

## Peak effect in a superconducting DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> film at microwave frequencies

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We report the observation of a peak in the microwave (9.55 GHz) surface resistance in an epitaxial DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> superconducting film in magnetic fields (parallel to the *c* axis) ranging between 0.2 to 0.9 T. Such a peak is absent in the measurements done in zero field. The temperature and field dependence of the peak suggests that this peak could be associated with the peak effect (PE) phenomenon reflecting the order-disorder transformation in the flux-line lattice (FLL). A strong frequency dependence of the PE is observed close to the depinning frequency of the FLL.

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The phenomenon of peak-effect (PE) in type II superconductors has attracted widespread attention in order to understand the order-disorder transition<sup>1</sup> in the flux line lattice (FLL) in the mixed state of type II superconductors. The physical phenomenon associated with the PE is the occurrence of a peak in the critical current density  $J_c$  below its superconducting-normal phase boundary.<sup>2</sup> In a varying temperature measurement, the vortex state in a type II superconductor undergoes a transition from an ordered state below the peak temperature ( $T_p$ ) to a highly disordered state above  $T_p$ .<sup>3-7</sup> This phenomenon is rationalized within the Larkin-Ovchinnikov<sup>8</sup> scenario, where the effective pinning force on the FLL is given by the expression,

$$BJ_c(H) = (n_p \langle f^2 \rangle / V_c)^{1/2}, \quad (1)$$

where  $n_p$  is the density of pinning sites,  $f$  is the elementary pinning force parameter,  $B$  is the magnetic induction, and  $V_c$  is the volume of Larkin domain within which the vortex lattice retains its spatial order. At  $T_p$ ,  $V_c$  reaches a minimum value due to the disordering of the FLL, thereby enhancing the  $J_c$ . Though this general description is widely accepted, the exact nature of the order-disorder transformation is still an issue of intense research.<sup>1-10</sup>

ac susceptibility measurements<sup>3,9,10</sup> carried out at excitation fields in the range of a few tens of Hz to a few MHz to understand the dynamics of FLL reveal no frequency dependence of the peak position of the PE. This suggests the association of a true thermodynamic phase transition with this effect.<sup>10</sup> In these measurements the variation of the  $J_c$  in the superconductor is probed, where the force on the vortices becomes equal to the maximum pinning force. On the other hand, a small microwave excitation induces a current, which is smaller than the  $J_c$ . Therefore, the vortices oscillate close to the minimum of the pinning potential and experience a restoring force close to it. The dynamics of the vortices at these frequencies is described by an equation of motion suggested by Gittleman and Rosenblum,<sup>16</sup>

$$\eta \dot{x} + kx = F, \quad (2)$$

where  $\eta$  is the Bardeen-Stephen viscous drag coefficient,  $k$  is the pinning constant and  $F$  is the external force on the vortex given by  $F = J\Phi_0$ , where  $\Phi_0$  is flux quantum  $hc/2e$ . The vortex impedance is thus given by

$$\rho_v = \frac{\Phi_0 H}{\eta \left( 1 + i \frac{\omega_p}{\omega} \right)}, \quad (3)$$

where  $\omega_p = (k/\eta)$  is the depinning frequency. At low frequencies ( $\omega \ll \omega_p$ ), the vortex impedance is mostly inductive and dominated by pinning; at high frequencies ( $\omega \gg \omega_p$ ), the dynamics of the FLL is mostly resistive with pinning playing a very minor role. There have been few studies<sup>11-15,17</sup> on the dynamics of the FLL in the microwave and radio frequency regime. However, there have been no reports pertaining to the observation of the PE at microwave frequencies in either a low  $T_c$  or a high  $T_c$  superconductor. It is instructive to explore the applicability of Eq. (2), within the collective pinning scenario,<sup>8,16</sup> where the vortices within a Larkin volume elastically respond like a semirigid body. In such a case, the total external force per unit volume on the FLL within  $V_c$  is given as,  $F = n\Phi_0 J = BJ$  (where  $n$  = vortex density). On the other hand, the total restoring force per unit volume will be same as in Eq. (1) and, therefore,  $k \propto (n_p \langle f^2 \rangle / V_c)^{1/2}$ . This will have the same temperature and field variation as  $J_c$ , and will show a peak-like feature close to  $T_c$  (or  $H_{c2}$ ).

In this paper we report the observation of a pronounced PE at microwave frequencies in a DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> (DBCO) superconducting film (2500 Å, 90 ± 0.2 K), grown by pulsed laser deposition on a single crystalline LaAlO<sub>3</sub> substrate. The film was subsequently patterned into a linear stripline of width 175 μm and length 10 mm, and the measurements of microwave transmission were performed by stripline resonator technique.<sup>18</sup> dc magnetic field up to 0.9 T was applied perpendicular to the film plane (parallel to the *c* axis of DBCO film) using an electromagnet, and the temperature was controlled within 30 mK.

Figure 1 shows the temperature variation of the surface resistance ( $R_s$ ) at 9.55 GHz (corresponding to the first har-

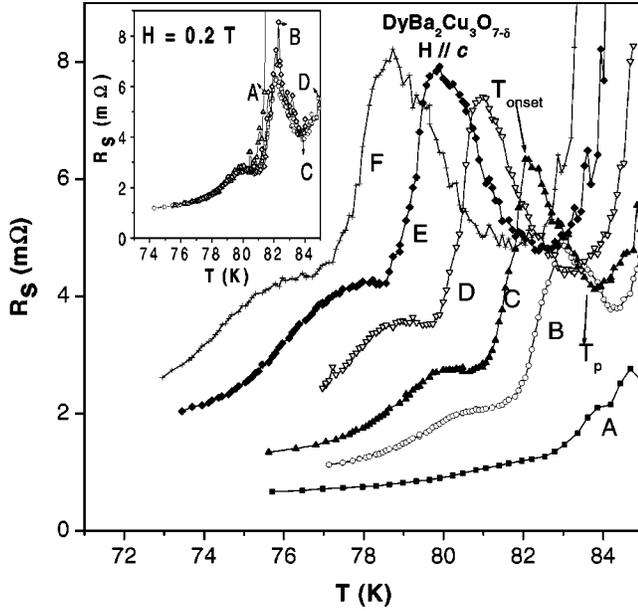


FIG. 1. Surface resistance  $R_s$  at a frequency of 9.55 GHz with 10 dB power for various applied fields ( $\parallel c$ ) as a function of temperature. Here  $A=0$ ,  $B=0.1$ ,  $C=0.2$ ,  $D=0.4$ ,  $E=0.6$ , and  $F=0.8$  T. Inset:  $R_s$  vs  $T$  plot in  $H=0.2$  T at various power levels,  $A=0$ ,  $B=2$ ,  $C=5$ , and  $D=10$  dB.

monic excitation of the stripline) measured in various magnetic fields. Here, the current induced by the microwaves was much smaller than the  $J_c$  of the material. Note that  $R_s$  displays a pronounced maximum followed by a dip feature before  $T_c$ . The temperatures corresponding to extreme positions shift to lower values as the magnetic field is increased. The inset shows the plots of  $R_s$  measured at different microwave power levels. The temperatures corresponding to the characteristic changes in  $R_s$  do not change with the variation in the microwave power level, indicating that the currents induced by the microwave field are lower than the  $J_c$  of the superconductor. In the stripline resonator technique one cannot access the normal state  $R_s$  of the superconducting material, and, hence, cannot determine the  $T_c(H)$  very accurately. The  $T_c(H)$  was therefore estimated from the upper critical field ( $H_{c2}$ ) determined from isothermal magnetization versus field (M-H) measurements (data not shown for brevity) on another film grown under identical conditions. No PE has been observed in these measurements since here one actually probes the macroscopic shielding currents induced in the superconductors.

To understand the origin of the peak in  $R_s$ , we have to consider the evolution of  $k$  [cf. Eq. (2)] within the collective pinning scenario. Its evolution is similar to that of  $J_c$  and will show a peak at the order-disorder transition (where  $V_c$  becomes a minimum) as the field or temperature is increased. Since within the Bardeen-Stephen model  $\eta$  varies smoothly with temperature, the depinning frequency,  $\omega_p$ , will also show a minimum followed by a peak at the order-disorder transition [see the schematic drawn in Fig. 2(a)]. We identify the frequency at the dip as  $\omega_p^{dip}$  and at the peak as  $\omega_p^{peak}$ , respectively. The observation of a peak in the  $R_s$  will criti-

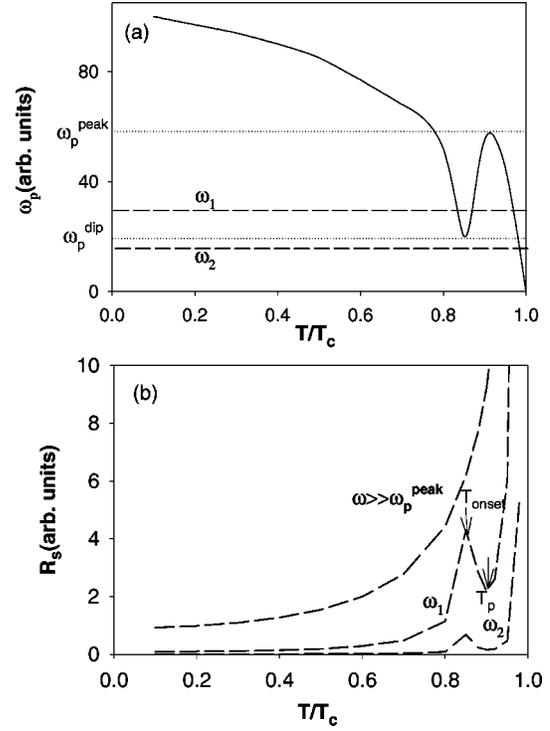


FIG. 2. Schematic diagrams of (a) variation of depinning frequency  $\omega_p$  with reduced temperature, which shows a dip followed by a peak in the order-disorder transition region, and (b) surface resistance  $R_s$  vs reduced temperature. Note that the comparison of plots in (a) and (b) shows that since  $\omega_p^{peak} > \omega_1 > \omega_p^{dip}$ ,  $R_s$  shows a pronounced peak and a dip, whereas for  $\omega_2 < \omega_p^{dip}$ ,  $R_s$  shows a less pronounced peak. For  $\omega \gg \omega_p^{peak}$ , the peak in  $R_s$  is not visible.

cally depend on the measurement frequency. When  $\omega \gg \omega_p^{peak}$ , the  $R_s$  will increase monotonically with field or temperature [see the schematics in Fig. 2(b)] without showing any peak. When  $\omega_p^{peak} > \omega > \omega_p^{dip}$  [i.e.,  $\omega_1$  in Fig. 2(b)], the measurement frequency will become larger than  $\omega_p$  at some temperature and the  $R_s$  will increase. However, since  $\omega_p$  passes through a peak, at a higher temperature the measurement frequency will again become lower than  $\omega_p$  causing the  $R_s$  to decrease. Therefore, in this frequency range, the  $R_s$  will show a pronounced peak [cf. Fig. 2(b)]. The position of the peak and the subsequent dip in  $R_s$  will coincide with the dip and peak in  $\omega_p$ , respectively. This also follows from Eq. (3). On the other hand, when  $\omega < \omega_p^{dip}$  [i.e.,  $\omega_2$  in Fig. 2(b)], the peak will be less pronounced since the measurement frequency will cross  $\omega_p$  only once, where the surface impedance will undergo a crossover from predominantly inductive to predominantly resistive behavior and  $R_s$  will increase. Usual estimates of the  $\omega_p$ , in a cuprate superconductor, such as,  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  vary between 5 to 40 GHz.<sup>11</sup> This is therefore consistent with the fact that we observe a pronounced peak when the measurements are done at 9.55 GHz. The main difference between this microwave PE and the PE observed in conventional low frequency measurements, such as magnetization or transport critical current experiments, is that in low frequency measurements one actually measures the peak in the  $J_c$ . This corresponds to the

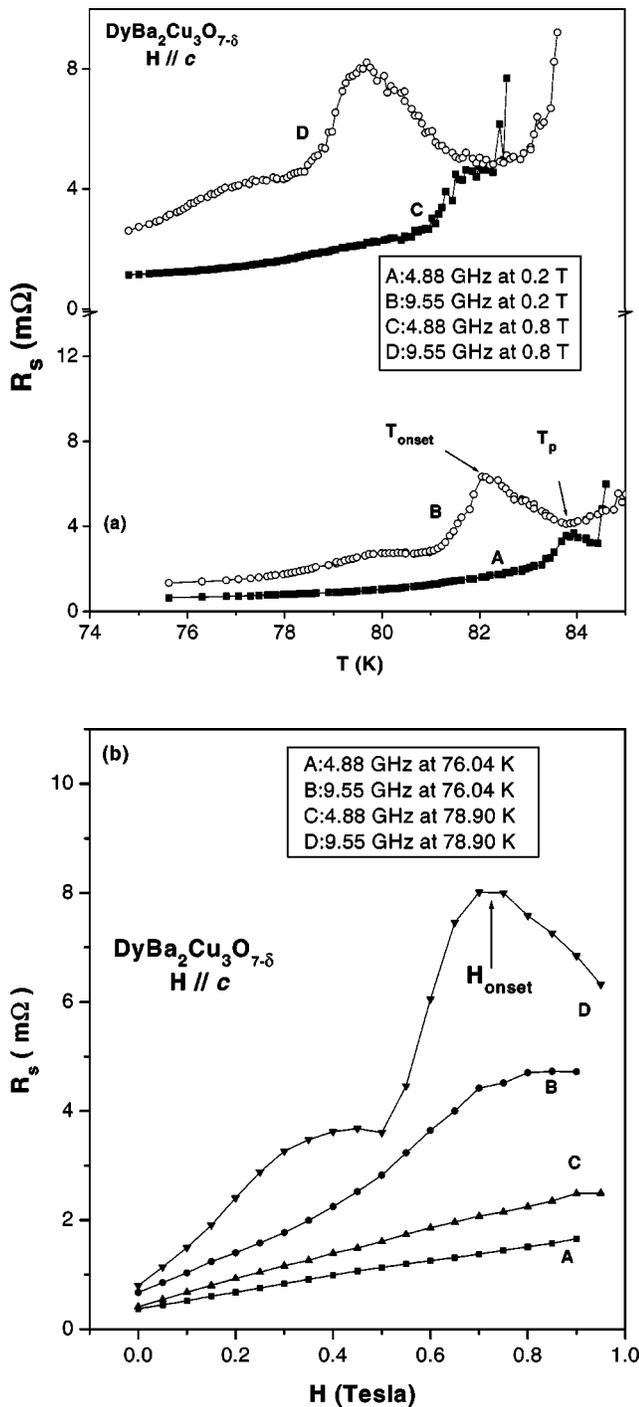


FIG. 3. (a) Plot of  $R_s$  vs temperature measured at fields ( $\parallel c$ ) at 0.2 and 0.8 T and with frequencies of 4.88 and 9.55 GHz. (b)  $R_s$  as a function of magnetic field at different temperatures and frequencies.

point where the force on the vortex lattice is equal to the maximum pinning force  $(dV(x)/dx)_{max}$  and the vortices start moving out of their pinning potential. Therefore, most conventional measurements probe the temperature or field dependence of  $(dV(x)/dx)_{max}$ . In microwave experiments, however, the current is lower than the critical current and therefore a vortex moves close to its potential minimum [i.e.,

at  $(dV(x)/dx)_{x \approx 0}$ ]. It is, however, to be noted that Eq. (2) is not applicable strictly at temperatures close to  $T_c$  due to large-scale motion of the vortices. This point will be elaborated further.

To explore the frequency dependence of  $R_s$ , the surface resistance was also measured using the fundamental resonance (4.88 GHz) of the stripline. The plots of  $R_s$  as a function of temperature at 4.88 GHz and 9.55 GHz are shown in Fig. 3(a) at magnetic fields of 0.2 and 0.8 T, respectively.  $R_s$  as a function of magnetic field for the same frequencies are shown in Fig. 3(b). Both for the isothermal and the isofield runs, we observe that the PE is much less pronounced and is absent for temperatures below 80 K [Fig. 3(b)], when the measurements are carried out at a frequency of 4.88 GHz. This is consistent with the scenario proposed earlier. However, one major discrepancy with the earlier scenario is the shift in the peak position to higher temperatures when the measurements are done at 4.88 GHz. According to Eq. (3) the parametric values of the peak and the dip positions in the  $R_s$  should be independent of the frequency. The usual treatment of the frequency dependence of the Labusch parameter due to thermal creep using the independent vortex scenario is also unable to account for the frequency dependence of the dip in the  $R_s$  values. This discrepancy could be due to our assumption that the collective pinning description strictly holds all across the PE region.

The independent vortex picture of Gittleman and Rosenblum<sup>16</sup> described by Eq. (3) assumes that each vortex remains within the pinning potential minimum and therefore flux creep is not taken into account. In the collective pinning scenario,<sup>8</sup> this picture remains valid provided the motion of the vortices inside  $V_c$  is small compared to the overall pinning potential arising collectively from the pinning centers inside the Larkin domain. Thus, within  $V_c$ , the vortices do not experience the distribution in the restoring force arising from the distribution in the pinning potential in the system. However, close to the order-disorder transition, the usual collective pinning scenario<sup>8</sup> may require some modification as the vortex state transforms to an amorphous phase<sup>7,9</sup> where individual vortices (or bunches of vortices) are pinned

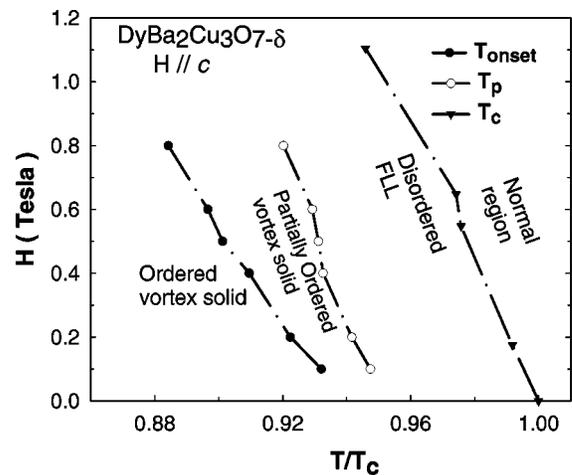


FIG. 4. Vortex phase diagram in a DyBa<sub>2</sub>Cu<sub>3</sub>O<sub>7-δ</sub> thin film sample for  $H \parallel c$ .

in potentials of varying strength  $k$ . The evidence for this kind of glassy state close to the PE in a twinned  $\text{YBa}_2\text{Cu}_3\text{O}_7$  crystal (with  $H\parallel c$ ) has recently been observed by Pal *et al.*<sup>19</sup> This could cause the system to have a distribution in time scales and lead to a shift in the position of the peak in  $R_s$ , when the measurements are carried out at different frequencies. At present we do not have a theory to explain this observation.

A point worth considering while analyzing the response of vortices at high frequencies is the effect of surface pinning. By studying the frequency response of the superconductor in the mixed state, Placais and co-workers<sup>14,15</sup> argue that the vortices in a single crystal of YBCO are held by surface pinning, while they are free to move inside the bulk. Their experiments were, however, restricted to a narrow temperature range close to  $T_c$ , which is higher than the range of temperature where we have observed a nonmonotonic behavior in  $R_s$ . It is not known, at this stage, how the collective pinning scenario can be modified in the presence of surface pinning alone. However, two factors could be responsible for observing bulk pinning in our sample. Firstly, the epitaxial films grown by laser ablation have a larger density of defects, including extended defects which act like surfaces inside the bulk of the crystal. Secondly, the thickness of these films are of the order of the penetration depth near the measurement temperature, which makes the distinction between surface and bulk pinning less significant as well as difficult to detect. This issue can be resolved by a complete spectral analysis of the complex penetration depth over a wide frequency range, which is beyond the scope of the present study.

Based on the temperature variation of  $R_s$  at 9.55 GHz measured at various fields, we have constructed in Fig. 4 a tentative vortex phase diagram for DBCO ( $H\parallel c$ ). The peak in  $R_s(T)$ , which corresponds to a minimum in the  $\omega_p$  marks the onset temperature ( $T_{onset}$ ) of the order-disorder transformation in the vortex state. The process of disordering is complete at the peak of  $\omega_p$  which corresponds to the minimum of  $R_s$  at  $T_p$  (cf. Fig. 1). The phase diagram comprises an ordered vortex state, which crosses over to a fully disordered state via a partially ordered phase, as the temperature or field is increased. This is in agreement with the vortex phase diagrams proposed at lower frequencies.<sup>9</sup>

In conclusion, we have observed a pronounced PE in a thin film of  $\text{DyBa}_2\text{Cu}_3\text{O}_{7-\delta}$  at subcritical currents at microwave frequencies close to the depinning limit (9.55 GHz) of the superconductor. This PE has been attributed to the order-disorder transformations of the FLL as the temperature or field is increased. In contrast to the low frequency measurements on the PE, this phenomenon at microwave region has a pronounced frequency dependence both in terms of the magnitude of the effect as well as the position of the peak temperature. It would be interesting to study PE in high temperature superconductors over a wider frequency range and at higher fields to understand the interrelation between the Labusch parameter, Larkin volume, and the vortex viscosity and their effect on the order-disorder transition of the FLL.

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