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DISCRETE MICROWAVE ABSORPTION LINES IN $YBa_2Cu_3O_{7-\delta}$ SINGLE CRYSTALS

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Discrete microwave absorption lines in $YBa_2Cu_3O_{7-\delta}$ single crystals are analyzed as a function of microwave power, temperature and prior exposure to higher fields. The intensity of the low field lines shows critical dependence on the microwave power and temperature. The lines broaden and saturate with increasing microwave power. No broadening is observed at higher temperatures, but only a decrease in intensity. Exposure of the sample to progressively higher fields initially introduces a shift in the position of the lines dependent on the direction of the field scan, and then vanishing of the signal.

Magnetic field dependent microwave absorption in $YBa_2Cu_3O_{7-\delta}$ single crystals has shown a number of interesting features. The observation of a given feature may depend critically on the experimental conditions such as the geometry of the fields and the position and orientation of the sample, microwave power and temperature. With the sample placed in the region of the maximum of the electric component of the microwave field, Pakulis et al. [1] have observed a cusp-like microwave absorption. Most of the measurements, however, were carried out with the sample in the maximum of the magnetic component of the microwave field and with a DC field perpendicular to it [2–6]. For better signal to noise ratio, an audio frequency modulation of the magnetic field with lock-in detection was employed. It was shown that, in the absence of hysteresis, the detected signals were the first derivatives of the microwave absorption with respect to the DC field [6]. Glarum et al. [3] and the present authors [4,6] studied the signals in $YBa_2Cu_3O_{7-\delta}$ single crystals with the microwave field in the *ab* crystallographic plane and at relatively high microwave power (10–20 dB below 200 mW). In good superconducting crystals, one observes a strong signal just below T_c. Its integral has the same cusp-like form as the signals observed by Pakulis et al. [1]. Partial oxygen depletion in the samples brings about a shift of the signal towards lower temperatures and the appearance of hysteretic signals at still lower temperatures [6]. Thus, the microwave technique was found to be a very sensitive test of the homogeneity and the superconducting quality of the samples. Blazey et al. [2] reported a remarkable observation of a series of regularly spaced absorption lines. The pattern could be nicely observed at low temperatures with low microwave power. The periodicity of the pattern was taken as a sign of a macroscopic flux quantization in the sample, quite distinct from the conventional vortex structure in type-II superconductors. It was noted that the period of the pattern was dependent on the thickness of the sample. In a sample about 100 μm thick, the period was 0.2 Oe, but when this sample was cleaved in half, the period observed was 0.4 Oe [5]. We reported [6] that in our samples, which were about 30 μm thick, the observed period was 0.7 Oe, i.e. in good agreement with the scaling found by Blazey et al. In this paper we wish to report on our experimental observations in more detail with a particular emphasis on some points which were not described by Blazey et al., or which are at variance with the results with their samples.

Microwave measurements were made using an electron spin resonance (ESR) spectrometer as described previously [2–6]. Conventional field modulation and lock-in detection were employed. No change in the spectrum was observed when the mod-

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ulation frequency was varied in the range 1.5–100 kHz. The modulation amplitude was 100 mOe, unless specified otherwise. The single crystal was mounted on a quartz holder and placed in the center of the TE_{102} microwave cavity where the magnetic component of the microwave field was maximum. The *c* axis of the crystal [6] was parallel to the polarization of the microwave field, and the DC field was in the *ab* plane.

The sample was cooled in zero magnetic field, and small field scans were used to record the spectrum. We observed the same dependence of the period of the line pattern on the orientation of the DC field within the *ab* plane as reported by Blazey et al. [2,5], and we find no need to describe it here in detail. The dependence of the absorption spectrum on the microwave power showed the same main features as in the case of Blazey et al. [5], but there were also some differences which are worth noting. In fig. 1 we show a set of spectra taken at power levels from 58 dB to 10 dB below 200 nW. The initial increase in the microwave power (from 58 dB to 50 dB) brings about a dramatic increase in the intensity of the second line, but a negligible change for other lines. Clearly, the intensity of the absorption lines does not rise linearly with the microwave field strength. The nature of this absorption must be highly nonlinear and possibly related to some critical parameters. Also, the shielding current induced by the DC field plays an important role. In the next step, at 46 dB, a giant increase is experienced by the first line. One can notice also that the lines broaden. This is the incipient evolution of the lineshape into a square-pulse form seen at still higher power levels. Note that the observed lines in fig. 1 are the derivatives of the actual absorption lines. The width of the square-pulse absorption lines increases linearly with the microwave field strength, as already reported by Blazey et al. [5]. It is also relevant to observe the integrated intensity (i.e. the double integral of the derivative signal) as a func-

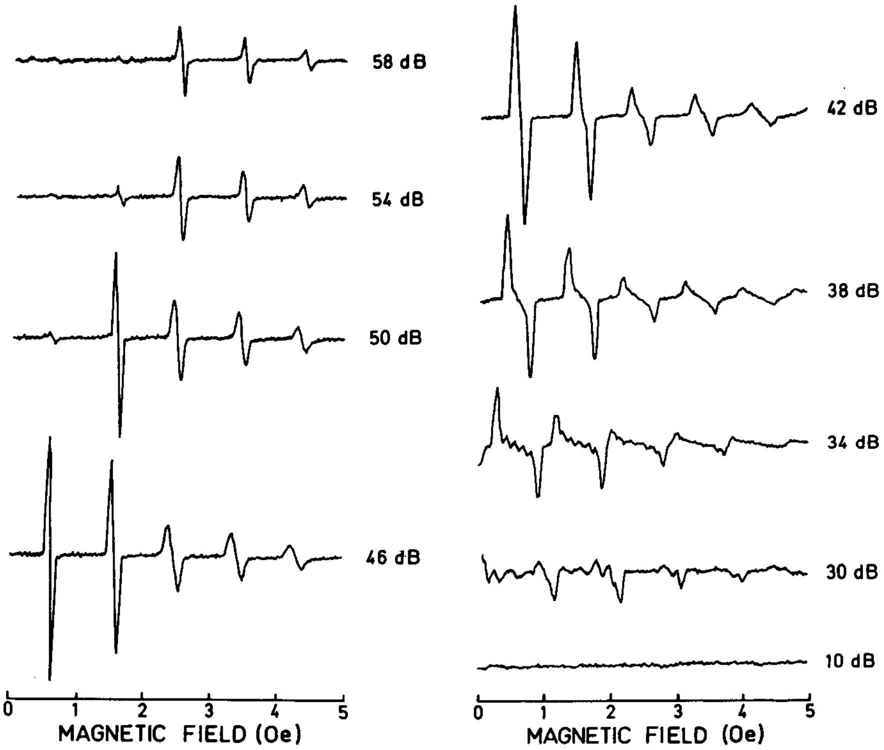

Fig. 1. Microwave absorption lines (first derivatives) in a single crystal of $YBa_2Cu_3O_{7-\delta}$ at 3 K. Attenuation of the microwave power is given in dB below 200 nW.

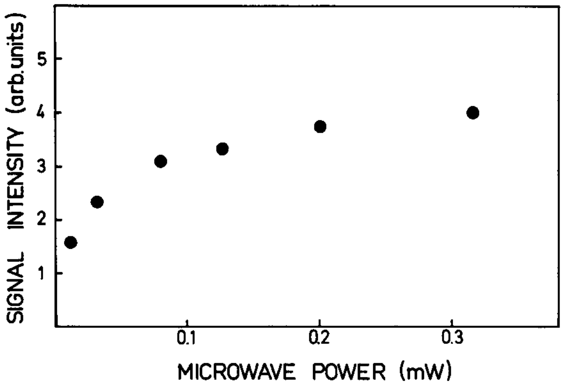

Fig. 2. Microwave absorption intensity (integrated area) as a function of the microwave power in a single crystal of $YBa_2Cu_3O_{7-\delta}$ at 3 K.

tion of microwave power. Fig. 2 shows that the absorption intensity saturates even at relatively low power levels. At higher power levels, the height of the lines cannot be followed with sufficient precision, and the experimental points are not plotted.

In the crystal studied by Blazey et al. [5], a new series of lines, with a different period, appeared at a higher power. These lines were more intense than the low power lines. In contrast, fig. 1 shows that no additional series of lines occurs in our single crystal. This result strongly suggests that the occurrence of multiple series is not an intrinsic property, but rather a sign of the sample inhomogeneity. In fig. 3 we show the spectra for 38 dB and 34 dB on an expanded scale and with a much lower modulation amplitude which enables resolution of the structure of the peaks. This structure is likely to be just another example of the sample inhomogeneity.

The temperature dependence of the absorption spectrum is also an important feature of the phenomenon. Fig. 4 shows the evolution of the absorption pattern when the temperature is raised from 3 K to 30 K. At some threshold temperature (10 K in the case of fig. 4), the first order lines exhibit a dramatic increase. This is similar to the effect of the microwave power described above. However, there is no significant broadening of the lines. This is at variance with Blazey et al. [5] who reported an observed widening similar to that induced by increasing the power at constant temperature. They also reported the appearance of new series at higher temperatures. Again, we may suggest that those effects are due to the sample inhomogeneity rather than representing an intrinsic property of the microwave absorption. The intensity of the lines in fig. 4 decreases at higher

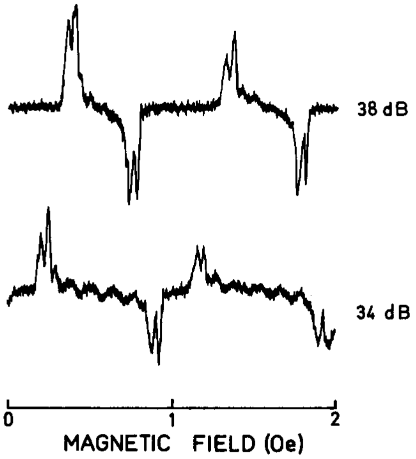

Fig. 3. The first two microwave absorption lines from fig. 1 at 38 dB and 34 dB taken with modulation amplitude 20 mOe.

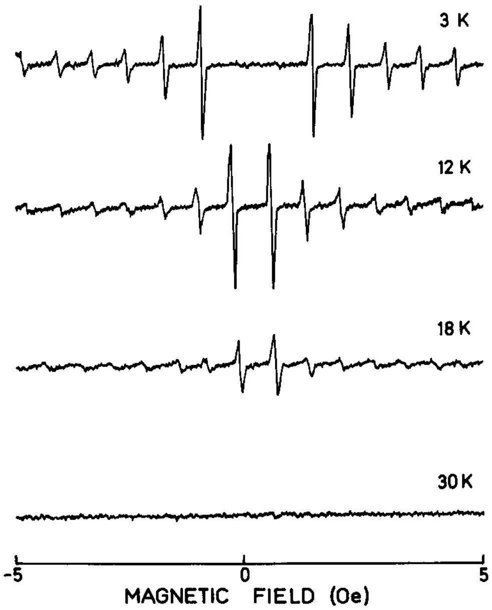

Fig. 4. Temperature dependence of the microwave absorption spectrum in a single crystal of $YBa_2Cu_3O_{7-\delta}$. The power was 52 dB below 200 mW.

temperatures, and the signal vanishes at 30 K. The original spectrum can be recovered if the temperature is again lowered to 3 K.

Finally, we have also observed some irreversible magnetic effects. If the sample is cooled in zero field and the spectra taken in small field scans, the positions and intensities of the lines are the same for both up-field or down-field scans. However, if the field is increased to 20 Oe, the reproducibility is lost. An example of such spectra is shown in fig. 5. Exposure to higher fields clearly introduces some magnetic history. If the field is cycled to 40 Oe and back, the spectrum is completely lost. It can be recovered in its original form only by cycling the temperature above T_c and back again. Thus, it seems that microwave absorption might become a useful technique for the study of subtle magnetic properties in single crystals.

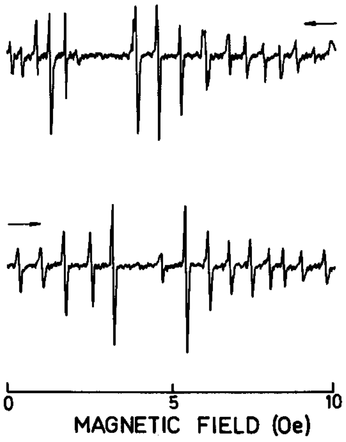

Fig. 5. Microwave absorption spectra taken after the single crystal $YBa_2Cu_3O_{7-\delta}$ was exposed to a magnetic field of 20 Oe. The arrows indicate the direction of the field sweep. The temperature was 3 K.

Blazey et al. [5] have proposed an explanation in terms of mixing of macroscopic flux states in domains associated with regularly spaced crystal twin boundaries. Their analysis predicts broadening of the lines both with microwave power and with temperature. It does not treat the behavior of the line intensity. We feel that domains formed by twin boundaries, or some other structural boundaries [7,8], could be at the origin of this phenomenon. If some kind of weak links are involved, the dependence of the line intensity on the microwave field strength and on temperature could be related to the critical currents of the weak links. In this picture, the appearance of multiple sets of lines in some crystals could be understood as the occurrence of multiple sets of structural boundaries with different periods and different critical currents. However, we cannot rule out the possibility of a completely different theoretical approach to this phenomenon.

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