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Peak effect at microwave frequencies in swift heavy ion irradiated $YBa_2Cu_3O_{7-\delta}$ thin films

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Abstract. The vortex dynamics at microwave frequencies in $YBa_2Cu_3O_{7-\delta}$ (YBCO) films have been studied. We observe a peak in the microwave (4.88 and 9.55 GHz) surface resistance in some films in magnetic fields up to 0.8 T. This is associated with the 'peak-effect' phenomenon and reflects the order–disorder transformation of the flux line lattice near the transition temperature. Introduction of artificial pinning centers like columnar defects created as a result of irradiation with 200 MeV Ag ion (at a fluence of 4×10^{10} ions/cm^2) leads to the suppression of the peak in films previously exhibiting 'peak effect'.

Keywords. Microwave surface resistance; superconductors; peak effect.

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1. Introduction

Over the years, much work has been carried out to study the vortex dynamics in the mixed state of type-II superconductors, as well as to study the mechanisms that pin the vortices in a magnetic field [1–3]. The competition between intervortex interaction and pinning by disorder, results in a peak in the critical current density J_c near T_c (H_{c2}), known as 'peak effect' (PE). The earliest understanding of the PE [4,5] is based on the collective pinning scenario that involves the softening of the elastic moduli (c_{66} and c_{44}) of the flux line lattice (FLL) near T_c (H_{c2}) where the superconducting order parameter is suppressed. In the weak collective pinning scenario of Larkin and Ovchinnikov, the critical current density, J_c, of an elastic medium pinned by weak disorder is given by

$$B J_c(H) = (n_p \langle f^2 \rangle / V_c)^{1/2}, \qquad (1)$$

where n_p is the volume density of pins, f is the elementary pinning force parameter, B is the magnetic induction and V_c is the volume of the Larkin domain. At the peak temperature, T_p, the dynamics of the FLL undergoes a transition from an ordered to a disordered state accompanied by a collapse in V_c.

Till date the studies of the statics and dynamics of the FLL, probed through various transport, magnetic and structural measurements, revealed the observation of a peak in J_c close to H_{c2}. ac Susceptibilty measurements, carried out in an excitation field ranging from few tens of Hz to a few MHz, probing the dynamics of the FLL revealed no frequency dependence of the peak position of the PE which is suggestive of a true thermodynamic phase transition. Studies of the vortex dynamics carried out at microwave and radio frequencies in low T_c and high T_c superconductors, do not report the observation of the PE at these frequencies. At such frequencies, a small microwave excitation induces a current that causes the vortices to oscillate close to the potential minimum. The dynamics of the vortices at these frequencies, neglecting Hall and stochastic thermal force, is given by the Gittleman and Rosenblum equation of motion [6] as

$$\eta\dot{x} + \kappa_p x = J \times \phi_0 \tag{2}$$

where η is the Bardeen–Stephen viscous drag coefficient, κ_p is the restoring force, $J(t)$ is the microwave driving current and ϕ_0 is the flux quantum $hc/2e$. The vortex impedance is then given by

$$\rho_v = \frac{\phi_0 B}{\eta}\frac{1}{(1 + i\omega_p/\omega)} \tag{3}$$

where the depinning frequency, ω_p, given as $\omega_p = \kappa_p/\eta$ represents a crossover from the pinned FLL ($\omega < \omega_p$) to the flux flow regime ($\omega > \omega_p$). Applying the above to the collective pinning scenario, where the vortices within a Larkin volume respond like a semi-rigid body, the total external force per unit volume is given as $F=n\phi_0 J=BJ$ (n=vortex density). On the other hand, the total restoring force per unit volume will be the same as in eq. (1) and therefore $\kappa_p \propto (n_p\langle f^2\rangle/V_c)^{1/2}$. This will have the same temperature and field variation as J_c and will show a peak-like feature close to T_c (or H_{c2}). This in turn gives a minimum in the surface resistance (R_s) at the order–disorder transition of the vortex lattice, where V_c is a minimum. Here, we report the microwave response of $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films at 4.88 GHz and 9.55 GHz, before and after irradiating them with 200 MeV Ag ions. The strong pinning provided by such controlled columnar defects (CDs) in high T_c superconductors completely alters the equilibrium properties of a clean vortex state and also improves their properties for potential application. Earlier, we had reported the first observation of the PE phenomenon in $DyBa_2Cu_3O_{7-\delta}$ films at a frequency of 9.55 GHz [7]. Here we try to isolate the probable defect structures responsible for the observation of the PE in these films and study the effect of introducing correlated columnar defects in them.

2. Experimental details

Several YBCO ($T_c = 92$ K) epitaxial thin films (thickness 2500 Å) were grown by pulsed laser deposition technique on twinned $\langle 100\rangle$ $LaAlO_3$ substrates. For microwave transmission studies, the films were subsequently patterned into linear microstrip resonators of width 175 μm and length 9 mm using UV photolithographic techniques. Details of the microwave measurements and determination of R_s have been described earlier [8]. dc Magnetic field varying from 0.2 T up to 0.9 T was applied perpendicular to the film plane using a conventional electromagnet. Irradiation was carried out using the 15 UD Pelletron accelerator at Nuclear Science Centre, New Delhi, using 200 MeV $^{109}Ag^{14+}$ ions at a fluence

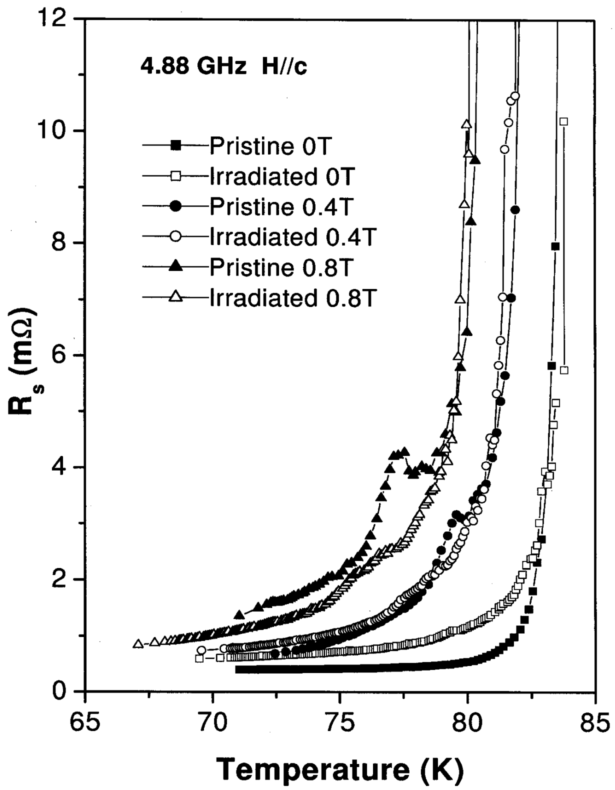

Figure 1. Surface resistance R_s vs. T plots at 4.88 GHz for various applied fields ($\| c$) for both pristine and irradiated films.

of 4×10^{10} ions/cm^2. The films were tilted by $5° \pm 1°$ away from the c-axis to avoid ion channeling.

3. Results and discussion

Figure 1 shows the temperature variation of R_s at 4.88 GHz (fundamental excitation of the microstrip) measured at various magnetic fields both before and after irradiation. R_s of the pristine film exhibits a pronounced maximum followed by a dip before T_c. The peak is found to shift to lower temperature as the magnetic field is increased. Irradiation with 200 MeV Ag ions at a fluence of 4×10^{10} ions/cm^2 (corresponding to a matching field of 0.8 T) causes the peaks to be suppressed. Irradiation introduces CDs that pin the flux lines along the entire length. The temperature variation of R_s at 9.55 GHz (corresponding to the first harmonic excitation of the microstrip) is shown in figure 2. Here we observe an additional peak at lower temperatures with increasing magnetic field. Disorder introduced in the system as a result of irradiation leads to an increase in R_s which is seen in the plots of R_s vs.

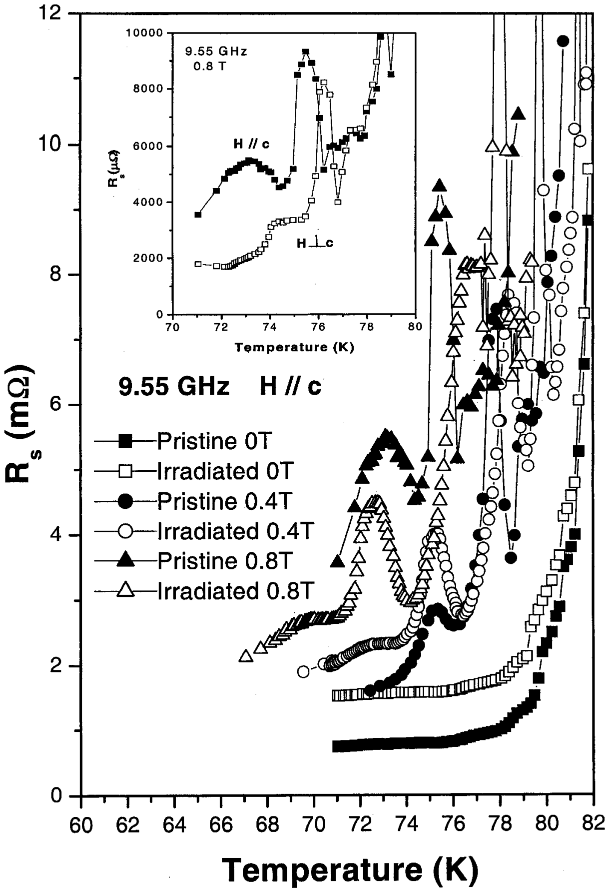

Figure 2. Surface resistance R_s vs. T plots at 9.55 GHz for various applied fields ($\| c$) for both pristine and irradiated films. Inset shows R_s vs. T plot at 0.8 T for $H \| c$ and $H \perp c$ at 9.55 GHz.

T up to a field value of 0.4 T. At the matching field of 0.8 T the effect of pinning by CDs far surpasses the effect of disorder caused by irradiation and this causes the value of R_s to decrease. The peak in R_s at 4.88 GHz arises due to the depinning of flux lines from weak pinning centers (represented by a single pinning potential). The peak is associated with a crossover from elastic to plastic motion of the FLL. At a higher frequency of 9.55 GHz, it is likely that the flux lines are depinned not only from such uncorrelated defect sites but also from strong and dilute pinning centers such as twin boundaries, extended defects etc. (having different κ_p values) thus giving rise to other secondary peaks at lower temperatures.Thin films grown by laser ablation have various types of uncorrelated statistically distributed defects like point defects and oxygen deficiencies, all of which act as efficient pinning centers. An angular correlation with the lower temperature peak was found at 9.55 GHz thus establishing that the secondary peak arises from pinning due to twin boundaries. With the external magnetic field perpendicular to the c-axis of the film,

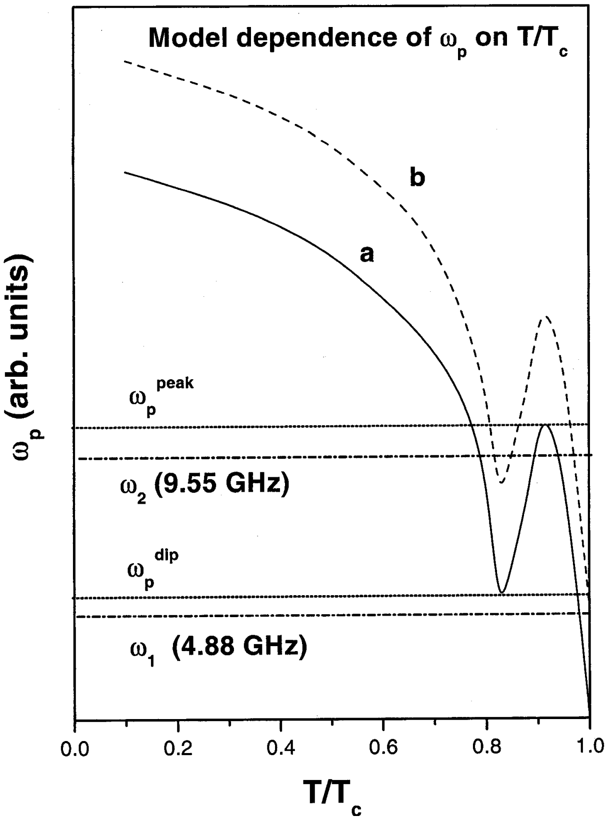

Figure 3. Model dependence of ω_p on T/T_c for (a) pristine sample which shows a dip followed by a peak in the order–disorder region for the pristine; (b) the sample irradiated with 200 MeV Ag ions at a fluence of 4×10^{10} ions/cm^2 which shows an upward shift of the whole plot to a higher depinning frequency.

it is seen that this secondary peak is significantly suppressed. However, the peak before T_c remains unaffected signifying that they are caused by other uncorrelated defects that do not have any angular correlation with the peak. The occurrence of twin boundaries in thin films of high T_c superconductors and its efficacy in flux pinning [9] has been quite well studied. Recent magneto-optical imaging and magnetization measurements have also pointed out that twin planes are easy paths for flux pinning [10,11]. The evolution of the peak in R_s is similar to that of κ_p which in turn follows the behavior of J_c, which shows a peak at the order–disorder transition as the field, or temperature is increased. Since, within the Bardeen–Stephen model, viscosity η varies smoothly with temperature, the depinning frequency ω_p will also show a minimum followed by a peak at the order–disorder transition. This is shown in our proposed model variation of the depinning frequency ω_p, with T/T_c as shown in figure 3. We see that the observation of the peak in R_s critically depends on where our measurement frequency actually is. For $\omega_p^{\text{peak}} > \omega > \omega_p^{\text{dip}}$ the measurement frequency becomes larger than ω_p and R_s increases. However, since ω_p passes through a peak (analogous to that of J_c), the measurement frequency will again become lower than ω_p causing R_s to decrease. The position of the peak and subsequent dip in R_s will coincide with the dip and peak in ω_p, respectively. The secondary peaks at 9.55 GHz can be attributed to a distribution of defect structures from where the flux lines are depinned at this frequency. Since the pinning interaction of these different defects with the vortices are distinctly different [12], they respond differently when the measurement frequency is changed from 4.88 to 9.55 GHz. The artificially introduced highly correlated but controlled defect structures like columnar defects pin a flux line strongly along its entire length and prevent a flux line to be depinned at 4.88 GHz from such sites. Thus, ω_p is shifted above 4.88 GHz. However, at a higher frequency of 9.55 GHz, the vortices pinned to other defect structures like correlated twin planes and CDs get depinned leading to a peak in the R_s at various temperatures. This change of ω_p is reflected in the model plot of ω_p vs. T/T_c (curve b of figure 3) which shifts upward indicating that ω_p has shifted above 4.88 GHz.

4. Conclusion

In conclusion, we have observed a pronounced peak at microwave frequencies in thin films of YBCO and its suppression after irradiating them with 200 MeV Ag ions at 4.88 GHz. The peak in R_s is attributed to an order–disorder transformation of the FLL as the temperature or field is increased. Irradiation introduces CDs which effectively pin the flux lines and prevent their depinning at a frequency of 4.88 GHz. Angular dependent measurements indicate that the low temperature peak at 9.55 GHz can be related to extended defects such as twin boundaries. From our proposed model plot it is seen that with the introduction of correlated CDs, the depinning frequency shifts to a value greater than 4.88 GHz.

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