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Published in:
Physica C: Superconductivity and its Applications

DOI:
10.1016/j.physc.2004.01.011

Publication date:
2004

Citation for published version (APA):
Banerjee, T., Bagwe, V. C., John, J., Pai, S. P., & Kumara, K. G. (2004). Role of twins in peak effect phenomenon observed at microwave frequencies in high Tc superconductor thin films. Physica C: Superconductivity and its Applications, 405(1), 14-24. DOI: 10.1016/j.physc.2004.01.011

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Physica C 405 (2004) 14–24

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Role of twins in peak effect phenomenon observed at microwave frequencies in high T_c superconductor thin films

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Received 9 April 2003; received in revised form 24 December 2003; accepted 22 January 2004

Abstract

Measurements of microwave surface resistance, R_s, at subcritical currents as a function of temperature with varying dc magnetic field upto 0.8 T have shown peak effect (PE) in epitaxial $DyBa_2Cu_3O_{7-\delta}$ (DBCO) and $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films grown by pulsed laser deposition on $\langle 100 \rangle$ $LaAlO_3$ substrates. Microwave measurements were performed on microstrip resonators as test vehicles. Occurrence of a peak in R_s in dc magnetic field is governed by the nature and concentration of defects. Evidence shows that thinner films with a higher ratio of areal density of extended defects, n_e (such as twin boundaries), to the areal density of point defects, n_p, show PE at the measurement frequencies 4.88 and 9.55 GHz; whereas, thicker films ($\geqslant$3000 Å) with a smaller n_e/n_p ratio do not show PE. 2500 Å thick YBCO film shows a double peak structure at 9.55 GHz, thereby suggesting two sets of twin boundaries in this film having different κ_p values. Measurements carried out on low-twinned $LaAlO_3$ substrates show that 2400 Å thick DBCO film does not exhibit the PE phenomenon at 4.88 GHz upto to an applied field of 0.8 T; this indicates that twins propagated from the $LaAlO_3$ substrates are responsible for the occurrence of PE at microwave frequencies. Oxygen ion irradiation (90 MeV, 3×10^{13} ions/cm^2) of 2500 Å DBCO film has been found to shift the peak to lower temperature at 4.88 GHz, but significantly suppress the peak at 9.55 GHz. Depinning frequency, ω_p vs. T plot obtained for the 2400 Å DBCO film shows a peak due to the peak in its R_s vs. T plots.

PACS: 74.76.bz; 74.25.Ha; 74.60.Ge; 78.70.G
Keywords: Peak effect; Microwave characteristics; Magnetic properties; Thin films and extended defects

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1. Introduction

The dynamics of flux line lattice (FLL) in the mixed state of type II superconductors have been the subject of both theoretical and experimental investigations for a long time [1–6]. Both ac and microwave fields in externally applied dc magnetic fields have been used for the study of FLL

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doi:10.1016/j.physc.2004.01.011

dynamics [7–9]. It is also known that pinning by material disorder and defects plays a vital role in determining the static as well as the dynamic behaviour of vortices [10–14]. The critical current density, J_c, is the single most important physical quantity probed to understand the behaviour of type II superconductors in dc and low frequency fields. However, at microwave frequencies the measurements are more complicated; they are generally performed at subcritical microwave currents and the most relevant physical parameters are surface impedance, Z_s and depinning frequency, ω_p (also known as pinning frequency earlier) [2,15,16].

The peak effect (PE) phenomenon in type II superconductors has been a subject of intense investigations during the last few years [17,18]. It is generally understood that PE in J_c vs. $T(H)$ plots results due to competition between intervortex interactions and pinning by defects or material disorder in weakly pinned type II superconductors. The earliest understanding of the phenomenon of PE in driven flux line lattices, the collective pinning theory [19], involves the softening of the elastic moduli of the FLL, so that the vortices may settle more deeply into the pinning potential and thus become more difficult to depin. No PE has been observed in thin films which are heavily pinned due to the high density of point defect disorder in them, and till recently peak effect has not been reported at microwave frequencies. While investigating the dynamics of FLL at microwave frequencies at subcritical currents under dc magnetic fields, we have observed PE in surface resistance, R_s in $DyBa_2Cu_3O_{7-\delta}$ (DBCO) thin films [7]. More recently, we have also observed PE in R_s of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films and have shown that ω_p can be modulated by generating columnar defects using heavy ion irradiation [14]. Motivated by these observations, we have carried out investigations of the defect structures responsible for the peak effect at microwave frequencies at subcritical currents and calculated ω_p as a function of temperature from the experimental R_s data of DBCO films. Based on evidence obtained via film thickness dependence of PE and substrate twins, we show that the occurrence of a peak in R_s of DBCO films is associated with extended defects such as twin boundaries at the substrate–film interface; we also present the results of our observations of PE at microwave frequencies in DBCO and YBCO thin films.

2. Experimental

Both DBCO and YBCO films were grown by pulsed laser deposition (PLD) on single crystal $\langle 1\,0\,0\rangle$ $LaAlO_3$ (LAO) substrates under optimized growth conditions. The substrate temperature was 780 °C and oxygen pressure during growth was 250 mTorr. The films were characterized by X-ray diffraction, four probe resistivity, and ac susceptibility measurements. The films were found to be c-axis oriented with a superconducting transition temperature, $T_c = 91 \pm 0.5$ K. Microwave transmission measurements were performed on capacitively coupled microstrip resonators having 9 mm length and 175 mm width patterned on 10 mm × 10 mm × 0.5 mm LAO substrates using UV lithography. DBCO film thickness was varied from 1800 to 3800 Å. YBCO film thickness was 2500 Å. A Hewlett–Packard scalar network analyzer and a synthesized sweep source were used for the microwave measurements. DC magnetic field in the range 0–0.8 T was applied perpendicular to the film plane ($H \| c$) using a conventional electromagnet. The measurements were carried out in a closed loop He cryocooler with temperature stability ∼30 mK. Details of microwave measurements and determination of R_s have been described earlier [20]. Oxygen ion irradiation was carried out at the 15 UD Pelletron accelerator at Nuclear Science Centre, New Delhi using 90 MeV O^{+7} ions at a fluence of 3×10^{13} ions/cm^2. The films were tilted by $5 \pm 1°$ away from the c-axis to avoid ion channeling. At this ion energy and fluence, irradiation with oxygen ions creates point defects and some extended defects.

3. Results and discussion

The high frequency response of type II superconductors is characterized by Z_s, the surface impedance, given by $Z_s = R_s + iX_s$. R_s determines dissipation and yields information on vortex dynamics governed by pinning centers and their energy distribution, whereas X_s, the surface reactance determines Λ, the magnetic field dependent complex penetration depth. A vortex line oscillates under the influence of a rf field and its motion is limited by frictional and pinning forces. Therefore, even in the linear regime at low rf power levels the rf field leads to an enhanced dissipation as ω approaches ω_p. The original theoretical model of linear vortex dynamics in rf currents is given by the equation of motion suggested by Gittleman and Rosenblum [21] and refined later by Coffey and Clem [22]. In the microwave regime with frequencies >1 GHz, the vortices are less sensitive of flux creep in YBCO thin films as shown by Revenaz et al. (i.e., though activated by thermal energy, vortices do not have sufficient time to breakaway from the pinning potential) [15] and reiterated by Golosovosky et al. [16]. Since measurement frequencies used by us are >1 GHz, we adopted the Rosenblum and Gittleman equation due to its simplicity which gave us R_s as a function of ω and ω_p [14]

$$R_s = \left(\frac{H}{H_{c2}}\rho_n\right)^{\frac{1}{2}}\left[\frac{\mu_o\omega^2}{\sqrt{\omega^2+\omega_p^2}}\left(\frac{\omega_p}{2\sqrt{\omega^2+\omega_p^2}}+1\right)\right]^{\frac{1}{2}}, \tag{1}$$

where $\omega_p = \kappa_p/\eta$ (where κ_p is the restoring force or pinning constant and η is the viscosity coefficient) separates the low frequency regime ($\omega < \omega_p$) dominated by pinning with inductive response, from a high frequency regime ($\omega > \omega_p$) of free vortex flow with dissipation. In other words, ω_p is the characteristic frequency at which the pinned vortex segments are no longer able to move fast enough to remain in phase with the applied microwave field. From Eq. (1), we see that for $\omega \ll \omega_p, R_s = C\sqrt{\frac{\omega^2}{\omega_p}}$, whereas for $\omega \gg \omega_p, R_s = D\sqrt{\omega}$, where C and D are constants; Eq. (1) gives the vortex contribution to R_s and hence, theoretically when $H = 0$, Eq. (1) vanishes: however, our "zero field" data imply measurements done at the low remnant field of the magnet (6–10 Oe) and hence, $H \neq 0$ but very low in this case.

Material disorder creates pinning centers whose density and energy distribution determine R_s, λ and ω_p [14,23]. Unlike high quality weakly pinned DBCO/YBCO crystals, thin films have a high density of point defects such as oxygen vacancies and impurities [24,25]. Thin films can also have other growth related extended defects such as twin boundaries, stacking faults etc. In high quality epitaxial DBCO/YBCO thin films point defects and twin boundaries (propagated through the twinned-LAO substrate) play an important role in governing the key transport parameters such as J_c, R_s, λ and ω_p [24–27]. The high density point defects pin the vortices, and hence, are responsible for high J_c in DBCO/YBCO thin films. Point defects also decrease the quasiparticle scattering time, τ and hence, decrease the quasiparticle (normal fluid) contribution to R_s as $R_s \propto \sigma_1$, where σ_1 is the real part of the conductivity associated with the normal fluid response:

$$\sigma_1 = \left(\frac{1}{\mu_o\lambda^2(0)}\right)X_n(T)\left(\frac{\tau(T)}{1+\omega^2\tau^2(T)}\right) \tag{2}$$

where $X_n(T) = 1 - X_s = 1 - [\frac{\lambda(0)}{\lambda(T)}]^2$ is the normal fluid fraction and X_s is the superfluid fraction. Hence, at 'zero' or very low applied magnetic fields, the measured R_s contains primarily the normal fluid contribution. As the field is increased, a large number of point defects pin the vortices, thus reducing the number available for scattering; this would increase the total measured R_s and hence, decrease ω_p as a first approximation, since $R_s \propto 1/\sqrt{\omega}_p$ for $\omega_p \ll \omega_p$. In other words, it is logical that since experimental evidence shows that point defects in DBCO/YBCO films lead to low values of R_s, then it must be extended defects which are responsible for the observed PE in R_s at microwave frequencies.

Since the areal density of point defects increases with film thickness [27] but the extended defects such as twin boundaries and interfacial strain remain primarily confined at the film substrate interface, we investigated a series of c-axis oriented DBCO films on $\langle 1\,0\,0\rangle$ LAO substrates with thickness in the range 1800–3800 Å. The zero field R_s vs. T plots of DBCO films of varying thickness at 4.88 GHz (fundamental excitation of the

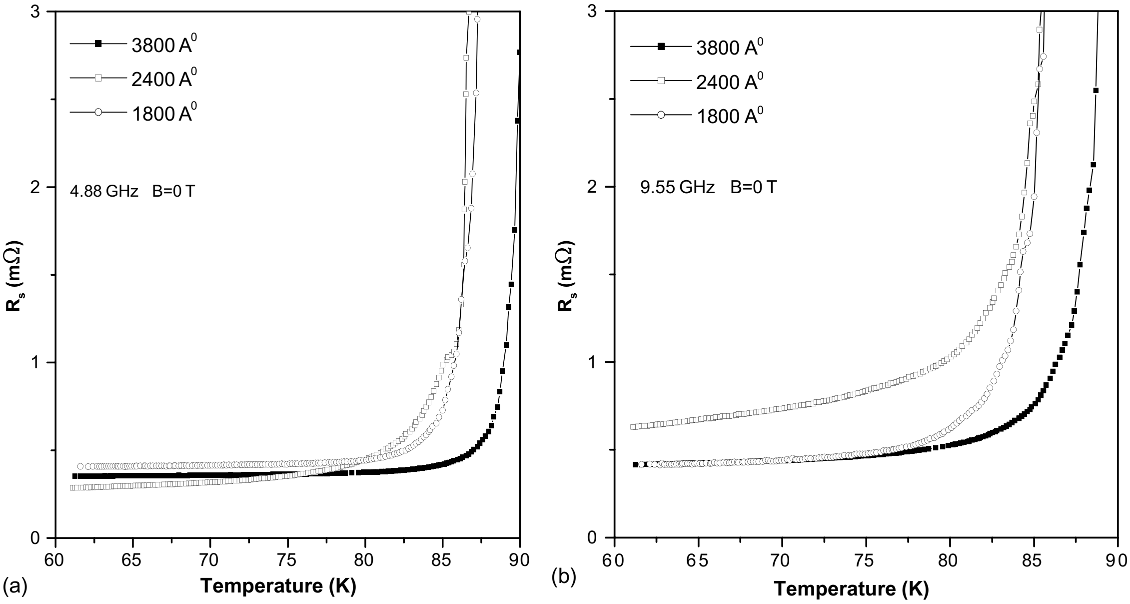

Fig. 1. Zero field R_s vs. T plots of DBCO films with thickness 1800, 2400 and 3800 Å: (a) 4.88 GHz, and (b) 9.55 GHz.

microstrip) are shown in Fig. 1(a). Fig. 1(b) shows the zero field R_s vs. T plots at 9.55 GHz (first harmonic excitation). It is clear from the figures that at zero field no PE is observed in R_s vs. T plots, confirming our earlier results [7,14]. However, as the magnetic field is increased, clear signature of PE is observed in thinner films both at 4.88 and 9.55 GHz; the intensity of the peaks increases as the field is increased till 0.8 T. However, thicker films (thickness $\geqslant$ 3000 Å) do not show peaks even at the maximum field of 0.8 T. These results are depicted in Fig. 2(a) and (b) for 4.88 and 9.55 GHz frequencies, respectively. All the films however, showed an increase in R_s with increasing field as expected, as the vortex contribution increases with the field.

It may also be noted that the zero field R_s vs. T plots of thinner films (1800 and 2400 Å) in Fig. 1(a) and (b) have an earlier rise as compared to thicker films. Thus, if we take the sharply rising point as T_c of these films, then $T_c \sim 87$ K at 4.88 GHz (Fig. 1(a)) and ~86 K at 9.55 GHz (Fig. 1(b)). However, the T_c of both thinner and thicker films measured using four probe resistivity and ac susceptibility methods was 91 ± 0.5 K. This discrepancy in T_c is due to the effect of penetration depth. Our earlier work (Ref. [20]) has shown that the London penetration depth, λ (77 K) of YBCO films is ~2500 Å at 77 K ($\lambda(0) \sim 1450$ Å). Since the thickness of thinner films is comparable to $\lambda(T)$, as one approaches T_c the R_s values rise sharply thereby giving an indication that the microwave T_c is lower than the T_c measured in dc/low frequency conditions. Similar effect can be seen at 0.8 T field in Fig. 2(a) and (b). Here the R_s vs. T plots show a steep rise at a lower temperature as compared to the corresponding zero field plots.

All the measurements were performed in the linear regime at 10 dBm microwave power. This was confirmed by carrying out R_s measurements at lower power levels of 0, 2 and 5 dBm, all of which neither showed a decrease in R_s nor a shift in the position of peaks both at 4.88 and 9.55 GHz. The linear regime indicates that our measurements are at subcritical (microwave) currents. The transport critical current densities measured in these films using patterned microbridges are about 2×10^6 A cm^{-2} at 77 K. No peak effect was observed in transport J_c. Further, isothermal magnetization vs.

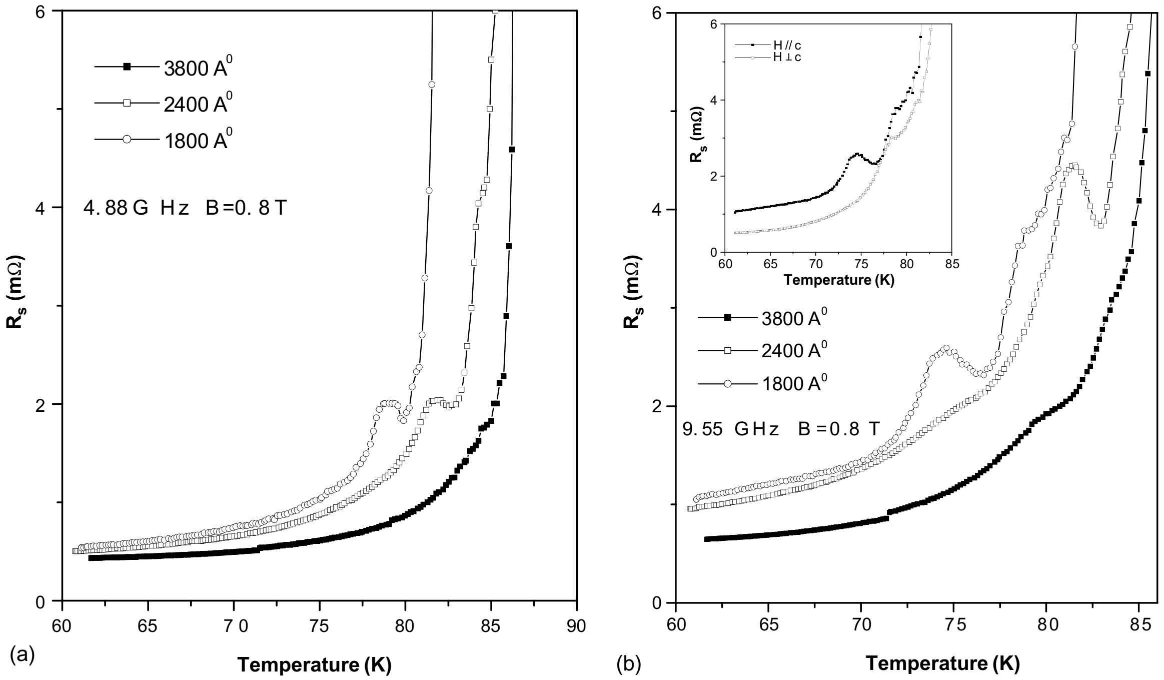

Fig. 2. Zero field cooled R_s vs. T plots of DBCO films with thickness 1800, 2400 and 3800 Å at 0.8 T field: (a) 4.88 GHz, and (b) 9.55 GHz.

field (MH) measurements performed on thick as well as thin films in the field range 0–2.5 T using a quantum design SQUID magnetometer did not show a peak in the M vs. H plots. Fig. 2 indicates that only thinner films show PE whereas the thicker films do not. It may be pointed out that the areal density n_p, of point defects increases with thickness. Since the areal density of extended defect, n_e, (primarily twins located close to the substrate–film interface) remains almost constant in films grown on identical substrates, the ratio $r = n_e/n_p$ is smaller for thicker films. This leads to an enhanced J_c, and low R_s and also high ω_p values in thicker films. On the other hand, thinner films having high $r = n_e/n_p$ values show a peak in R_s. Another evidence for the extended defects being responsible for PE is shown in the inset in Fig. 2(b). This inset shows a comparison of R_s vs. T plots of 1800 Å thick film at $H = 0.8$ T obtained with $H \| c$ and $H \perp c$. A distinct angular dependence of PE is seen which can be due to extended defects such as twin boundaries and not due to random pinning disorder caused by point defects. It may be mentioned here that even in weakly pinned YBCO crystals point defects such as oxygen vacancies have not been identified with the conventional PE [23].

The PE phenomenon observed in YBCO films on LAO substrates is shown in Fig. 3. Fig. 3(a) shows the R_s vs. T plots with varying field obtained for 2500 Å thick YBCO film at 4.88 GHz fundamental excitation; shown in Fig. 3(b) are similar plots for YBCO film at 9.55 GHz first harmonic. It is seen that the PE signature at 4.88 GHz is small, similar to the PE signature observed in the DBCO film. However, it is interesting that the results at 9.55 GHz are quite different. In the case of YBCO film a satellite peak is seen at a lower temperature ($\sim$73 K) besides the main peak at $\sim$76 K. We believe that the satellite peak is due to another set of extended defects in the YBCO film. In other words, the YBCO film studied by us has two distinct sets of extended defects, possibly both twin boundaries, with different distributions of pinning constant, κ_p which are responsible for the two peaks observed.

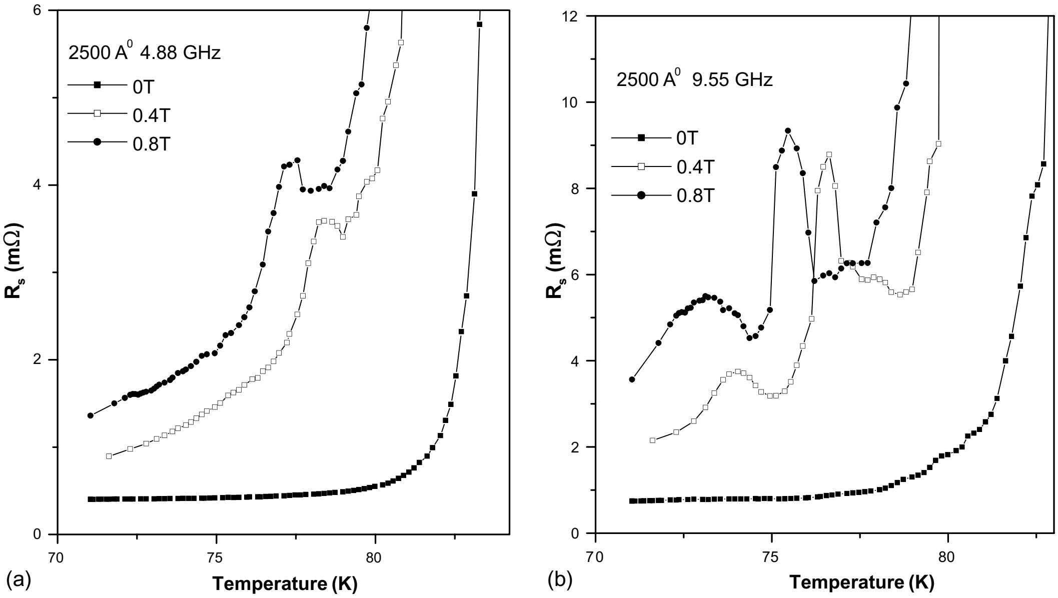

Fig. 3. Zero field cooled R_s vs. T plots of 2500 Å thick YBCO film at 0, 0.4 and 0.8 T fields ($H\|c$): (a) 4.88 GHz, and (b) 9.55 GHz.

While looking for a direct evidence for the cause of PE by substrate twins propagated into the DBCO/YBCO films, we thought it would be interesting to explore low-loss (twin-free) LAO substrates. In the absence of low-loss twin-free substrates, however, we used LAO substrates with low-twin density. Shown in Fig. 4 are the optical micrographs of normal and low-twinned LAO substrates obtained with differential interference contrast. The black line in the middle is the 175 μm wide DBCO resonator device. The microwave measurements carried out on the low-twinned device showed very interesting results. Although it showed a rather weak PE signature at 9.55 GHz, no PE was seen at 4.88 GHz. Fig. 5 shows a comparison of 4.88 GHz R_s vs. T plots of 2400 Å thick DBCO films grown on low-twinned LAO and on the normal-LAO substrate. R_s vs. T plots obtained both at zero field and 0.8 T field are compared in the figure. The observation that the low-twinned DBCO film does not show any PE signature at 4.88 GHz is a reasonable evidence for our conjecture that extended defects such as substrate twins propagated into the DBCO/YBCO films are responsible for PE signature in thin (<3000 Å) films. It may also be noted that due to a higher defect density in the normal-LAO substrates, R_s of DBCO films on normal-LAO is higher than that of the film on low-twinned LAO.

In another parallel experiment we investigated the effect of oxygen ion irradiation on microwave properties of 2500 Å thick DBCO films. 90 MeV oxygen ions at a medium fluence of 3×10^{13} ions/cm^2 creates both point defect disorder and some columnar defects. Shown in Fig. 6(a) are R_s vs. T plots obtained for this DBCO film at 4.88 GHz both before and after oxygen ion irradiation. We notice that the peak observed in the pristine film becomes more intense and shifts to lower temperature after irradiation. This implies that the effective pinning constant, κ_p of twin boundaries existing in the pristine film and of extended defects (point defect clusters) generated due to a considerably high dose of oxygen ion irradiation has significantly changed after irradiation. Equally interesting are the results obtained at 9.55 GHz shown in Fig. 6(b). Due to a heavy dose of oxygen ion irradiation, the defect disorder is seen to be dominant in the oxygen irradiated film as the values of R_s are not only more sensitive to applied field (irradiated film shows higher R_s with increasing field) but also the peaks observed in the

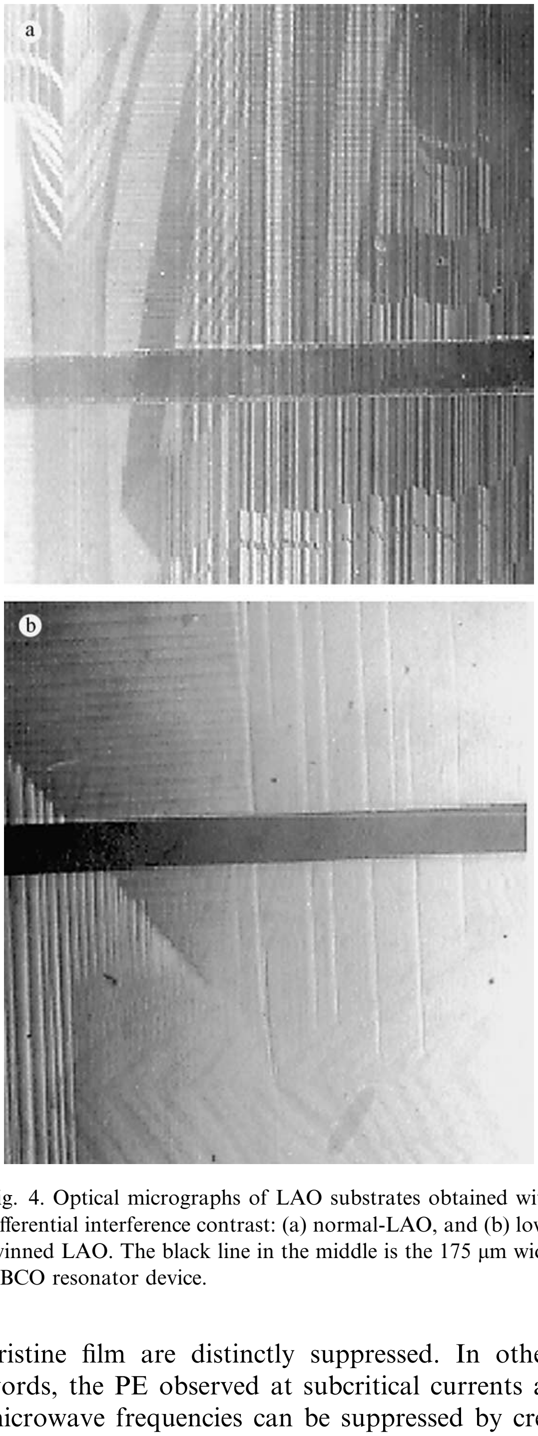

Fig. 4. Optical micrographs of LAO substrates obtained with differential interference contrast: (a) normal-LAO, and (b) low-twinned LAO. The black line in the middle is the 175 μm wide DBCO resonator device.

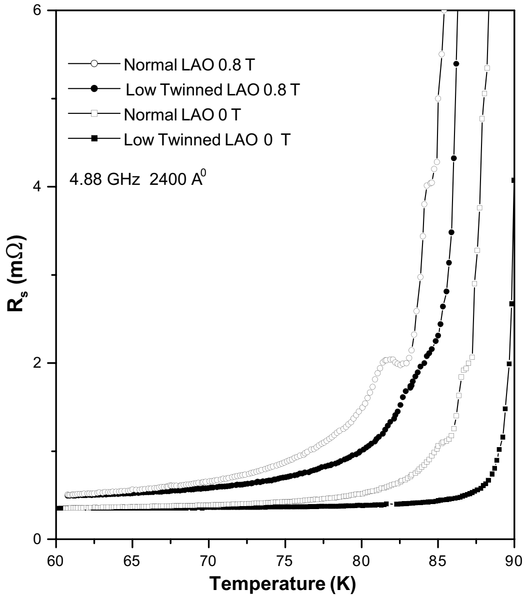

Fig. 5. Comparison of 4.88 GHz R_s vs. T plots of 2400 Å DBCO films grown on normal- and low-twinned LAO substrates obtained at 0 and 0.8 T fields ($H \| c$).

pristine film are distinctly suppressed. In other words, the PE observed at subcritical currents at microwave frequencies can be suppressed by creating a heavy defect disorder in the DBCO films.

As mentioned earlier, conventional PE has not been observed in transport J_c vs. T and M vs. H measurements carried out in the DBCO/YBCO thin films. This can be explained by the fact that the high density of defect disorder in the films, both due to point defects and extended defects, suppresses the PE in J_c vs. T and M vs. H measurements. The reported observations which indicate that the conventional PE is seen only in weakly pinned single crystals (eg., $NbSe_2$, YBCO, etc.) also support this view [17,18]. Therefore, our observations on oxygen ion irradiated DBCO films go a step further, viz., even the PE observed in R_s vs. T plots at microwave frequencies can be suppressed by generating a heavy defect disorder (both due to point defects and extended defects) in the films.

The conventional PE in J_c vs. $T(H)$ plots observed in twinned YBCO (and also in some low temperature superconductor crystals) has been related to the twin structure [17,18]. Further, in twinned YBCO crystals the peak has been found to depend strongly on the orientation of the applied field relative to the twin planes. PE has been found to be the strongest for vortex motion along the twin planes with the applied field parallel to

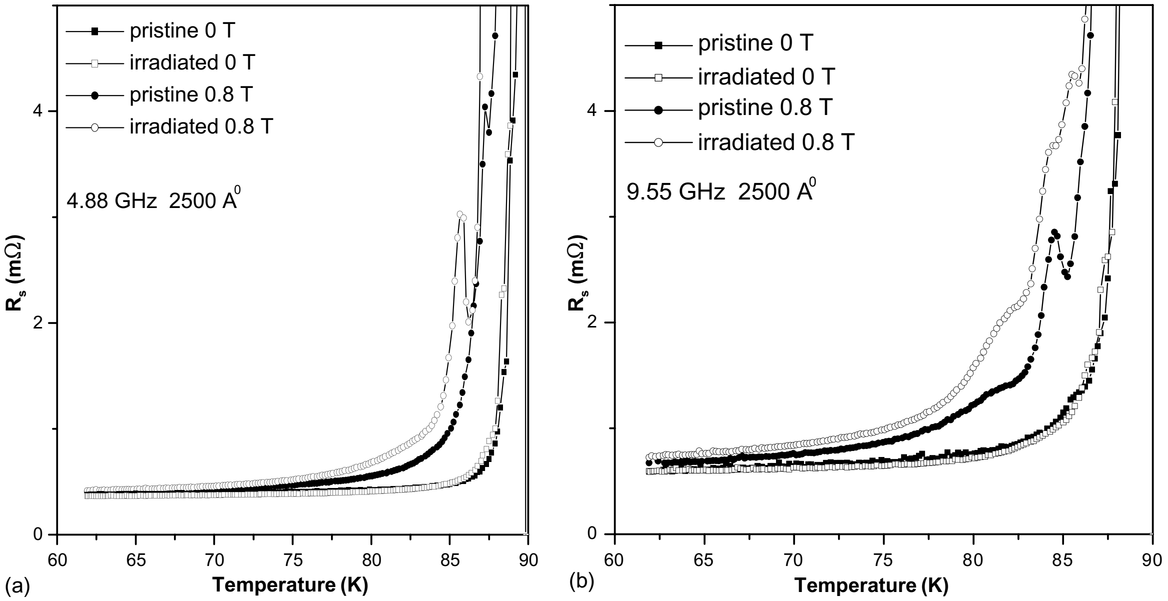

Fig. 6. Comparison of R_s vs. T plots of 2500 Å thick pristine and irradiated DBCO film at 0 and 0.8 T field ($H\|c$): (a) 4.88 GHz, and (b) 9.55 GHz.

c-axis and weakest if the field is tilted out of the plane of the twins. It is also interesting to note that in pure YBCO crystals, oxygen vacancy clusters, but not point defects due to individual oxygen vacancies, has also been related to PE in J_c [23]. Therefore, it is clear that the conventional PE is dependent on the defect structure and is not intrinsic to the crystal structure. Our experimental observations too led us to believe that the PE observed by us in R_s vs. T plots at subcritical currents at microwave frequencies is also not intrinsic to the crystal structure of the YBCO films but to the nature of the defects in them. Experimental evidence indicates that the extended defects such as twins at the substrate–film interface propagated from the LAO substrate, and possibly point defect clusters generated due to a heavy dose of oxygen ion irradiation, but not the point defects, are responsible for the PE at microwave frequencies. However, the similarity between the conventional PE in J_c and microwave PE in R_s ends here.

The conventional PE in J_c vs. $T(H)$ plots is observed in a driven FLL [12]. However, the central parameter which controls the dynamics of FLL at subcritical currents at microwave frequencies is not J_c but $\omega_p = \kappa_p/\eta$, which in turn is dependant on the nature and distribution of pinning centers. Since PLD grown DBCO/YBCO thin films have a distribution of defects both correlated extended defects and uncorrelated point defects, the characteristic depinning frequency, ω_p, of the film can be considered as an effective sum of the depinning frequencies $\omega_{p1}, \omega_{p2}, \ldots$, associated with different sets of defects, each of which would be determined by the density and pinning constant, κ_p. Since the areal density of the point defects is lower in thinner films as compared to the thicker ones, ω_p of these films is mainly determined by the characteristic ω_{p1} associated with the interfacial defects such as twin boundaries. As the film thickness increases, the relative areal density of point defects increases, and although ω_p is governed both by ω_{p1} of the extended defects and ω_{p2} of the point defects, it is increasingly dominated by ω_{p2}. Hence, thicker films with a higher areal density of point defects as compared to the interfacial extended defects, show low R_s, high ω_p and no PE as observed by us. Further, our observation of two peaks (the main and the satellite peak) in the 2500

Å thick YBCO film suggests that there are two distinct sets of interfacial extended defects or two types of twin boundaries in this film with two sets of pinning constants, κ_p, which are responsible for the two peaks.

The values of ω_p have been calculated from Eq. (1) both for thinner and thicker films using the measured values of R_s at 4.88 and 9.55 GHz. Shown in Fig. 7 are the ω_p vs. T plots obtained for 2400 and 3000 Å thick DBCO films at 0.8 T. As expected, the 3000 Å thick film shows high ω_p values. On the other hand, the thinner film shows smaller ω_p values. The plot for the 2400 Å thick film also has a peak which is a result of the peaks in R_s vs. T plots of this film at 4.88 and 9.55 GHz measurement frequencies.

Larkin and Ovchinnikov have presented a quantitative explanation for the conventional PE in J_c vs. $T(H)$ [19]. Earlier, Pippard had proposed that the increase in J_c is associated with the softening of the shear modulus C_{66} [28]. The main similarity between the conventional PE in J_c and microwave PE in R_s is that both are governed by a set of defects which act as characteristic pinning centers. Furthermore, in both cases, the peak shifts to lower temperatures as the magnetic field is increased. However, the similarity between the conventional PE in J_c and the microwave PE in R_s ends here. As the central parameter in microwave PE is $\omega_p = \kappa_p/\eta$ and not J_c, the model of vortex dynamics proposed by Pippard [28] and later by Larkin and Ovchinnikov [19] may not be applicable to microwave PE. Nevertheless, one can think of a plastic flow of vortex array involving the formation of channels in which the vortex array is more ordered and weakly pinned than in the surrounding areas resulting in an increase in R_s with temperature. Subsequent jamming or blocking of these channels by strong pins like extended defects hinders the flow of vortex array, thus reducing R_s. Possibility of weakly pinned channels has been proposed in low frequency ac current [29,30]. However, it is difficult to propose at this stage a precise mechanism responsible for the occurrence of PE at microwave frequencies. Nevertheless, it is evident from the experimental observations so far that a particular set of extended defects which have characteristic ω_p values cause PE in R_s at microwave frequencies.

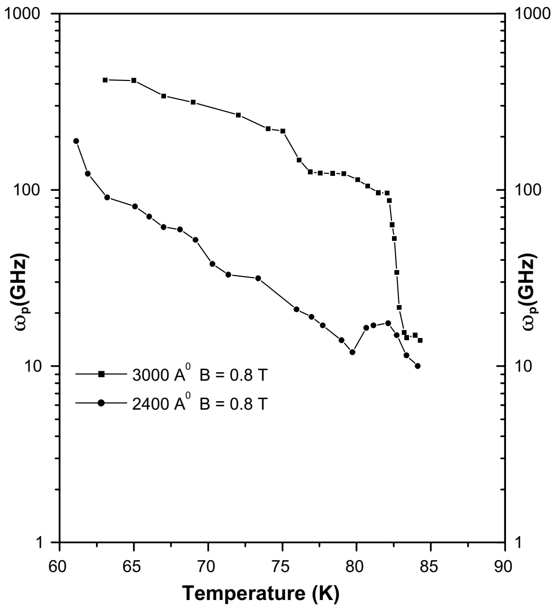

Fig. 7. ω_p vs. T plots of 2400 and 3000 Å DBCO films at 0.8 T field.

However, high T_c superconductors such as YBCO are complicated materials. Even c-axis oriented epitaxial YBCO thin films have grain boundaries besides twin boundaries and point defects like oxygen vacancies and impurities. Grain boundaries, especially low angle grain boundaries are weak links (S–N–S or S–I–N–I–S type) which act as Josephson junctions [31]. As proposed by Tinkham [32], at low applied fields, Josephson fluxons (JF) get pinned at the weak link surfaces, especially at the crossover of weak links. The penetration of intergrain weak links by JF gives rise to rapid degradation of Z_s (also R_s and J_c) for fields $H \geqslant H_{c1J} \sim 1$ Oe. These weak links are source of high residual resistance, R_{res}, seen in these films as $T \to 0$. In strong pins, as field increases, J_{cJ} increases ($\sim 10^6$–10^7 A cm^{-2} at very low temperatures) and JF become more like Abrikosov fluxons (AF), named as Abrikosov Josephson fluxons (AJF). With fields increasing further ($H \geqslant H_{c1}$), AF become more prominent. Further, because of their normal conducting core AF show a higher viscosity η and higher pinning constant

κ_p. This yields a smaller Campbell penetration depth, $\lambda' \propto \sqrt{B}/\kappa_p$ than JF have. $\omega_p = \kappa_p/\eta$ for JF or AJF is about a factor of 10 larger than for AF since η is a factor of 10–100 times smaller overcompensating for their smaller κ_p. Although the static pinning properties of JF, AJF and AF are comparable, their dynamic properties are qualitatively and quantitatively different. This is due to the insulating core of JF and AJF which causes reduced flow dissipation, the energy being mostly electromagnetic. JF/AJF are also created fast ($\leqslant 10^{-12}$ sec) and move fast with velocity of light along the weak links. Thus, with increasing fields $H \gg H_{c1} \sim 0.1$ T AF penetrate the YBCO film and get pinned by defects (strong pins). Since pinning strength of AF is stronger than that of JF, Campbell penetration depth λ' $(H > H_{c1}) \propto \sqrt{B}/\kappa_p$ shrinks thereby increasing J_c. $\lambda'(H)$ would increase subsequently with increasing AF line density. Thus at certain fields while $\lambda'(H)$ shows a minimum, $J_c(H)$ will show a maximum which is the so-called 'fish-tail' effect (another form of PE) seen by many authors. Hence, it is proposed that the transition from JF/AJF to AF dominance in pinning and dissipation is the cause of the 'fish-tail' [31]. Can we adopt this conjecture of transition from JF/AJF to AF dominance to our observations of microwave PE? Our observations indeed show that microwave PE appears for $H > H_{c1}$ (0.1 T in thinner films), thereby indicating AF dominance. However, more experimental investigations will be needed to find out if the microwave PE in R_s is due to a maximum in $\lambda'(H,T) \propto \sqrt{B}/\kappa_p$ or due to a minimum in $\omega_p = \kappa_p/\eta$ (our model ω_p vs. T in Ref. [7]) because of a large increase in viscosity η far overcompensating the increase in κ_p.

One can also propose alternate mechanisms for microwave PE in R_s. For example, Belk et al. [24,25] have used the model originally proposed by Koshelov and Vinokur [33] for explaining their observations of frequency and temperature dependence of Z_s and X_s of YBCO thin films in a dc magnetic field. This model assumes that the pinning potential is random and that, while majority of the vortices are strongly pinned, some of the vortices are pinned in metastable states separated by energy barriers. In high-T_c materials like YBCO/DBCO films the density of randomly distributed point defects such as oxygen vacancies and atomic interstitials is high enough so that a segment of a vortex core can contain several such defects per copper oxide layer [34]. The point defects have volumes $D_v \ll \xi^3$ (where ξ is coherence length), pinning ranges $r \sim \xi$ and small pinning energies depending upon the nature of their interaction with the vortex core. The short characteristic pinning lengths and low pinning energies of randomly distributed point defects make it likely that many of the vortex segments are pinned in local energy minima which are separated from other minima by distances $\sim \xi$ and by energy barriers U_b as small as a few K. The characteristic frequencies of thermally assisted transitions between metastable states could then be in the range of the frequencies of the applied rf signal for an appreciable number of vortex segments at the measurement frequencies and temperatures. Therefore, the microwave PE in R_s observed by us could be explained as due to thermally induced transitions of vortex segments in metastable states from weaker to stronger pins which cause a drop in R_s as temperature is increased. It is possible that the extended defects such as twin boundaries act as point defect clusters giving rise to metastable states for pinning vortex segments.

4. Summary

We have investigated the dynamics of FLL at subcritical currents at microwave frequencies in epitaxial PLD grown DBCO thin films in the thickness range 1800–3800 Å. Occurrence of a peak in R_s in dc magnetic fields in films of varying thickness is governed by the nature and concentration of defects. Experimental evidence shows that thinner films with a higher ratio, n_e/n_p, of areal density of extended defects (such as twin boundaries) to areal density of point defects show PE at both 4.88 and 9.55 GHz; whereas the thicker films ($\geqslant 3000$ Å thickness) with a smaller n_e/n_p ratio do not show PE. 2500 Å thick YBCO film (on LAO) too has shown PE in R_s vs. T plots at 4.88 GHz and a twin peak structure at 9.55 GHz, thereby suggesting two sets of twins in this film having different κ_p values. Measurements carried on low-twinned LAO substrates have shown that 2400 Å thick DBCO film does not exhibit PE at 4.88 GHz upto an applied field of 0.8 T thereby indicating that twins propagated from the LAO substrates are responsible for the occurrence of PE at microwave frequencies. Further, oxygen ion irradiation at a relatively heavy dose of 3×10^{13} ions/cm^2 has been found to shift the peak in 2500 Å thick DBCO film to lower temperature at 4.88 GHz, but suppress the peak at 9.55 GHz. The latter is due to the generation of high density of extended defects and point defects in oxygen irradiated sample; this is akin to suppression of conventional PE in J_c in DBCO/YBCO thin films due to a high density of point defect disorder. Field dependent ω_p values, calculated from experimental R_s vs. T data of DBCO films, have been found to decrease with increasing temperature; and the ω_p vs. T plot obtained for the 2400 Å DBCO film has been found to show a peak due to the peak in its R_s vs. T plots.

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