Chapter 5

Conclusion

Microstrip ring and line resonators made of double-sided $YBa_2Cu_3O_{7-\delta}$ (YBCO) and $Y_{0.7}Ca_{0.3}Ba_2Cu_3O_{7-\delta}$ (Ca-YBCO) films have been demonstrated to have great potential for engineering applications and scientific studies. By controlling the oxygen contents of the same resonator, the hole concentration p determined from the empirical relation, $T_c/T_{c,max}=1-82.6(p-0.16)^2$, was controlled from the over- to the underdoped regime. From the temperature dependence of the resonance frequency and also with the help of the Chang's inductive formula and THz experiments, the temperature dependence of the magnetic penetration depth $\lambda(T)$ and its absolute value $\lambda(5K)$ can be found, from which the magnitude of the d-wave energy gap and some universal relations, such as Uemura's relation, can be delineated. Furthermore, a universal relation, that is the superfluid density n_s at 5K proportional to the product of critical temperature (T_c) and the d.c. conductivity σ_{dc} at T_c was also revealed from the experimental results. Then we apply the Ferrell-Glover-Tinkham (FGT) sum rule to explain the universal relation and also to extract the doping dependence of normalized energy gap $2\Delta_0/k_BT_c$, which is consistent with the one obtained by other experiments in the d-wave pairing symmetry. The result gives evidence indirectly that not only the symmetry of the superconducting energy gap is d-wave but also the conservation of charge in the CuO_2 plane is obeyed.

From the measurement of the magnetic penetration depth $\lambda(T)$, the temperature dependence of the superfluid density $1/\lambda^2(T)$ was obtained. The linear-T dependence of the $1/\lambda^2(T)$ gives evidence of thermally excited BCS-like quasiparticles near the nodes in d-wave gap, as in Wen and Lee's model. Then, the Fermi-liquid correction factor α from the model was revealed as $\alpha \leq 1$ and almost independent of doping for the YBCO and Ca-YBCO thin films. This result is consistent with that predicted by Wen and Lee's model. Therefore, the basic nature of quasiparticles in the superconducting state can be attributed to the normal Fermi liquid in all levels of doping.

We also analyzed the microwave conductivities $\sigma_1(T)$ and $\sigma_2(T)$, the unique superconducting quantity, because the experimental results are reasonably well established, and the prediction of the localized state for the evolution of the T-dependence of $\sigma_1(T)$. The equations, $\sigma_1 = \sigma_1(5K)(1-e^{-E_{g1}(T)/k_BT})$ and $\sigma_2 = \sigma_2(5K)(1-e^{-E_{g2}(T)/k_BT})$ give the strong evidence of thermal hopping behavior for the quasiparticles and superfluid below T_c, respectively. At $T/T_c<0.1$ the macroscopic quantum tunneling of the quasiparticles will dominate the behavior of σ_1 via thermal hopping in our thin film samples. Moreover, the thermal phase fluctuations will appear in σ_1 at $0.5<T/T_c$. The microwave conductivities σ_1 and σ_2 are interpreted as the dissipations due to quasiparticle tunneling and the non-dissipative quantity by Josephson tunneling in the weak-link structures of our samples, respectively. Also, this closed form, $\sigma_2(5K)(1-e^{-E_{g2}(T)/k_BT})$, is fitted to σ_2, and it was found that an characteristic energy scale $T^*_{\sigma 2}$ which is higher than T_c when $\sigma_2 = 0$. The phase diagram of $T^*_{\sigma 2}$ versus hole concentration *p* is similar to that predicted by Emery and Kivelson's model. Hence, we propose that $T^*_{\sigma 2}$ would be the upper bound on the phase ordering temperature $T_\theta^{\max}$ in the underdoped

regime, and in the overdoped regime, $T^*_{\sigma 2}$ corresponding to the mean field transition temperature T^{MF}.

When $T > T_c$, the classical phase fluctuations play a key role in forming the Cooper pairs of the short range order by these quasiparticles. When T is approaching to T_c, the superconductivity with long range order begins to form by the Josephson tunneling of superfluid (Cooper pairs). In the superconducting state ($T < T_c$), the $\sigma_2(T)$ was attributed to the effect of Josephson tunneling in the weak links in our thin film samples of the unitary limit. Whereas, there are two cases for $\sigma_1(T)$. One is that $\sigma_1(T)$ can be thoroughly attributed to the effect of quasiparticle tunneling in the weak links. It implies that the quasiparticles are localized within the grains, and the feature of $\sigma_1(T)$ can be realized as that of quasiparticles in thermal insulator phase in the superconducting state of the samples in the unitary limit. Another is that $\sigma_1(T)$ can be attributed to two components of quasiparticles. One is due to the effect of quasiparticle tunneling through the weak links, in which quasiparticles are localized within the grains. And the other is that the quasiparticles are delocalized through the samples. So, for the case 2, there are two distinct phases of the samples in the clean limit: the thermal-metal and the thermal-insulator, as well as the samples of Hardy's group for high-purity single crystals. The features of σ_1 would indeed be favored by phase inhomogeneity in the superconducting cuprates, in agreement with previous reports giving evidence of intrinsic granularity in these materials. Finally we want to emphasize that there are two energy scales which correspond to two characteristic temperatures in the formation of the superconducting state of the HTSC materials: T_c below which coherence is established, and some higher temperature $T^*_{\sigma 2}$ where the pairs are formed. We note that these two energy scales are close to each other in the all levels of doping.