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattice in conjunction with the electromagnetic waves propagating in the medium is sketched in Fig. 1. The transverse wave vector $\mathbf{q}$ for a p-polarized wave propagating in the insulator has components of $\mathbf{q}=(Q,0,\pm q)$ specifying a wave form of $\psi=\psi_0 e^{iqz}e^{i(\mathbf{Q}\cdot\mathbf{x}-\omega t)}$. Inside the metal film, the excitation of collective charge motion can stimulate both the transverse and longitudinal waves with wave vectors given, respectively, by $\mathbf{k}=(Q,0,k)$ and $\mathbf{l}=(Q,0,l)$. Since the dielectric constant ϵ_M of $YBa_2Cu_3O_7$ is very large, the optical size effect can be neglected and the dispersion relation of the transverse wave vector $Q(\omega)$ (Ref. 10) as dictated in Eq. (5) of Ref. 11 can be simplified to yield

$$2\cosh(Qa)\sinh(Qb)+\sinh(Qa)[P_2e^{Qb}-P_1e^{-Qb}]=0\ , \tag{1}$$

where

$$P_1=\frac{\epsilon_I^2-\epsilon_M\epsilon_c}{\epsilon_I(\epsilon_c-\epsilon_M)} \quad\text{and}\quad P_2=\frac{\epsilon_I^2+\epsilon_M\epsilon_c}{\epsilon_I(\epsilon_c+\epsilon_M)}\ .$$

This equation constrains the allowable values of the wave vector parallel to the surface.

To elucidate the transformation of the wave propagating through multilayers of media, we employ a transfer matrix $\underline{M}'$ to correlate the electric and magnetic fields at layer Z_M+d with the next neighboring $Z_{M'}$ such as

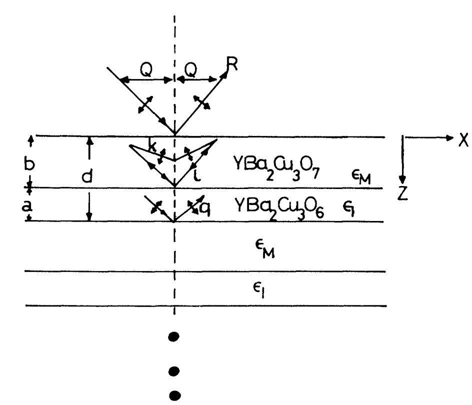

FIG. 1. Schematic diagram of the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattice. The transverse wave vectors $\mathbf{q}$ and $\mathbf{k}$ are for the insulator and superconductor layers, respectively, while in the superconductor there exists another longitudinal mode $\mathbf{l}=(Q,0,l)$.

$$\begin{bmatrix} E_x \\ B_y \end{bmatrix}_{Z_M+d} = \underline{M}' \begin{bmatrix} E_x \\ B_y \end{bmatrix}_{Z_M} = \begin{bmatrix} m'_{11} & m'_{12} \\ m'_{21} & m'_{22} \end{bmatrix} \begin{bmatrix} E_x \\ B_y \end{bmatrix}_{Z_M} . \quad (2)$$

Exploiting the continuity equations of B and E at the boundaries of insulator and metal films in aid of Gauss's and Ampere's laws, we can obtain the transfer-matrix elements for the boundary condition that the cover layer of the semi-infinite superlattice is metal film. They are

$$\begin{aligned} m'_{11} &= m_{11}\cos^2 qa + m_{22}\sin^2 qa \\ &\quad + i(Z_I m_{21} - Y_I m_{12})\sin qa \cos qa , \\ m'_{12} &= m_{12}\cos^2 qa + m_{21} Z_I^2 \sin^2 qa \\ &\quad + i(m_{22} - m_{11}) Z_I \sin qa \cos qa , \\ m'_{21} &= m_{21}\cos^2 qa + m_{12} Y_I^2 \sin^2 qa \\ &\quad + i(m_{11} - m_{22}) Y_I \sin qa \cos qa , \\ m'_{22} &= m_{22}\cos^2 qa + m_{11}\sin^2 qa \\ &\quad + i(Y_I m_{12} - Z_I m_{21})\sin qa \cos qa , \end{aligned} \quad (3)$$

where m_{ij} are the transfer-matrix elements tabulated in Ref. 12 in the case of the covering layer being an insulator, and $Z_I = qc/\epsilon_I \omega$, $Y_I = 1/Z_I$ are the surface impedance and the conductance of the insulator, respectively.

For waves propagating in a superlattice with period d, the solution of the Schrödinger equation takes the Bloch form $e^{ipz}u(z)$. Here $p(\omega)$ is the one-dimensional (1D) Bloch wave vector which yields

$$\begin{bmatrix} E_x \\ B_y \end{bmatrix}_{Z+d} = e^{ipd} \begin{bmatrix} E_x \\ B_y \end{bmatrix}_{Z} . \quad (4)$$

The nontrivial solution of Eqs. (2) and (4) requires that the secular determinant

$$|\underline{M}' - 1e^{ipd}| = 0 . \quad (5)$$

The solution of p implies the permitted bands in the dispersion spectrum, which are determined by

$$\cos pd = \Big[\cos(qa)[l\sin lb \cos kb - Q(W_I - W_M) Y_M \cos lb \sin lb] + \sin(qa)[Q(W_I - W_M) Y_I (1 - \cos lb \cos kb)] - \frac{1}{2}\left\{ l Y_I Z_M + l Z_I Y_M + \frac{Y_I Y_M}{l} Q^2 (W_I - W_M)^2 \right\} \sin lb \sin kb \Big] [l \sin lb - Q(W_I - W_M) Y_M \sin kb]^{-1} , \quad (6)$$

where $W_a = -(Q/\epsilon_a)(c/\omega)$. The eigenvector equation $(\underline{M}' - 1e^{ipd})[{E_x \atop B_y}]_0 = 0$ can be solved explicitly to yield the surface impedance of the superlattice as given by

$$Z = (E_x/B_y) = -\frac{m'_{12}}{m'_{11} - e^{ipd}} = -\frac{m'_{22} - e^{ipd}}{m'_{21}} . \quad (7)$$

With the value of Z, we can evaluate the effective reflectance of the superlattice.

The dielectric constant ϵ_I of the insulator $YBa_2Cu_3O_6$ is always positive[13,8] and occasionally the ϵ_M for the superconducting $YBa_2Cu_3O_7$ is negative in the infrared region at $E < 0.1$ eV. The dielectric constant $\epsilon = \epsilon_1 + i\epsilon_2$ is evaluated using the reported reflectivities and conductivities by manipulating the equations

$$\begin{aligned} \epsilon_1 &= n^2 - k^2 , \quad \epsilon_2 = 2nk = \sigma/\omega\epsilon_0 , \\ R &= |r|^2 = \left| \frac{(n-1)+ik}{(n+1)+ik} \right|^2 . \end{aligned} \quad (8)$$

The results are plotted in Figs. 2 and 3 for $YBa_2Cu_3O_{7-\delta}$ and $YBa_2Cu_3O_6$, respectively.

The numerical values of $\epsilon_I(\omega)$ and $\epsilon_M(\omega)$ are substituted into Eq. (1) to solve for the transverse wave vectors $Q(\omega)$ which are permitted to propagate through the superlattice and are shown in Fig. 4. The line shapes remain similar for different thicknesses of the insulating layer, except that the magnitude of $Q(\omega)$ decreases as the thickness of $YBa_2Cu_3O_6$ increases as the result of a suppression of plasmon-polariton coupling between metallic layers. To find the effective dielectric constant of the superlattice, we may consider the whole structure to be like a new material. This material exhibits its exotic reflectance relevant to the coupled surface-plasmon-polariton waves. The reflectance of the superlattice arising from the mismatch of the surface impedance is given by

$$r = (Z_v - Z)/(Z_v + Z) , \quad (9)$$

where $Z_v = (1 - Q^2c^2/\omega^2)^{1/2}$ is the surface impedance of

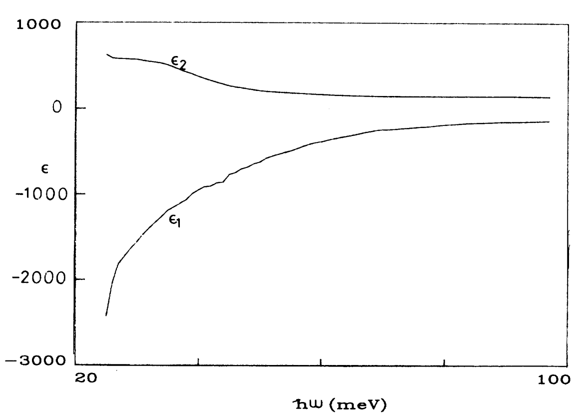

FIG. 2. The real ϵ_1 and imaginary ϵ_2 parts of the dielectric constant of $YBa_2Cu_3O_7$ at 20 K in the infrared region.

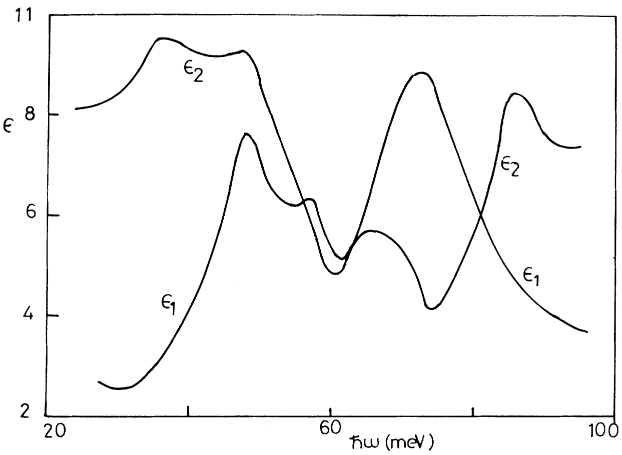

FIG. 3. The ϵ_1 and ϵ_2 for $YBa_2Cu_3O_6$.

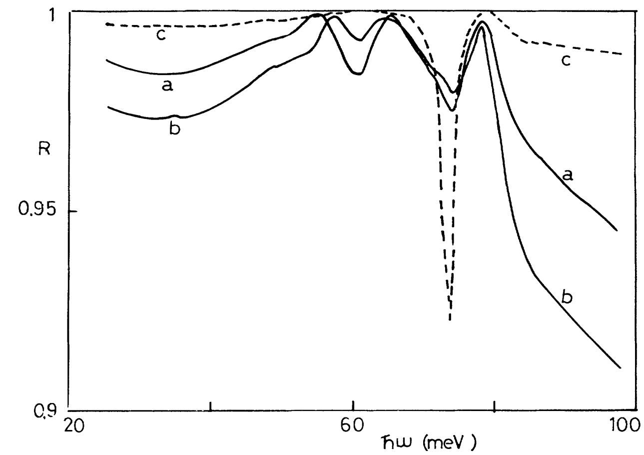

FIG. 5. The simulated reflectance of the same superlattice with a thickness ratio of (a) 1.2:1.2, (b) 1.2:4.8, and (c) 1.2:9.6, respectively.

air. The transfer matrix elements m'_{11}, m'_{12} and the dispersion of the 1D Bloch wave vector $p(\omega)$ can be evaluated by using Eqs. (3) and (6). The parameters for the $YBa_2Cu_3O_7$ used in this calculation are $\omega_p = 0.58$ eV, $\tau = 4.5\times10^{-15}$ s, and $V_F = 5\times10^5$ m/s. The calculated reflectance for the superlattice obtained by considering the 1D Bloch dispersion relation is shown in Fig. 5, which indicates a resonant coupled surface-plasmon-polariton dip near 70 meV. This value is close to the energy gap relevant to the CuO_2 planes (i.e., $2\Delta = 8kT_c = 63.4$ meV). With the reflectance of the superlattice, the real and imaginary parts of the effective dielectric constant of the system can be retrieved from Eq. (8) and are depicted in Figs. 6 and 7, respectively. The absolute values for ϵ_1 and ϵ_2 both increase sharply as the thickness of the interposing insulating layer decreases. Keeping the thickness of the $YBa_2Cu_3O_6$ layer to be below 2.4 nm, the magnitudes of ϵ_1 and ϵ_2 increase slightly as the thickness of the insulating layer increases, thus indicating a critical thickness of the metal film for effective excitation of surface plasmons.

The general equation for the critical temperature including the nonphononic-mediated mechanism can be expressed by[14]

$$T_c \simeq 1.14\theta \exp[-1/(\lambda-\mu^*)] , \qquad (10)$$

where θ is some characteristic temperature and the quantities λ and μ^* are directly connected with the effective interaction between electrons governed by the dielectric function $\epsilon'(\omega,q)$ of the system as given by

$$\lambda-\mu^* = N(0)\langle V_{\text{eff}}(\omega,q)\rangle = N(0)\left\langle \frac{4\pi e^2}{q^2\epsilon'(\omega,q)} \right\rangle . \qquad (11)$$

The superconducting state appears only when the force between electron pairs is attractive, which implies that $\epsilon'(\omega,q) < 0$, in which T_c has an upper limit and the smaller the value of $|\epsilon'(\omega,q)|$, the higher the T_c. From the Kramers-Kronig relation, we have the static dielectric function

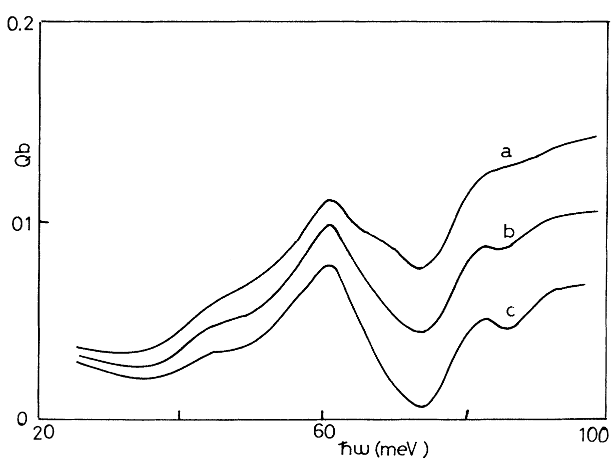

FIG. 4. The dispersion of the transverse wave vector $Q(\omega)$ for the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattice with a thickness ratio of (a) 1.2:1.2, (b) 1.2:4.8, and (c) 1.2:9.6, respectively.

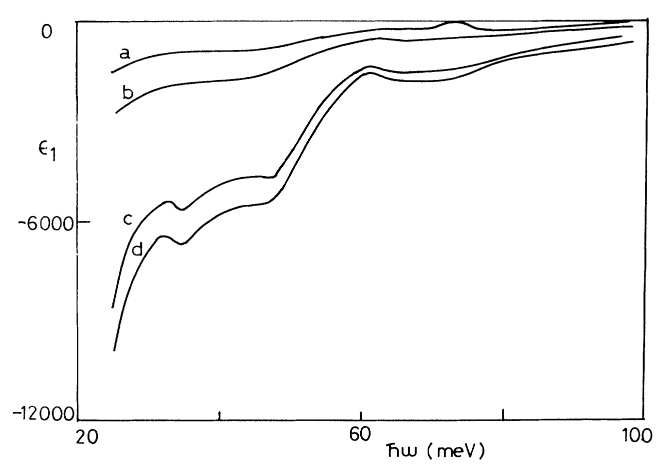

FIG. 6. The calculated real part of the effective dielectric constant of the same superlattice for a thickness ratio of (a) 1.2:9.6, (b) 1.2:4.8, (c) 1.2:1.2, and (d) 2.4:2.4, respectively.

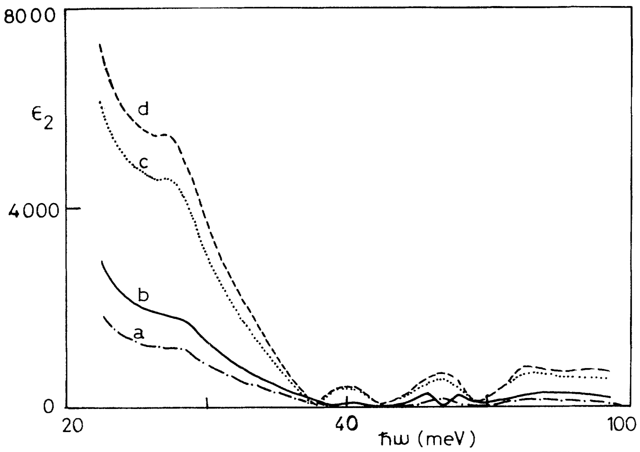

FIG. 7. The calculated imaginary part of the dielectric constant for the superlattice described in the caption of Fig. 5.

$$\epsilon'(0,q)=1+\frac{1}{\pi}\int_0^\infty \frac{d\omega'^2}{\omega'^2}\mathrm{Im}\epsilon'(\omega',q) \ . \tag{12}$$

If the imaginary part of the dynamic dielectric function is positive, then the static dielectric function $\epsilon(0,q)\geq 1$. The requirement that $\epsilon'(\omega,q)<0$ for the appearance of the superconducting state does not preclude the static dielectric function $\epsilon(0,q)$ from being positive. The retention of the superconducting state by keeping $\epsilon'(\omega,q)<0$ in the $YBa_2Cu_3O_7/YBa_2Cu_3O_6$ superlattice even when the thickness of the insulating layer is larger than the coherence length ξ_c is consistent with the experimental results.[3,4] A superficial inspection of Eq. (10) would lead us to expect degrading of T_c in the superlattice structure due to the negative suppression of the ac effective dielectric constant. But envisaging the possible increase of the density of states $N(0)$ near the Fermi level in the superlattice, as a result of the constraint of conduction-electron wave function in the potential well, the critical temperature can be kept at a rather high value. As demonstrated in the experimental works of Ref. 4, the smaller the real part of the dynamic dielectric function, the higher the T_c. Therefore, merely counting on the value of $\epsilon'(\omega,q)$ in Eq. (11) to evaluate T_c is not adequate.

In conclusion, we find that the effective dynamical dielectric function of the superconductor/insulator superlattice is largely suppressed to a negative value by the coupled surface-plasmon-polariton waves in the infrared region. Since a negative dynamical dielectric function is essential for yielding pairing electrons, we surmise that the superconductivity mechanism of the layered structure might be plasmon mediated. This work also elucidates that the lower the negative value of the real part of the effective dynamical dielectric function, the higher the T_c.

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