Anisotropic dielectric constant of the parent antiferromagnet Bi$_2$Sr$_2$M Cu$_2$O$_8$ ($M$=Dy, Y and Er) single crystals

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Abstract: The anisotropic dielectric constants of the parent antiferromagnet Bi$_2$Sr$_2$M Cu$_2$O$_8$ ($M$=Dy, Y and Er) single crystals were measured from 80 to 300 K. The in-plane dielectric constant is found to be very huge ($10^4 - 10^5$). This suggests a remnant of the Fermi surface of the parent antiferromagnet. The out-of-plane dielectric constant is 50-200, which is three orders of magnitude smaller than the in-plane one. A significant anomaly is that a similar out-of-plane dielectric constant is observed in superconducting samples.

Keywords: parent antiferromagnet, dielectric constant, insulator-metal transition

INTRODUCTION

In a low hole density, the CuO$_2$ plane shows high resistivity and antiferromagnetic (AF) order at low temperature, which is called a parent AF insulator. With doping, an insulator-metal transition (IMT) arises, and the system changes from the AF insulator to a superconductor. For IMT, the dielectric constant $\varepsilon$ is of great importance in the sense that it provides a measure of localization length in the insulator. Chen et al. have first pointed out the importance of $\varepsilon$ in the studies of high-$T_c$ cuprates (HTSC). However, they studied $\varepsilon$ only for La$_2$CuO$_4+\delta$, which has various structural phase transitions that might affect $\varepsilon$ seriously. Another problem is that they studied $\varepsilon$ only near 4.2 K, although the resistivity anisotropy was strongly dependent on temperature. Thus it should be further examined to study $\varepsilon$ for other HTSC over a wider temperature range.

We have been studying the charge transport of the parent insulator Bi$_2$Sr$_2$M Cu$_2$O$_8$ ($M$=Y and rare-earth). In this proceedings we report on measurements and analyses of the anisotropic dielectric constants from 80 to 300 K.

EXPERIMENTAL

Single crystals of Bi$_2$Sr$_2$M Cu$_2$O$_8$ ($M$=Dy, Y and Er) were grown by a self-flux method. The growth conditions and the sample characterization were described in Ref 2. The resistivity was measured using a four-probe technique, and a ring configuration was used for the out-of-plane direction. The dielectric constants were measured with a two-probe technique using a lock-in amplifier (Stanford Research SR630 and SR844). A typical contact resistance was 50-100 $\Omega$ for the in-plane direction, and 1-10 $\Omega$ for the out-of-plane direction. Thus the measurement along the in-plane direction is less accurate near room temperature, where the contact resistance becomes comparable with the sample resistance. Detailed information on the measurements will be written elsewhere.

All the samples of Bi$_2$Sr$_2$M Cu$_2$O$_8$ were insulating, and the doping levels of the as-grown crystals were slightly different for different $M$. We do not yet understand the $M$ dependence, but the melting points and/or the liquidus lines may depend on $M$ to give a slight variation in composition. Thus crystals with different $M$’s act as a set of parent insulators with slightly different doping levels. We estimated the hole concentration per Cu ($p$) by measuring the room-temperature thermopower. With good reproducibility, $M$=Dy was nearly undoped ($p$=0-0.02), and $M$=Er and Y were slightly doped ($p$=0.02-0.04). The doping levels (and the measurement results) were nearly the
The reciprocal of the dielectric constant ($1/\varepsilon$) plotted as a function of hole concentration per Cu. The temperature dependence is also different between $M=\text{Er}$ and $M=\text{Dy}$. In particular, $\rho_{ab}$ for $M=\text{Er}$ is nearly independent of temperature at 300 K, which indicates that the in-plane conduction is nearly metallic. It should be noted here that $\rho_{ab}/\rho_{a}^{0}$ is strongly dependent on temperature and the doping levels, which suggests the confinement behavior in the AF insulator.

RESULTS AND DISCUSSION

Figure 1 shows the in-plane resistivity ($\rho_{ab}$) and the out-of-plane resistivity ($\rho_{c}$) for $M=\text{Er}$ and Dy. Reflecting the different doping levels, both $\rho_{ab}$ and $\rho_{c}$ are larger for $M=\text{Dy}$ than for $M=\text{Er}$. The temperature dependence is also different between $M=\text{Dy}$ and $M=\text{Er}$. In particular, $\rho_{ab}$ for $M=\text{Er}$ is nearly independent of temperature at 300 K, which indicates that the in-plane conduction is nearly metallic. It should be noted here that $\rho_{ab}/\rho_{a}^{0}$ is strongly dependent on temperature and the doping levels, which suggests the confinement behavior in the AF insulator.

Figure 2 shows the in-plane dielectric constant ($\varepsilon_{ab}$) and the out-of-plane dielectric constant ($\varepsilon_{c}$) for $M=\text{Er}$ and Dy at 1 MHz. Both $\varepsilon_{ab}$ and $\varepsilon_{c}$ are larger for $M=\text{Er}$ than $M=\text{Dy}$, which indicates that the sample for $M=\text{Er}$ is closer to IMT boundary. It should be emphasized that $\varepsilon_{ab}$ is as huge as $10^{4}$-$10^{5}$. We think that the huge $\varepsilon_{ab}$ comes from an electronic origin, because (1) $\varepsilon_{ab}$ is very sensitive to the doping levels and (2) the dielectric loss $\text{Im} \varepsilon_{ab} \propto 1/\rho_{ab}$ is large compared with conventional ferroelectric materials. The charge order or the variable range hopping may be an origin of the huge $\varepsilon_{ab}$. Thus we may say that the huge $\varepsilon_{ab}$ is a remnant of the the Fermi surface calculated by band theories.

An important feature is that $\varepsilon_{c}$ remains positive and finite in the superconducting samples. Kitano et al. [1] found that $\varepsilon_{c}$ of Bi$_2$Sr$_2$CaCu$_2$O$_8$ near $T_c$ was 40-50 at 10 GHz, whereas Terasaki and Tajima [1] measured that it was 120 at 100 MHz. These values are of the same order of $\varepsilon_{c}$ for the parent insulators, and we may say that the out-of-plane conductance of HTSC is a “remnant” of the parent insulator. Another feature is that the temperature dependence of $\varepsilon_{c}$ is different between $M=\text{Er}$ and Dy. Recently we have found that $\varepsilon_{c}$ for all the samples, including superconducting ones, can be understood with the Debye description of dielectric relaxation [2], which has been used for the analyses of the dielectric response of the charge density wave [3].

The reciprocal of the dielectric constant ($1/\varepsilon_{ab}$ and $1/\varepsilon_{c}$) at 80 K is plotted as a function of...
hole concentration per Cu in Fig. 3. For comparison, the data for the superconducting samples are also plotted. $\varepsilon_c$ is employed from Refs. [5, 6], and $\varepsilon_{ab}$ is estimated from the Drude model as $\varepsilon_{ab}(\omega \to 0) = - (\omega_p/\gamma)^2$, where $\omega_p$ and $\gamma$ are the plasma frequency and the damping factor respectively. By putting $\hbar\omega_p = 1.1$ eV and $\hbar\gamma = k_B T$, we get $\varepsilon_{ab} = -2.5 \times 10^4$, which is in the same order of $\varepsilon_{ab}$ for $M=$Dy and Er. As shown in Fig. 3(a), $1/\varepsilon_{ab}$ crosses zero near $\rho = 0.05$, and goes negative in the metallic side. This is exactly what we see IMT in doped Si. On the other hand, although $1/\varepsilon_c$ becomes smaller for $M=$Er than for $M=$Dy, $1/\varepsilon_c$ for the superconducting samples is positive, and stay at the same order. Thus $\varepsilon_c$ is unlikely to diverge at IMT, as Chen et al. previously found that $\varepsilon_c$ for La$_2$CuO$_{4+\delta}$ does not diverge at IMT [1]. We should note that the gross feature of Fig. 3 is not largely dependent on frequency and temperature, although the data for 1MHz at 80 K was rather arbitrarily selected. More detailed analysis is in progress.

Chen et al. pointed out two possibilities for the non-divergent $\varepsilon_c$. One is that IMT in HTSC occurs only along the in-plane direction, and the other is that the heavy effective mass along the out-of-plane direction makes the effective Bohr radius of a hole shorter than the $c$-axis length. Our data favors the former scenario. According to the latter scenario, $\varepsilon_{ab}/\varepsilon_c$ would be equal to the effective mass ratio, which disagrees with our observation that $\varepsilon_c$ for Bi$_2$Sr$_2$CuO$_{4+\delta}$ is larger than $\varepsilon_c$ for La$_2$CuO$_{4+\delta}$. Thus the non-divergent $\varepsilon_c$ does not solely comes from the anisotropic effective mass, but from the anomalous conduction mechanism such as “confinement”.

**SUMMARY**

In summary, we prepared single crystals of Bi$_2$Sr$_2$MCu$_2$O$_8$ ($M=$Y and rare-earth) and measured the anisotropic dielectric constants $\varepsilon_{ab}$ and $\varepsilon_c$ from 80 to 300 K. The present study has revealed that $\varepsilon_{ab}$ ($10^4$-$10^5$) is about three orders of magnitude larger than $\varepsilon_c$ ($10^2$). The huge $\varepsilon_{ab}$ is a remnant of the Fermi surface, where the dc conductivity is suppressed by the strong correlation or localization. We have found that $\varepsilon_c$ remains near $10^2$ across the insulator-metal transition, which means that the transition occurs only along the in-plane direction. This can be a piece of evidence of the confinement behavior of the parent insulators.

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