Temperature dependence of the electronic Raman spectra of $Bi_2Sr_2CaCu_2O_8$ above T_c

M. Hangyo
Research Center for Superconducting Materials and Electronics, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565, Japan

N. Nagasaki and S. Nakashima
Department of Applied Physics, Faculty of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565, Japan
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Electronic Raman spectra of $Bi_2Sr_2CaCu_2O_8$ single crystals have been measured, with attention focussed on the temperature dependence above T_c. The relaxational response function is fitted to the experimental spectra under the assumption that the damping rate is frequency- and temperature-dependent. The temperature dependence of the electrical resistivity calculated using this damping rate coincides well with that of the dc resistivity. Although the spectra divided by the Bose factor show a linear increase with frequency in the low-frequency region, the temperature dependence of the slope seems to be inconsistent with that predicted by the marginal-Fermi-liquid model.

Since the discovery of superconducting-gap excitations,[1,2] two-magnon excitations,[3,4] and anomalous softening of some phonon modes at T_c (Ref. 5) in the Raman spectra of oxide superconductors (and related compounds), there has been much work on Raman scattering of these compounds in order to obtain information on the mechanism of high-T_c superconductivity. The unusual behavior of various physical properties above T_c is though to be closely related to the mechanism of high-T_c superconductivity. Slakey *et al.*[6] measured the temperature dependence of the broad electronic Raman spectra of $YBa_2Cu_3O_7$ (YBCO) above T_c and interpreted the spectra in terms of the imaginary response function associated with the fluctuations of carriers. In this paper, we measured temperature dependence of the electronic Raman spectra of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) in the temperature range mainly above T_c to investigate whether their shape and temperature dependence are common for the high-T_c oxide superconductors. BSCCO has an advantage for the investigation of the electronic spectra compared with YBCO because no strong phonon lines appear in the B_{1g} polarization in BSCCO (Refs. 7 and 8); the strong phonon modes make it difficult to separate the contribution of the electronic part from the phonon part in the low-frequency region for YBCO.

Single crystals used in this study were grown by the KCl flux method.[9–11] Platelike crystals with an area of about 2×2 mm^2 were used for the Raman-scattering measurements. Figure 1 shows the magnetization curve of the specimen used in this study. The critical temperature T_c is $\sim$80 K and the magnetization curve shows a sharp transition at T_c with increasing temperature, indicating that the crystal used in this study has good quality. Raman spectra were excited by the 4880 Å line of an Ar-ion laser. The measurements were done under low laser power densities of less than 10 W/cm^2. The scattered light was dispersed by a double monochromator and detected using conventional photon counting electronics. The sample was mounted on a cold finger of a closed-cycle helium refrigerator and good thermal contact was ensured by securing the sample to a copper plate with silver paint.

Figure 2 shows the polarized (XX) (A_{1g} in the tetragonal symmetry) and depolarized (XY) (B_{1g}) spectra measured at 40 K. Broad background scattering spectra, which peaked at about 300 cm^{-1} for the (XX) polarization and at about 350 cm^{-1} for the (XY) polarization, are seen in the spectra. These broad bands are of electronic origin and associated with the superconducting-gap excitations below T_c.[2] The shapes and peak frequencies of the broad bands are consistent with those reported so far,[2,12] which again indicates a good quality of the sample.

Figures 3 and 4 show the temperature dependence of the (XX) and (XY) spectra above T_c, respectively. The spectra are divided by the Bose factor $n+1$, where

$$n = 1/[\exp(\hbar\omega/kT)-1]$$

and the dark-noise background is subtracted in the spectra. Relatively sharp lines observed in the (XX) spectra have been assigned to phonon modes. No strong phonon bands are seen in the (XY) spectra. Broad background scattering which starts at $\omega=0$ and extends up to above

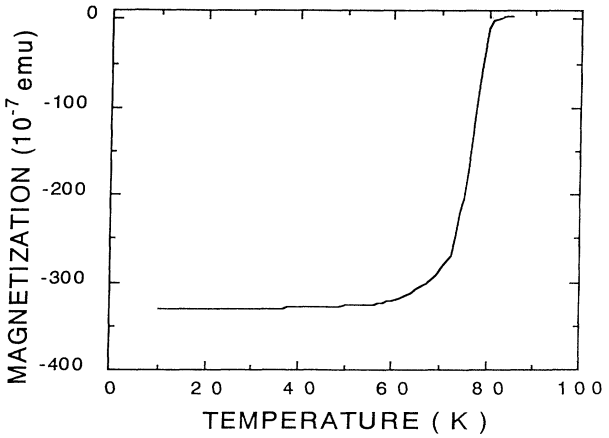

FIG. 1. Magnetization curve of the single crystal used in the Raman-scattering experiment.

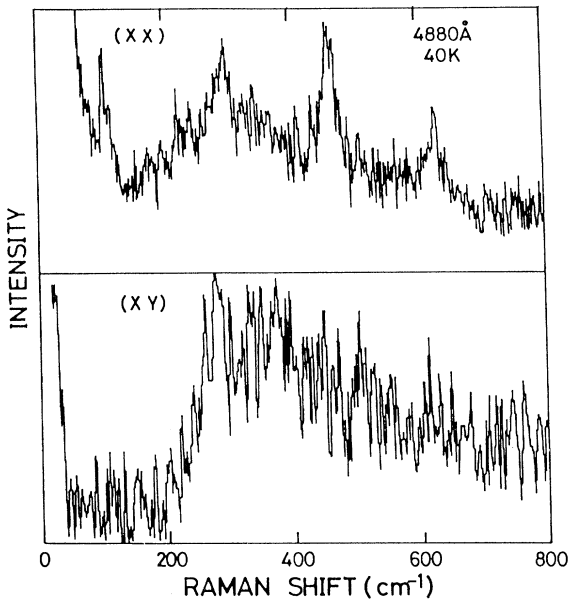

FIG. 2. Raman spectra of the BSCCO single crystal for the (XX) (A_{1g}) and (XY) (B_{1g}) polarizations measured at 40 K.

1000 cm^{-1} is seen for both (XX) and (XY) polarizations. For the (XY) spectra, the scattering intensity increases linearly with frequency ω in the low-frequency region and becomes constant in the high-frequency region at all temperatures. The increase in intensity towards $\omega=0$ for the (XX) spectra may be due to the stray light of the exciting laser light which enters the monochromator.

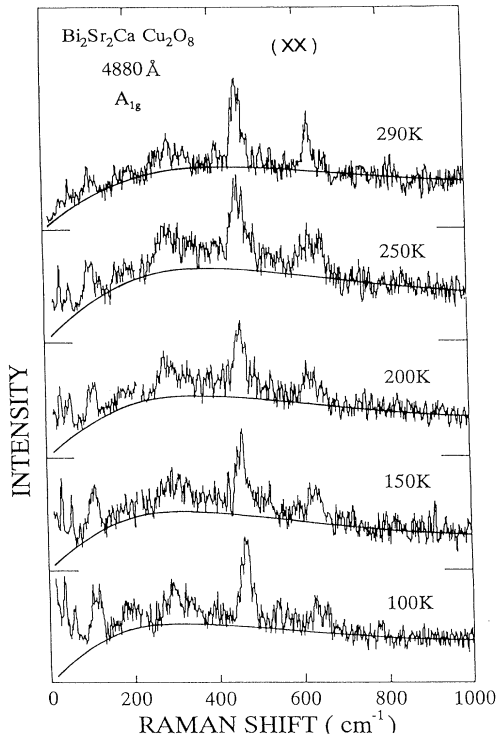

FIG. 3. Temperature dependence of the Raman spectra for the (XX) polarization. The spectra are corrected for the Bose factor. The solid curves represent fits to Eq. (1)

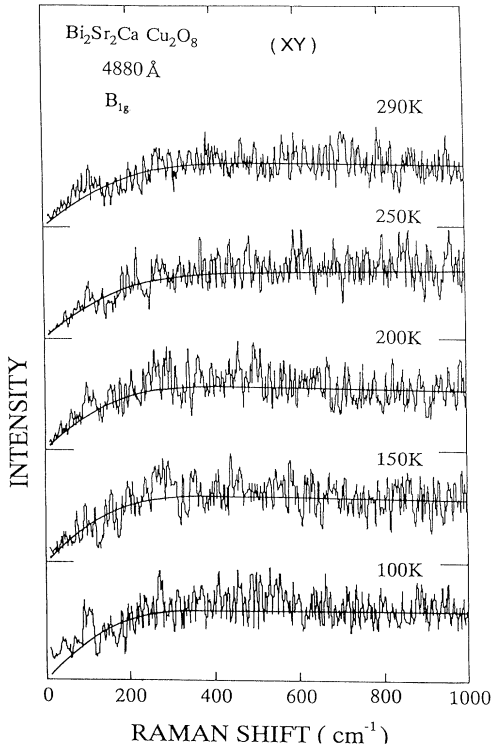

FIG. 4. Temperature dependence of the Raman spectra for the (XY) polarization. The spectra are corrected for the Bose factor. The solid curves represent fits to Eq. (1).

Following the analysis for YBCO performed by Slakey *et al.*,[6] we assume that the broad background in the normal state is caused by the inelastic light scattering by the electron liquid which fluctuates with a characteristic damping constant Γ. In this case, the Raman intensity corrected for the Bose factor, $I_c(\omega,T)$, is expressed as follows:

$$I_c(\omega,T)\propto\omega\Gamma/(\omega^2+\Gamma^2)\ , \tag{1}$$

where Γ is taken to be a function of ω and T as

$$\Gamma=[(\alpha\omega)^2+(\beta T)^2]^{1/2}\ . \tag{2}$$

It follows from Eqs. (1) and (2) that $I_c(\omega,T)$ is proportional to $1/T$ in the region $\hbar\omega\ll kT$ and constant in the region $kT\ll\hbar\omega$. The value α is related to the scattering intensity in the high-frequency region and the value β is related to that in the low-frequency region. Before the least-square fitting taking α and β as parameters, the experimental spectra were smoothed. The fitting spectral range was taken to be 20–1000 cm^{-1} for the B_{1g} spectra except for the spectrum at 100 K. Since the 100 K spectrum seems to be overlapped with the strong Raleigh tail below 100 cm^{-1}, the fitting was done in the range 100–1000 cm^{-1}. The fitting for the A_{1g} spectra is rather difficult because of the overlapping of the strong phonon lines. We subtracted the phonon lines at 120, 190, 220, 290, 345, 470, and 620 cm^{-1} from the spectra before fitting, although the subtraction is somewhat arbitrary.

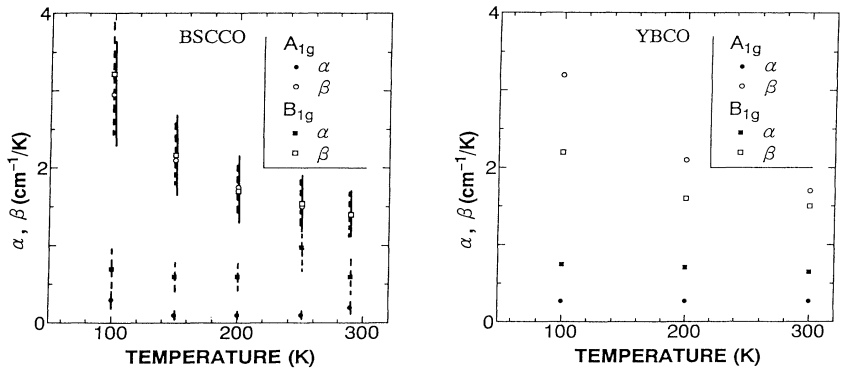

FIG. 5. Temperature dependence of the fitting parameters α and β for the A_{1g} and B_{1g} polarizations for BSCCO. The solid and broken error bars correspond to the A_{1g} and B_{1g} modes, respectively. The results for YBCO by Slakey *et al.* (Ref. 6) are also shown.

We neglected the contribution of the two-phonon scattering because the two-phonon contribution is thought to be small compared with the electronic scattering.[2] The fitting was done in the 80–1000 cm^{-1} range for the A_{1g} spectra. The result of the fitting is shown by solid curves in Figs. 3 and 4. The values of α and β obtained from the fitting are plotted versus temperature in Fig. 5 together with the values obtained for YBCO by Slakey *et al.*[6] The value of β shows similar temperature variation for both compounds and decreases monotonically with temperature. The difference of β between A_{1g} and B_{1g} is larger for BSCCO than YBCO. The accuracy of α is relatively low and the value seems to be insensitive to temperature.

The dc resistivity can be calculated if we assume that the damping constant Γ at $\omega=0$ coincides with the inverse of the scattering time of the free carriers which contribute to the dc conductivity. Figure 6 shows the dc resistivity calculated using the equation $\rho(T)=4\pi\Gamma(T)/\omega_p^2$, where ω_p is the plasma frequency and is taken to be 11 600 cm^{-1}.[13] The dc resistivity measured on the single crystal of BSCCO using the four-point probe method by Nomura *et al.*[14] is also shown for comparison. The agreement between the temperature dependence of the resistivity calculated using the damping constant obtained from the fitting to the Raman spectra and that measured by the four-point probe method is quite good, which supports the assumption that the broad background scattering in the Raman spectra is caused by the inelastic light scattering by the carriers fluctuating with the characteristic damping rate Γ.

There is considerable interest in whether the slope of $I_c(\omega,T)$ in the frequency region $\hbar\omega<kT$ is proportional to $1/T$ or not. The marginal-Fermi-liquid model predicts that the slope of the Raman intensity corrected for the Bose factor in the low-frequency region is proportional to $1/T$.[15,16] Slakey *et al.*[6] have shown that this is true for YBCO, that is, the slope multiplied by temperature is constant above T_c. This also seems to be true for $Tl_2Ba_2CaCu_2O_8$.[17] On the other hand, Sugai[18] compared the slopes of $I_c(\omega,T)$ at 100 and 273 K for $La_{1.8}Sr_{0.2}CuO_4$, and obtained

$$\text{slope}(100\text{ K})/\text{slope}(273\text{ K})=2.1$$

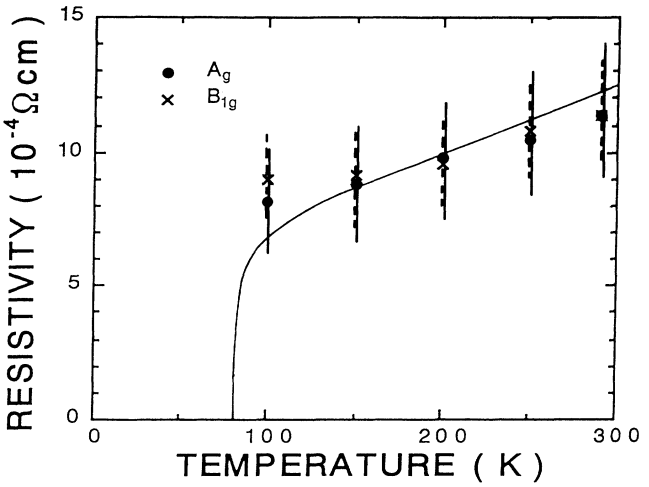

FIG. 6. Temperature dependence of the dc resistivity calculated by the equation $\rho(T)=4\pi\Gamma(T)/\omega_p^2$ with fitting parameters for the electronic Raman spectra. The solid and broken error bars correspond to the A_{1g} and B_{1g} modes, respectively. The temperature dependence of the dc resistivity of the BSCCO single crystal using the four-point probe method by Nomura *et al.* (Ref. 14) is also shown for comparison.

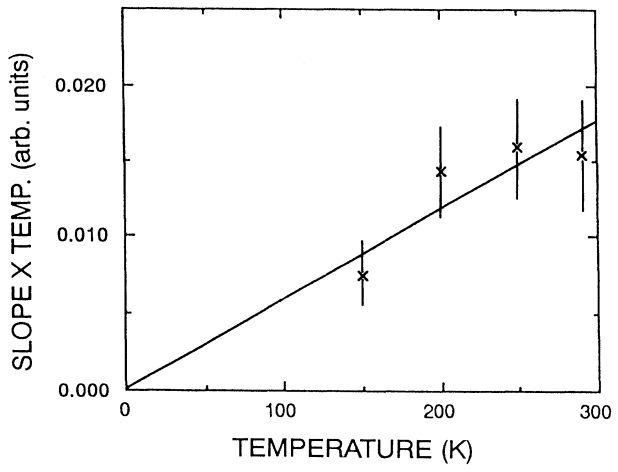

FIG. 7. Temperature dependence of slope multiplied by temperature for the B_{1g} electronic Raman spectra. The slope is obtained by the fitting in the region $\hbar\omega<0.8kT$.

for the $(X'X')$ spectra and 1.8 for the $(X'Y')$ spectra. These ratios are smaller than $\frac{273}{100}=2.73$ expected from the marginal-Fermi-liquid model. However, the low-frequency phonon modes overlapping with the electronic Raman scattering prevent us from drawing a definite conclusion. Figure 7 shows the slope multiplied by temperature for the B_{1g} mode of BSCCO, in which no strong phonon modes appear. It is seen that slope multiplied by temperature increases with temperature. If the marginal-Fermi-liquid model can be applied to BSCCO, slope multiplied by temperature is expected to be constant irrespective of temperature, which apparently contradicts the experimental result. However, it should be noted that the energy of the incident and scattered light is in the energy of absorption bands of BSCCO and the penetration depth of the incident and scattered light may be temperature dependent. This may cause the apparent change of the efficiency of the Raman scattering. In this case, the slope in the low-frequency region may be affected by the penetration depth of light and not follow $1/T$ even if the microscopic scattering efficiency is given by Eqs. (1) and (2).

In summary, electronic Raman spectra of $Bi_2Sr_2CaCu_2O_8$ single crystals have been measured with special interest in the temperature dependence above T_c. The electronic Raman spectra extending up to above 1000 cm^{-1} are fitted by the relaxational response function assuming that the spectra are caused by the electronic fluctuation with the characteristic damping constant Γ. The temperature dependence of the electrical resistivity calculated using this damping constant coincides well with the dc resistivity. However, the slope of the spectra corrected for the Bose factor in the low-frequency region is not proportional to $1/T$, which seems to be inconsistent with the prediction of the marginal-Fermi-liquid model.

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