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ORIGINAL PAPER

Second and Third Peaks in the Non-resonant Microwave Absorption Spectra of Superconducting Bi2212 Crystals

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Abstract Non-resonant microwave absorption (NMA) measurements at liquid nitrogen temperature with systematic microwave power variation showed a two-peak structure in the Bi-2212 textured crystals, similar to that observed in the Bi-2212 single crystals (Srinivasu et al., in J. Supercond. Incorp. Nov. Magn. 14:41, 2001). NMA signals from the aged Bi-2212 single crystals show an emergence of a 'third peak' as a function of microwave power. We qualitatively interpret these second and third peaks as due to the microwave power induced phase locking of several number of junctions into coherent groups and then the destruction of the phase locking by the applied DC field leading to decoupling or fluxon motion, which gives the loss in individual junctions belonging to these otherwise coherent groups.

Keywords Non-resonant microwave absorption · Bi2212 · Weak links

1 Introduction

Ever since the discovery of the Non-resonant microwave/RF absorption (NMA) in the High-Tc Superconductors (HTS) [1] and followed by others [2–6], NMA has evolved into a powerful spectroscopic tool to probe the superconductivity properties in HTS, such as granularity, critical current density and fluxon viscosity coefficient, etc. [7–14]. NMA spectra in anisotropic superconductors, such as Bi2212 and Bi 2223 powders, single crystals and films, showed new and complex features [15–21] as compared to very simple lineshapes in $YBa_2Cu_3O_{7-x}$ (YBCO) [9].

For example, NMA when measured in a configuration with the applied field perpendicular to the Bi2212 crystal ab-plane, shows a narrow low field peak followed by a broad shoulder like peak extending to high fields [16–21]. These new features in the NMA lineshapes of the Bi-2212 single crystals have assumed significance, as they are interpreted in terms of the intrinsic Josephson effect by Rastogi et al. [18], AC magnetic field shaking of Josephson vortices [21]. Two crucial experimental observations have to be noted from Ref. [18]. The second peak in the NMA spectra of Bi-2212 single crystal occurs only in a temperature window of 2–3 K, at the so-called 'magic temperature' near T_c, and it occurs only when the DC applied field is perpendicular to the crystal ab-plane [18]. The second peak is absent when the DC field is applied parallel to ab-plane. However, a more careful and systematic measurements by Srinivasu et al. [19] showed that: (1) there is an evolution of the second peak with microwave power and (2) the second peak occurs even in the field configuration where the applied DC field is parallel to the crystal ab-plane but with the microwave magnetic field perpendicular to the ab-plane, at appropriate microwave powers. Which means the second peak in the NMA spectra of Bi2212 single crystal depends on the mutual orientation of the applied DC field, microwave magnetic field and the crystal ab-plane, and actually evolves as a function of microwave power. Excellent reproducibility of the experimental results of Ref. [19] are demonstrated by Ahmad et al. [20]. Thus one can see that the second peak in NMA spectra of Bi-2212 crystals has great significance and may be talking new physics. In this light, we report here about the aging effects of the same Bi2212 single crystal studied in Ref. [19], on the peak structure of NMA spectra showing the microwave power dependent evolution of a

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'third peak' that occurs at much higher fields. Also we report the microwave power evolution of the second peak in the Bi2212 textured crystals for the first time.

2 Experimental

NMA measurements are done using an ESR spectrometer. Residual field is nullified using a pair of compensating Helmholtz coils, ensuring that the field sweep actually passes through zero field. The sample is placed in the cavity where the microwave magnetic field is maximal. The microwave frequency is 9.28–9.32 GHz. The microwave power is varied between 0.1 and 10 mW. All absorption signals are recorded in the derivative form, which is usual in NMA measurements. All measurements are done at 77 K. Further details of the NMA measurements are given elsewhere [19].

The Bi-2212 single crystal was grown by the self-flux method, at UNICAMP, as described in Refs. [19, 22]. The bulk textured crystals are grown at the crystal growth center, Anna University, by an indigenously built floating zone apparatus, at a slow growth rate of 1 mm/h, as described in Ref. [23].

3 Results and Discussion

Figure 1 shows the NMA signal vs. applied DC field (H_{dc}) at various microwave powers (0.1 to 10 mW), measured at 77 K. The field configuration is $H_{dc} \perp$ ab-plane and the microwave field is $H_{mw} \parallel$ ab-plane. One can see a very narrow first peak (P_1) and a broad second peak (P_2), which evolve with the microwave power. However, the power evolution of the second peak is not as dramatic as is seen in the Bi-2212 single crystal (see Figs. 3 and 4 in Ref. [19]). But one can see the two-peak structure as similar to that observed in Bi-2212 single crystal. As this second peak has many interpretations, we would like to discuss more about this peak here. Masiakowski et al. [15], who observed this second peak in the NMA spectra of Bi-2212, have associated this peak with the second phase in their sample. However, this cannot be true because now many groups [16–21] have observed this second peak in several Bi-2212 crystals grown in different laboratories of the world and not all these crystals are defective with impurities and second phases.

In fact, such a second phase is not reflected in any of the characterization methods, X-ray diffraction, transport or susceptibility measurements. Further, the fact that the second peak evolves as a function of microwave power, and that it depends on the mutual orientation of the H_{dc}, H_{mw} and ab-plane of the crystal [19], simply rules out the 'second phase' interpretation. Ahmed et al. [20], on the other hand, explain it by a 'reentrant phase' model. However, even though the

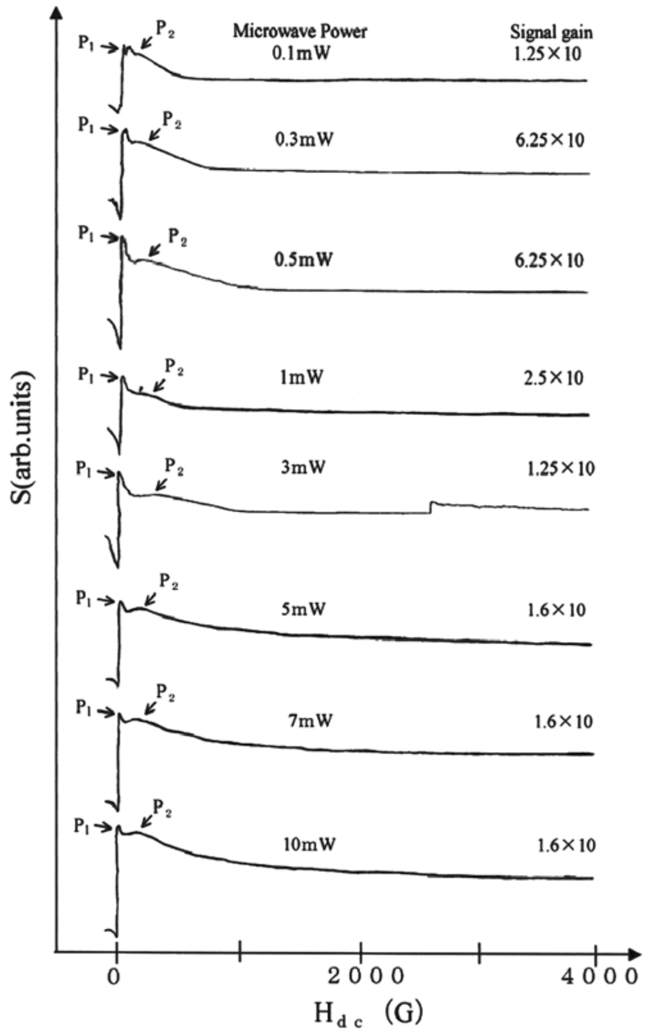

Fig. 1 NMA signals from Bi-2212 textured crystal measured at different power levels at 77 K, 9.32 GHz. The field configuration is $H_{dc} \perp$ ab-plane and the microwave field is $H_{mw} \parallel$ ab-plane

'reentrant phase' of Fisher, Lee and Nelson [24, 25] is well established, to connect this phase diagram with the NMA spectra and the peak structure, one has to describe the origin of the microwave absorption or the loss mechanism. Experimentally it is the microwave loss that is measured in NMA and not the vortex phase diagram. Without the description of the loss mechanism, the interpretation has no meaning. Further, we would like to draw attention to the emergence of a 'third peak' in the same Bi-2212 single crystalline sample after considerable aging (after going through several cooling and warming cycles and as well as several months of time lapse) as shown in Figs. 2, 3.

As the microwave power is varied, a third peak (P_3) evolves in the NMA spectrum of the aged Bi-2212 crystal, in the field configuration $H_{dc} \perp$ ab-plane and the microwave field $H_{mw} \parallel$ ab-plane. This 'third peak' (shown in Fig. 3) cannot be explained by the reentrant phase model by Ahmed et al. [20], as they have used up all the available

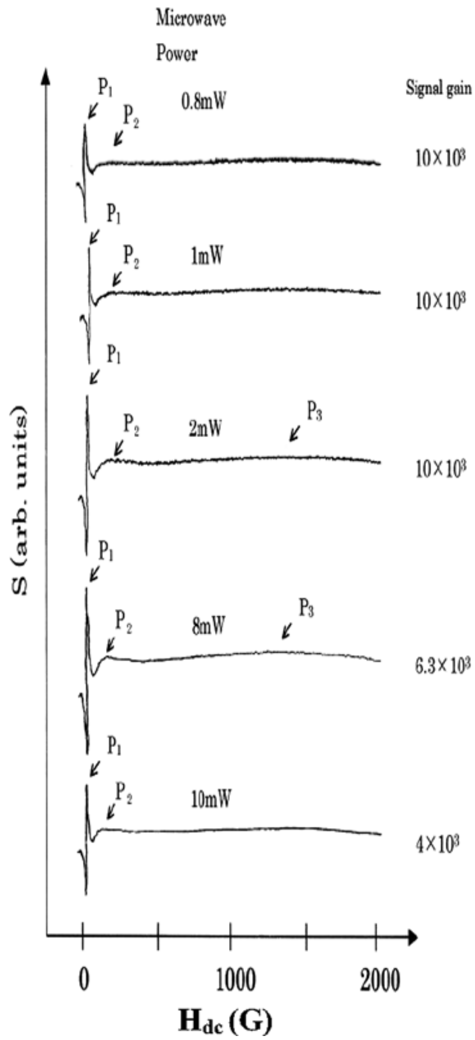

Fig. 2 NMA signals from aged Bi-2212 crystal measured at different microwave power levels at 77 K, 9.28 GHz. The field configuration is $H_{dc} \perp$ ab-plane and the microwave field is $H_{mw} \parallel$ ab-plane

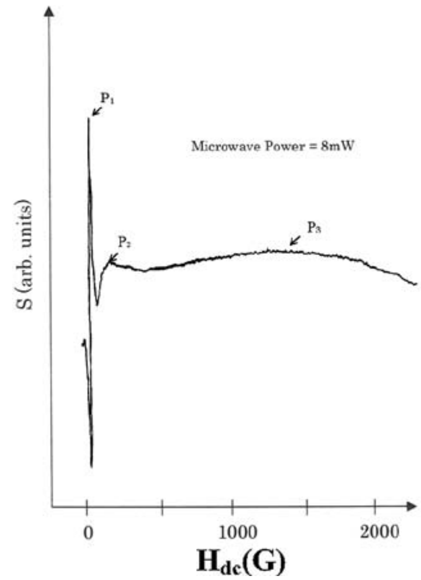

Fig. 3 Blown up NMA signal at 8 mW from the aged Bi-2212 crystal. The third peak (P_3) is clearly visible

phases for the first and second peaks and valleys in the NMA spectrum. This result from the aged Bi-2212 sample rules out the 'reentrant phase' interpretation. The origin of experimentally measured microwave loss and the peak structure has been explained by Rastogi et al. [18] in terms of intrinsic Josephson junction effect. Such a model is reasonable, because Bi-2212 is highly anisotropic, and intrinsic Josephson effect is well known in these crystals. Further, they actually derived a microwave loss expression and simulated the signals with the first and second peaks in the NMA spectra. Further, Shaltiel et al. have interpreted the second peak in terms of shaking of Josephson vortices [21].

3.1 Second and Third peaks

The microwave power dependent evolution of the second and third peaks as seen in Figs. 1, 2, 3 in this paper and also in Figs. 3 and 4 in Ref. [19] has to be understood at least qualitatively. In the following we give a possible qualitative explanation. The second peak could be originating from the intrinsic Josephson coupling. Such intrinsic Josephson coupling was first established in Bi-2212 crystal by Kleiner and Muller [26]. One of the very interesting results in their paper is that the steps observed in I–V characteristics by microwave irradiation shift to higher voltages as the microwave power is increased, indicating an increase in the number of phase-locked junctions' increases with an increase of microwave power. Thus microwave power induces phase coherence among several junctions, and they act as a single coherent group. Application of external magnetic field shall destroy this coherence leading to easy decoupling of the junctions. This will cause additional microwave loss. The width of loss peak now shall depend on the distribution of coupling strengths of the junctions in that particular group. This can explain the second peak. Aging can modify or weaken some of the junctions or possibly modify or create new vacancies and defects inside the crystal, which can then act as weak links. This is because vacancies or defects on the length scale of coherence length can in fact act as weak links [27]. Suitable microwave power can then bring these weak links to phase coherence which now act as another group whose mean coupling strength, as well as the width of distribution of coupling strengths, is different to that of the group of weak links that is associated with the second peak. Applied field then can bring decoherence in this new group of weak links giving rise to the 'third peak' in the NMA spectrum. Thus in our interpretation, the second and third peaks can arise in the following way. As the microwave power variation can bring in phase coherence among several junctions at a suitable power level, applied DC field brings in decoherence, destroying phase locking and then decoupling these intrinsic junctions. Decoherence and destruction of phase locking shall decrease the shielding ability of the group of junctions. Then the junctions become more vulnerable to flux as they no longer act as coherent group but as single individual junctions. Flux can now either enter junctions as fluxons or decouple the junction itself, giving rise to microwave loss as described in the equations for microwave loss by Rastogi et al. [18].

4 Conclusion

NMA spectra of Bi-2212 textured crystal shows two-peak structure similar to that of Bi-2212 single crystals. The second peak evolves with the microwave power. We reported possible emergence of a new third peak in the NMA spectra of aged Bi-2212 single crystal. We have given a possible qualitative explanation for the origin of the second and third peaks in the NMA spectra of Bi-2212 crystals as due to the microwave-induced phase coherence in the intrinsic weak links and then the destruction of coherence among the groups of weak links by applied DC field. Applied DC field then decouples the junctions themselves, giving rise to the microwave losses and the peaks.

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