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Analysis of High-T_c Superconducting Films Using a Free Electron Laser

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The photoelectronic properties of the high-temperature superconductors are analyzed by using a free electron laser (FEL). The method is a type of photoelectron spectroscopy and called a free electron laser internal photoemission. It is found that when the high-temperature $YBa_2Cu_3O_{7-x}$ film is irradiated by FEL, the photocurrent is induced in an unbias condition and its amplitude increases with increasing of the FEL power. The temperature dependence of the photocurrent is also investigated.
Key words: Free electron laser; High-Tc superconductor

1. INTRODUCTION

Since the discovery of high-temperature cuprate superconductors, various experimental methods have been devised to study the dynamical mechanism behind them. [1]. Of these methods, the spectroscopic one such as photoelectron spectroscopy is a simple and direct method for evaluating the electronic structure of high-temperature superconductors [2]. Here we investigate the high-temperature cuprate superconductors by method using a free electron laser (FEL). This method is a type of photoelectron spectroscopy and is called a free electron laser internal photoemission. FEL has two main characteristics, wavelength tunability and ultrashort–pulse operation (~5 ps) with intense peak power (~MW). The spectroscopy using FEL can be thus expected to have a high sensitivity of energy resolution. In previous studies we have investigated the electronic structure of semiconductor hetero-junctions using FEL [3-5]. We indicated that the analytic method using FEL was very effective to evaluate the key parameters such as band discontinuities of semiconductors hetero-interface. Since the superconductive gap energy of high-temperature superconductivity is identified as an order of 10 meV, the optical source of spectroscopy will be also required to have the similar photon energy (wavelength of 10~50μm). We expected that if the carriers in the ground state of high-temperature superconductivity are excited by FEL with the photon energy larger than superconductive gap energy, the photocurrent could occur as a result of the relaxation process.

2. EXPERIMENTAL SETUP

The detection of photocurrent, based on the principle of internal photoemission, is archived by amplifying and measuring the external photocurrent under optical pumping. A schematic for the FEL irradiation measurement is shown in Fig.1. The wavelength of FEL is 9.5 μm and its beam consists of trains of 5 ps pulses (micropulses) with 45 ns separation. Moreover, the trains continues for about 20 μs (macropulses) being repeated at 10 Hz. The macropulse and micropulse of FEL are schematically shown in Fig. 2, respectively. The FEL is led to the ZnSe window of the cryostat through the mirrors and can be focused to the high-temperature superconductor sample in an optical cryostat using the concave lens. The irradiated area is about 1 mm^2. The photocurrent signal was recorded on a digital oscilloscope triggered by the macropulse of the electron beam in the FEL apparatus. In order to detect the induced photocurrent more effectively, it was amplified by the low noise current amplifier. We selected $YBa_2Cu_3O_{7-x}$ film as a superconductor sample. The sample was prepared on the $SrTiO_3$ substrate by RF sputtering. The critical temperature (T_c) of the $YBa_2Cu_3O_{7-x}$ film is about 80 K. Two electrical contacts were made of deposited Ag. FEL was irradiated to the neighborhood of one electrode (electrical contact) on the $YBa_2Cu_3O_{7-x}$ film. FEL power was estimated by a pyroelectric joulemeter.

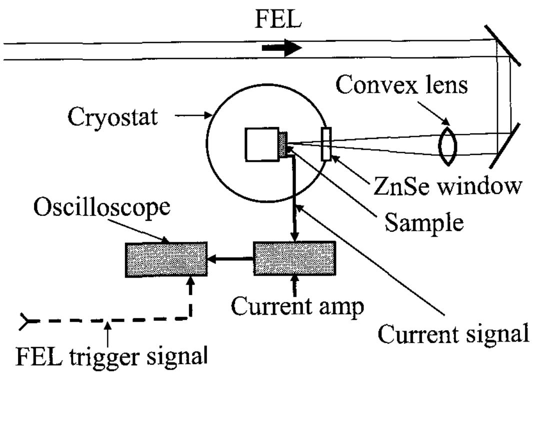

Fig. 1 Experimental setup.

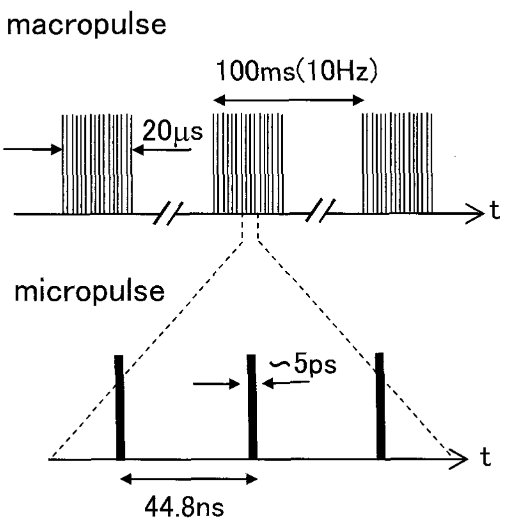

Fig. 2 Time structure of FEL.

3. RESULTS AND DISCUSSIONS

Figure 3 (a)~(c) shows the photocurrent signal induced by FEL in the cases of 10 K–45 K. Measurement was made in an unbias condition. Since FEL is a pulse laser (the macropulse width of ~ 20 μs), the signal of the photocurrent becomes also pulse like. Here the sign of the current indicated in Fig. 3 is positive when the current flows from the $YBa_2Cu_3O_{7-x}$ to the Ag electrode. In the case of 10 K (Fig.3(a)) the photocurrent occurred from the Ag electrode to the $YBa_2Cu_3O_{7-x}$ side. It is shown that the amplitude of the photocurrent increases with increasing the FEL power. It is easily seen that the current amplitude decreases at 20 K (Fig.3(b)). Also, at 30 K (Fig. 3(c)), the sign of the current becomes reverse. For the power lower than 1 mW, the photocurrent could not be detected in every cases.

Figure 4 shows temperature dependence of the photocurrent in the FEL power density of 20 mW/mm^2. In the case of 45 K the photocurrent occurred from the $YBa_2Cu_3O_{7-x}$ side to the Ag electrode. The current with the reverse direction begins to appear in near 30 K, and it becomes reverse completely in 20 K. For 10 K the current value is~0.2 μA. These results can be interpreted as follows. Since FEL with wavelength of 9.5 μm has photon energy of about 130 meV much more than $YBa_2Cu_3O_{7-x}$ superconductive gap energy (~20 meV), electrons in ground state will easily excited by FEL. The optically excited electrons can move to the Ag side because the excited state energy of superconductor is higher than the Fermi level of Ag. This means that the photocurrent usually flows from Ag electrode to the $YBa_2Cu_3O_{7-x}$. In the case of 10 K, the electrons excited from the ground state will contribute to the photocurrent. This is consistent with above discussions. However, figure 4 indicates that the

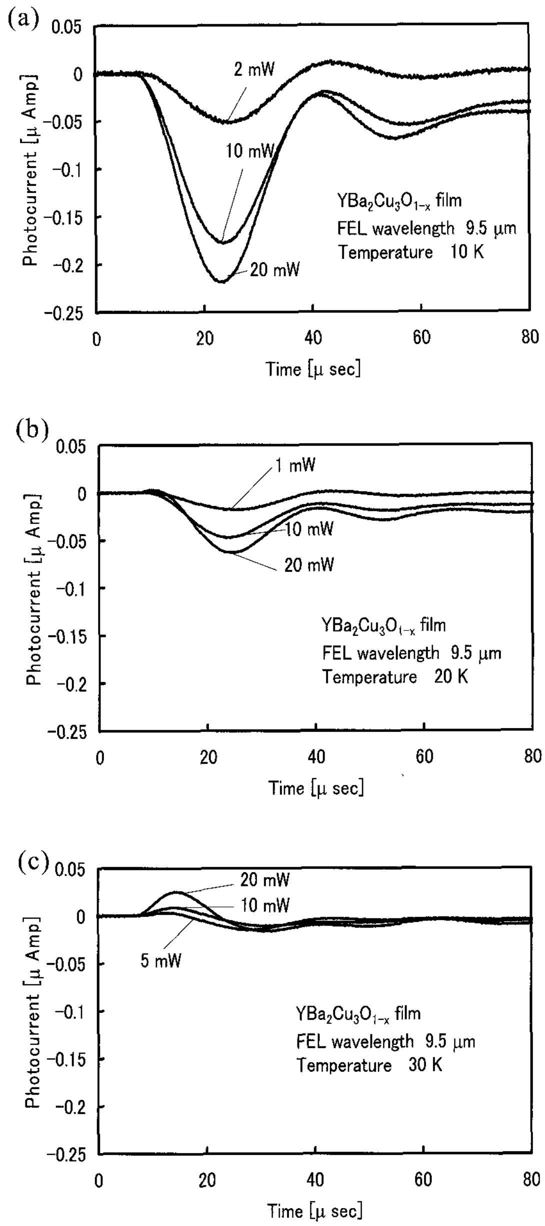

Fig. 3 Photocurrent signal indicating the FEL power dependence in the $YBa_2Cu_3O_{7-x}$ film: (a) 10 K; (b) 20 K; (c) 30 K.

sign of the current can change dependent on the temperature. From those discussions, it is difficult to explain the temperature dependence of the photocurrent. Since the photocurrent flows through the Ag electrode, it seems necessary to consider the electronic structure of the interface between $YBa_2Cu_3O_{7-x}$ film and Ag electrode. We assume the interface model shown in Fig.5. This figure presents a schematic energy diagram at the interface. The left side here shows the energy structure of $YBa_2Cu_3O_{7-x}$ superconductor which consists of superconductive ground state and quasiparticle excited state, and the right side shows the energy diagram of Ag, respectively. Also, it is natural to assume the energy barrier at the interface. Now, what the direction of current

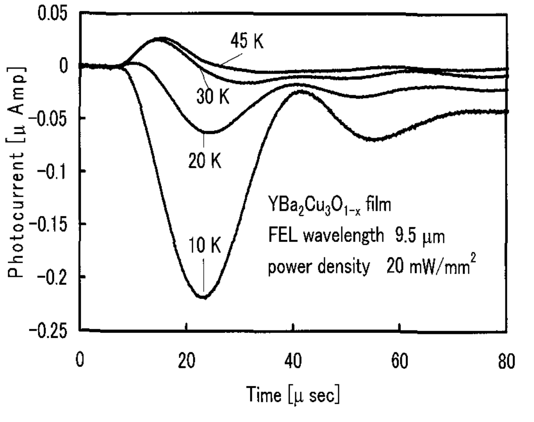

Fig. 4 Photocurrent signal indicating the temperature dependence in the $YBa_2Cu_3O_{7-x}$ film.

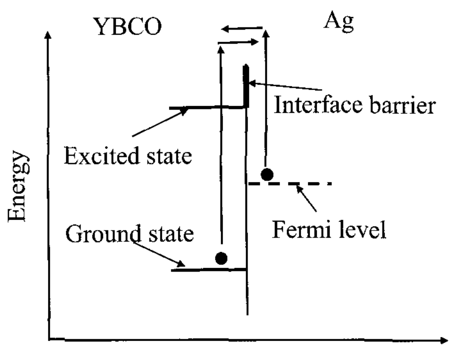

Fig.5 A schematic energy diagram at the interface between $YBa_2Cu_3O_{7-x}$ film and Ag electrode.

changes with the temperature suggests that there are two types of the photocurrent which have the different temperature dependence and the reverse direction each other. As the measurement is carried out in an unbias condition, the electrons moving over the interface barrier will contribute the detecting current. One of the detecting current is due to the electrons optically excited from the superconducting ground state. Those electrons moving over the interface barrier correspond to the current flow from the Ag to the $YBa_2Cu_3O_{7-x}$. Since the sample is irradiated by FEL at the neighborhood of the Ag electrode, the electrons in Ag can be also optically excited and can move to the $YBa_2Cu_3O_{7-x}$ film. Notice that those two types of the current flow reversely each other. The amplitude of the photocurrent excited from the Ag electrode is almost independent on the temperature. On the other hand, electrons excited from $YBa_2Cu_3O_{7-x}$ ground state will decrease with the increase of the temperature. As a result, it is expected that as increasing of the temperature, the photocurrent excited from the Ag electrode will overwhelm the photocurrent excited from $YBa_2Cu_3O_{7-x}$ ground state. This can explain the reverse phenomena of the photocurrent. However, from experimental results here, we cannot still find the new aspects of the electronic structure in the $YBa_2Cu_3O_{7-x}$. In order to investigate the electronic structure of high-temperature superconductors more deeply, we need to carry out the FEL experiments in the various range of wavelength.

4. CONCLUSION

The high-Tc $YBa_2Cu_3O_{7-x}$ superconductor is analyzed by using a free electron laser (FEL). It is found that when the $YBa_2Cu_3O_{7-x}$ film is irradiated by FEL, the photocurrent is induced in an unbias condition. Also, it is indicated that the photocurrent is increasing with the decrease of temperature. In order to reveal the significant properties such as the high temperature superconductive gap, it will be needed to develop this analytic method.

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