POLARITON-LIKE INTERACTION BETWEEN MICROWAVES AND ELECTRONIC SUBSYSTEM OF METAL OXIDE SUPERCONDUCTOR[*]

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Abstract

In studying the microwave (10 GHz) response of both single crystal and ceramic samples of the $YBa_2Cu_3O_7$ in Nb resonator we have found strongly wave-vector-dependent dielectric permittivity resulting in appearance of the new dielectric resonances with hysteretic temperature behaviour. Data show the importance of the non-conducting "bound" electron polarization in strong local fields and spatial dispersion, which lead to the polariton-like interaction between microwaves and electrons in a high−T_c superconductor. The effects of the polariton-like microwave excitations on the limiting mechanisms in superconducting cavities are discussed.

1 INTRODUCTION

Early it was argued that superconductivity with a high critical temperature T_c requires a negative sign of $\varepsilon(0,\mathbf{k})$ the longitudinal static dielectric permittivity at $\mathbf{k}\neq 0$ which should originate from the presence of relatively strong local (acting) electric fields and spatial dispersion ($\mathbf{k}\neq 0$) effects in permittivity [1], [2], [3]. To avoid the occurrence of the lattice instability due to a negative permittivity $\varepsilon(0,\mathbf{k})$ the exchange-correlation interactions (the difference between the mean and acting electric fields) should be significant.

We study the microwave (10 GHz) response of both single crystal and ceramic samples of the $YBa_2Cu_3O_7$. The strongly $\mathbf{k}$-dependent permittivity $\varepsilon(\omega,\mathbf{k})$ have been found resulting in appearance of the new dielectric resonances with hysteretic temperature behaviour. The obtained results reveal the important role of the non-conducting "bound" electron polarization in occurrence of the strong local electric field and spatial dispersion effects, which lead to the polariton-like interaction between microwaves and electronic subsystem in HTSC. It is shown that an excitation of the coupled with the medium oscillations electromagnetic waves inside the HTSC material is possible due to the high value of the lattice part of permittivity in microwaves. High permittivity results in the retardation of electromagnetic waves down to the Fermi velocities of electrons and as a consequence in the change of sign and the occurrence of the positive total permittivity caused by the spatial dispersion effects. An efficient excitation of the polariton-like microwave

oscillations in the HTSC samples is realized in the superconducting microstrip resonators, which are characterized by inherent substantially retarded modes (over two orders of magnitude less than the value of c the speed of electromagnetic radiation in vacuum) in the spectrum of resonant oscillations.

2 PRINCIPLES OF EXPERIMENT

2.1 Spatial dispersion of permittivity in superconductors

The pronounced spatial dispersion effects in permittivity could result in the unusual microwave response of a superconductor. Neglecting the dissipation, its permittivity can be approximated in superconducting state by the following relation (see [4], for example)

$$\varepsilon(\omega, k) = \varepsilon'_p(\omega, k) + \frac{\omega_p^2}{-\omega^2 + v_F^2 k^2}$$

in which $\varepsilon'_p(\omega,k)$ is the real part of the lattice permittivity, ω_P, v_F are the values of plasma frequency and Fermi velocity of current carriers and ω, k are the values of frequency and wave vector of electromagnetic wave. Obviously, the permittivity could be positive due to the spatial dispersion effect for microwave radiation with $\omega/k \leq v_F$. This radiation should penetrate and propagate in the bulk of superconductor. A new extraordinary polariton-like wave will appear in addition to an ordinary wave which does not propagate into the bulk and is reflected by the metallic surface because of the negative permittivity $\varepsilon(\omega,k)$ for the ordinary wave characterised by the relation $\omega/k > v_F$.

2.2 Experimental technique

The microwave response of the $YBa_2Cu_3O_7$ samples was measured in the Nb microstrip resonator (Fig.1). The $YBa_2Cu_3O_7$ single crystal was grown in an alumina crucible [5] and was characterized by $T_c=90$ K and $\Delta T_c\sim 3$ K. The T_c of the $YBa_2Cu_3O_7$ ceramic sample [6] was about 92 K with $\Delta T_c\sim 3$ K. We have measured the resonance frequency (f_p) of a resonator perturbed by $YBa_2Cu_3O_7$ sample as a function of the spatial position of the sample relatively to the resonant strip at frequencies

around 9 GHz, between 4.2 and 300 K The sample position was characterized by an angle α measured in plane of the resonant strip off the polar axis, directed along the transverse axis of the strip (Fig. 1).
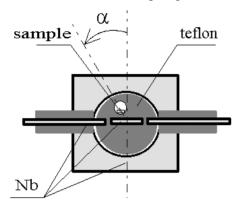

Figure 1: Layout of the measuring symmetric microstrip Nb resonator. Top view without of the upper cap of Nb shielding. A sample is inserted in a hole drilled in the upper teflon disk. Teflon parts are shown as if these would be light transparent.

2.3 Microstrip resonator as a retardation structure for investigations of spatial dispersion effects in metals
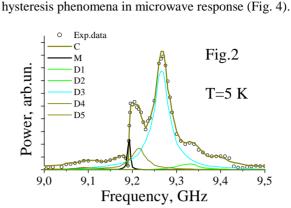
It has been found [7], [8] that the phase velocity $v_{ph} = \omega/k$ of higher-order spatial modes of the essentially multi-mode resonant field of a microstrip resonator is retarded significantly (over two order of magnitude) and becomes comparable with Fermi velocities of electrons $\omega/k \leq v_F$. As the length of mean free path of electrons rises with decreasing temperature, that allows to study the spatial dispersion effects and quasi-static properties in conducting materials at microwave frequencies.

2.4 Lattice permittivity effects

Taking into account the local electric field effects, we have estimated from microwave measurements [6], [9] that the lattice part of the total permittivity of the $YBa_2Cu_3O_7$ approaches a value of $\varepsilon'_p \sim 10^4\varepsilon_0$, where ε_0 is the vacuum dielectric constant, in fair agreement with other estimations [10], [11], [12]. The resulting decrease of the electromagnetic wave phase velocity $v_{ph} = \omega/k \sim (\varepsilon'_p)^{-1/2}$ make it comparable with v_F, assists the effective coupling between microwaves and conducting electrons, enhances the appearance of the polariton-like excitations and the spatial dispersion effects in ε under conditions of $v_F \geq \omega/k$.

3 RESULTS AND DISCUSSION

In the $YBa_2Cu_3O_7$ single crystals, as well as in ceramic samples we have found [6-8], [13], [14] the anomalously

strong variations of ε depending on spatial position of the sample in the resonator field, appearance of the new dielectric-type resonances (Figs. 2 and 3), temperature hysteresis phenomena in microwave response (Fig. 4).

Figure 2: Spectrum composition of the microwave response of the ceramic sample No.7p in microstrip resonator: M - metallic resonance (reflection by sample surface), 0° phase; D1, D2, D3, D4, D5 - dielectric resonance modes (wave, penetrating into the sample), 185° phase; C - calculated signal; Exp.data - experimental data.
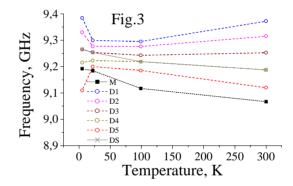

Figure 3: The central frequencies of metallic and dielectric modes (cf. Fig. 2) depending on temperature. DS - frequency of the dielectric resonance envelop; symbols – experimental data

The found effects are not consistent with the model of metallic surface impedance and reveal the polariton-like interaction between microwaves and electronic subsystem. In all investigated samples, including the macroscopically isotropic ceramic sample (Fig. 2), a superposition of the new resonances (positive ε' at all temperatures (Fig. 3)) was found in addition to the ordinary mode reflected by a metallic surface (negative ε'). These can be explained by the induced anisotropy (birefringence) due to the pronounced spatial dispersion of ε. An existence of both reflected and penetrating waves, which differ by a vector of propagation, suggests the polariton type of interaction between microwaves and metal oxide.
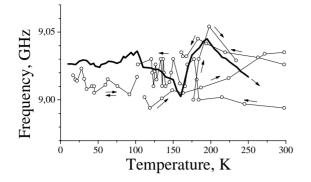
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Figure 4: Hysteresis phenomena in temperature dependence of the dielectric-resonance envelop frequency of the ceramic sample No.7: circles – experimental data; thick solid line – data of magneto-acoustic RF measurements from Ref. [10] in arb. units for comparison.

A value of component of the total permittivity tensor, which corresponds to the penetrating waves, can be estimated from a frequency spacing between the dielectric resonances. Data of Fig. 3 for the ceramic sample No.7p give the positive value of order of $10^5\varepsilon_0$ for this component of the $\varepsilon'(\omega,k)$ tensor at liquid helium and room temperatures in fair agreement with previous estimations [6], [9]. The observed high values of the lattice permittivity ε'_p, changes of sign and value of the quasi-static total permittivity $\varepsilon'(\omega,k)$ and hysteresis phenomena in the temperature behaviour of $\varepsilon(\omega,k)$ point to the important role of electrons in a tendency of the lattice to instability under the conditions of $\varepsilon(0,\mathbf{k})<0$.

The effects of the possible polariton-like microwave excitations on the limiting mechanisms in superconducting cavities should be investigated. Studies of Nb samples [7], [8] revealed rather strong spatial dispersion effects in microwave permittivity of this material. These may affect properties of the RF unit especially if it contains small-scale spatial inhomogeneities in its structure, which correspond to the large values of wave vector $\mathbf{k}$ and enhance spatial dispersion effects.

4 REFERENCES

[1] "High temperature superconductivity" ed. by V.L. Ginzburg and D.A. Kirzhnits, Consultants Bureau, New York - London (1982)

[2] O.V. Dolgov, E.G. Maksimov, Uspehi Fiz. Nauk [Soviet Phys. Uspekhi], v.138, No.1 (1982) 95

[3] V.L. Ginzburg, Contemporary Physics, v.33 (1992) 15

[4] A.S. Davydov, "THEORY OF SOLID STATE", Moscow, "Nauka" (1976)

[5]. G.G. Kacharava, Yu.F. El'tsev, V.R. Karasik, E.Yu. Dovidenko and G.A. Tsintsadze, Supercond. Sci. Technol. 4 (1991) 707

[6] E.M. Golyamina, V.A. Dravin, B.G. Zhurkin, A.L. Karuzskii, A.N. Lykov, and V.N. Murzin, Kratk. Soobsh. Fizike FIAN, Nos.1-2 (1993)

14 [Bulletin of the Lebedev Phys. Inst., No.1 (1993) 10]; ibid., Nos.5-6 (1993) 17 [No.5 (1993) 13]; Physica C 235-240 (1994) 2072

[7] V.N. Apakina, V.A. Dravin, Yu.F. Eltsev, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, N.A. Volchkov, B.G. Zhurkin. Physica C 282-287 (1997) 1585

[8] V.N. Apakina, V.A. Dravin, Yu.F. Eltsev, I.A. Istomin, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, in Proc. 8th Workshop on RF Superconductivity, Abano Terme (Padova), Italy, October 6-10, 1997. V. Palmieri, A. Lombardi Eds. LNL-INFN (Rep)133/98, Vol.II, 352

[9] A.L. Karuzskii, in Proc. 8th Workshop on RF Superconductivity, Abano Terme (Padova), Italy, October 6-10, 1997. V. Palmieri, A. Lombardi Eds. LNL-INFN (Rep)133/98, Vol.II, 362; Physica C 282-287 (1997) 1581

[10] V. Müller, C. Hucho, K. de Groot, D. Winau, D. Maurer, and K.H. Rieder, Solid State Commun. 67 (1989) 997; Ferroelectrics 130 (1992) 45

[11] F.M. Mueller, S.P. Chen, M.L. Pruitt, J.F. Smith, J.L. Smith, and D. Wohlleben, Phys. Rev. B 37 (1988) 5837

[12] L.R. Testardi, W.G. Moulton, H. Matthias, H.K. Ng and C.M. Rey, Phys. Rev. B 37 (1988) 2324

[13] V.N. Apakina, V.A. Dravin, Yu.F. Eltsev, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, B.G. Zhurkin. Physica C 282-287 (1997) 1583

[14] V.N. Apakina, V.A. Dravin, Yu.F. Eltsev, I.A. Istomin, A.L. Karuzskii, V.N. Murzin, A.V. Perestoronin, in Proc. 8th Workshop on RF Superconductivity, Abano Terme (Padova), Italy, October 6-10, 1997. V. Palmieri, A. Lombardi Eds. LNL-INFN (Rep)133/98, Vol.II, 357