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Peak effect in laser ablated $DyBa_2Cu_3O_{7-\delta}$ films at microwave frequencies at subcritical currents

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In this article we report the observation of a peak in the microwave surface resistance (at frequencies ~10 GHz) of laser ablated $DyBa_2Cu_3O_{7-\delta}$ films in magnetic field ranging from 2 to 9 kOe ($\parallel c$) close to the superconducting transition temperature $[T_c(H)]$. The exact nature of the peak is sample dependent but it follows a general behavior. The peak shifts to lower temperature when the magnetic field is increased. It has strong frequency dependence and the peak is pronounced at frequencies close to the depinning frequency of the flux line lattice. From the observed temperature and field dependence we argue that this peak is associated with the order–disorder transition of the flux line lattice close to $T_c(H)$. [DOI: 10.1063/1.1356046]

The phenomenon of ''peak effect'' associated with a peak in the critical current (J_c) below the superconductor-normal boundary in type-II superconductors has attracted widespread attention in order to understand the order–disorder transition[1] in the flux line lattice (FLL) in type-II superconductors in the presence of pinning arising from defects in a crystallographic lattice. In varying temperature or field measurement this peak is manifested in both transport and magnetic measurements such as resistivity,[1] magnetization,[2] or ac susceptibility.[3] Whereas the static measurements such as magnetization probe the response of the static FLL to an external applied field or temperature, the dynamics of the vortex lattice is probed by applying a small time dependent perturbation and measuring the response of the FLL or by measuring the transport properties above the critical current $[J_c(H)]$ when the flux lines are moving. Both kinds of measurements have yielded useful information in recent times regarding the process of disordering of the FLL.

The peak in the critical currents occurring due to the order–disorder transition of the FLL is rationalized within the Larkin–Ovchinikov[4] scenario where the effective pinning force on the FLL is given by $BJ_c(H)=(n_p\langle f^2\rangle/V_c)^{1/2}$ where n_p is the density of pinning centers, f is the elementary pinning force parameter, and V_c is the Larkin volume over which the FLL maintains its spatial order. With increasing temperature or field $\langle f^2\rangle$ decreases thereby decreasing the critical current density. However, at an order–disorder transition of the FLL V_c goes to zero thereby giving rise to the peak in $J_c(H)$. The exact details of the order–disorder transition have remained an issue of intense debate. Several scenarios, such as the melting of the FLL[5] or its amorphization to a state with quenched random disorder[6] have been proposed as the mechanism governing the peak effect phenomenon in type-II superconductors.

In typical ac susceptibility measurements used to study the dynamics of the FLL the measurement frequencies vary from a few hertz to a few megahertz. These measurements do not reveal any frequency dependence of the peak effect in agreement with a true phase transition.[7] There are, however, no reports of peak effect in microwave frequencies. Recently we have been able to observe a pronounced peak effect in epitaxial thin films of $DyBa_2Cu_3O_{7-\delta}$ (DBCO) at gigahertz frequencies.[8] In a typical microwave measurement the small microwave excitation induces a current which is smaller than the critical current of the superconductor. The vortices therefore move back and forth close to the minimum of the pinning potential (V) and experience a restoring force close to the potential minimum. The motion at these frequencies is described by the equation of motion of a massless harmonic oscillator in a viscous medium given by[9]

$$\eta\dot{x}+kx=F, \tag{1}$$

where η is the Bardeen–Stephen viscous drag coefficient, k is the pinning force constant, and F is the external force on the vortex which is given by $F=J\Phi_0$. It can be shown that the vortex impedance is given by

$$Z_v=\frac{\Phi_0 H}{\eta}\frac{1}{(1+i\omega_p/\omega)}, \tag{2}$$

where ω_p is the depinning frequency given by $\omega_p=(k/\eta)$. It follows from Eq. (2) that the vortex motion crosses over from inductive for $\omega\ll\omega_p$ to resistive for frequencies $\omega\gg\omega_p$ giving rise to dissipation. To understand the origin of

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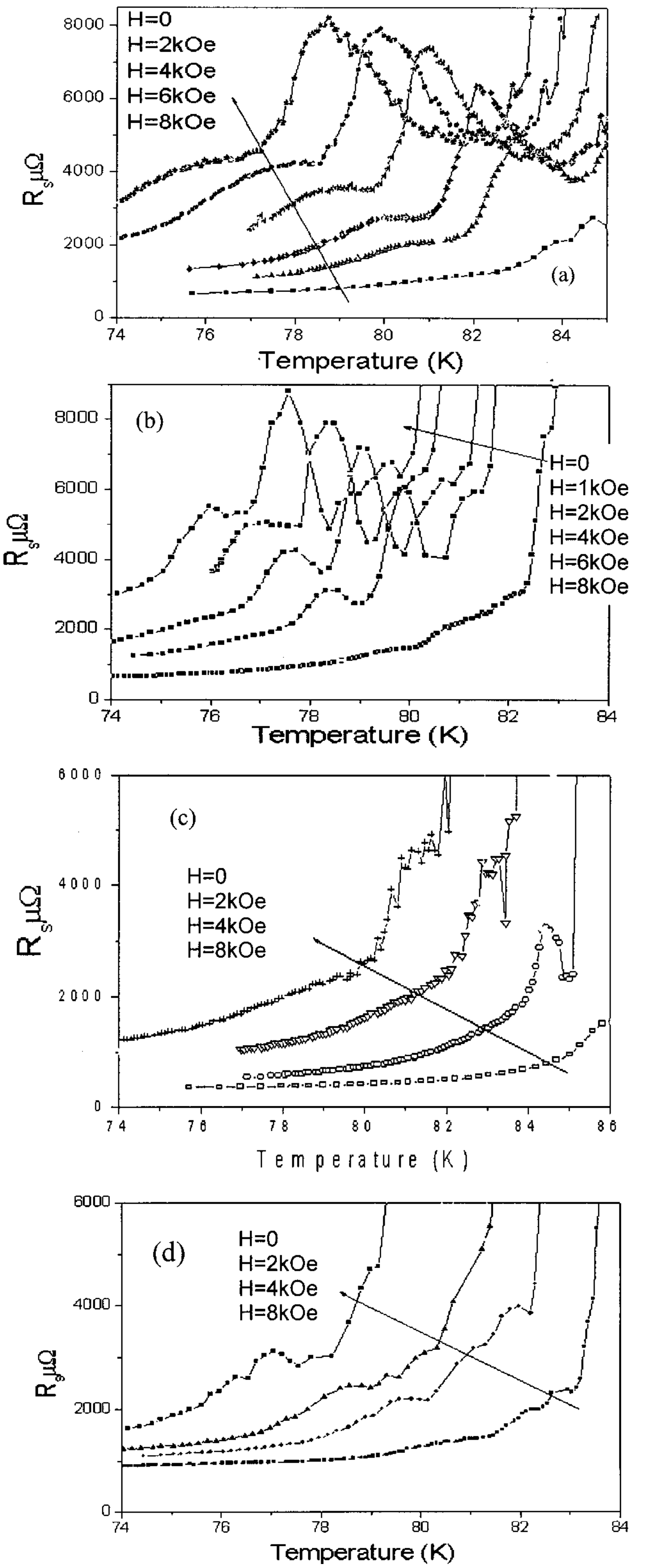

FIG. 1. R_s vs temperature at 9.5 GHz for (a) S1 and (b) S2 for different fields. The same at 4.75 GHz for (c) S1 and (d) S2.

the peak using Eq. (2) we have to note that in the collective pinning scenario the vortices within a Larkin volume V_c move together like a semirigid body. Therefore the effective restoring force constant on the vortices will be given by the effective restoring force on all the vortices in V_c. Therefore the effective restoring force constant on the vortices within

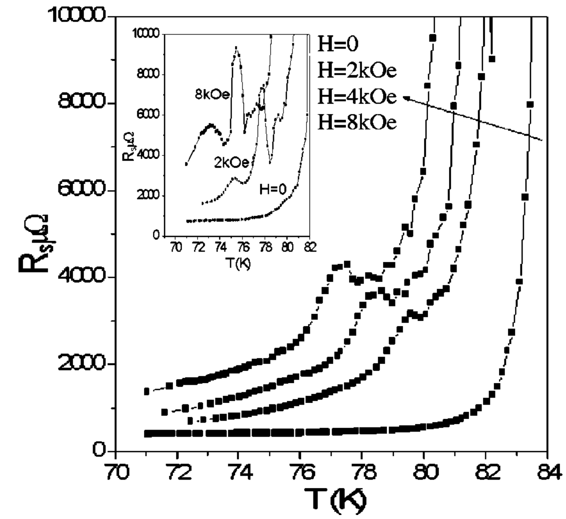

FIG. 2. R_s vs temperature for the YBCO film at 4.75 GHz at different fields; the inset shows the same for 9.5 GHz.

V_c will be given by $k \propto (n_p \langle f^2 \rangle / V_c)^{1/2}$ and will show a peak at the order–disorder transition of the FLL.[9] Since η decreases monotonically with an increase in temperature, this will give rise to a peak in ω_p. Therefore if the measurement frequency ω is close to the depinning frequency the surface resistance will show a dip (corresponding to the peak in ω_p) as one crosses the order–disorder transition. On the other hand this effect will be much less prominent if the measurements are done much below or above the depinning frequency, namely, for $\omega \gg \omega_p$ or $\omega \ll \omega_p$. In high T_c cuprates with 123 structure the depinning frequency has been reported to vary in the range 5–40 GHz.[10]

In this article we report the microwave response of two superconducting $DyBa_2Cu_3O_{7-\delta}$ films (with c perpendicular to substrate) grown by pulsed laser deposition on single crystalline $LaAlO_3$ substrates. They are denoted as samples S1 and S2. The films were grown in 250 mTorr ambient oxygen pressure. The substrate temperature was kept between 750 and 780 °C and the target substrate temperature was fixed at 4 cm. The T_c of both films measured through ac susceptibility using flat coil geometry was 90 ± 0.2 K. The films were subsequently patterned into striplines with a width of 175 μm and a length of 10 mm. The measurements of microwave surface resistance were carried out using the stripline resonator technique using a Hewlett–Packard scalar network analyzer.[11] All the measurements were carried out at the same relative incident microwave power level. Magnetic fields up to 9 kOe were applied parallel to the c axis using a conventional electromagnet.

Figures 1(a)–1(d) show the surface resistance (R_s) as a function of temperature measured at 4.75 and 9.5 GHz (corresponding to the fundamental and first harmonic excitation of the striplines) of the S1 and S2 samples, respectively. Both display a pronounced peak followed by a dip in the R_s measured at 9.5 GHz. The evolution of the peak in R_s with magnetic field shows a common behavior in both samples. With increasing magnetic field R_s increases and the peak shifts to lower temperatures. For the R_s measured at 4.75 GHz the peak becomes much less prominent. However, the peak in R_s at 9.5 GHz is sharper in sample S2 than in S1. On the other hand the peak in R_s at 4.75 GHz is more pronounced in S1 than S2. Also in addition to the main peak, the surface resistance at 9.5 GHz shows a broad hump like structure before the main peak. This kind of complex structure is not uncommon near the peak effect region and has been reported earlier in ac susceptibility and transport measurements.

To understand the difference between S1 and S2 we first note that though samples S1 and S2 have nominally the same T_c they contain different amount of disorder since they were grown in separate runs. Consequently, n_p and therefore the effective k and ω_p are different in the two samples. We have shown earlier that the peak in microwave will be most prominent close to ω_p. From the present results it can be argued that ω_p is smaller in S1 than S2 though both lie in the range of a few GHz to tens of GHz since at lower frequencies the peak is more prominent in S1 and at higher frequencies it is more prominent is S2. This implies that S1 has a smaller density of disorder than S2 which is seen from the value of the R_s at 75 K at 4.75 GHz in zero field which is 300 $\mu\Omega$ for S1 and 900 $\mu\Omega$ for S2. It is, however, to be noted that Eq. (2) is not strictly valid for temperatures close to T_c where large scale motion of the vortices can take place due to thermal excitation. This could be in part the reason why the peaks at 4.75 and 9.5 GHz do not occur at the same temperature and fields.

In order to check whether the magnetic ion Dy has any particular role in the peak effect observed in microwaves we have also carried out these measurements in a laser ablated film of the isostructural superconductor $YBa_2Cu_3O_{7-\delta}$ (YBCO) (Fig. 2). The peak effect in the YBCO film is similar to the peak effect in S2. The peak in the R_s at 9.5 GHz is sharp. Though less pronounced a clear peak effect is observed in the R_s at 4.75 GHz.

In summary we have observed a pronounced peak effect in the microwave surface resistance of superconducting 123 films in the presence of a dc magnetic field. From the temperature and field dependence of the peak we have argued that the peak is due to the order–disorder transition of the vortex lattice. Though related, this, however, is different from the peak in J_c observed from transport or magnetization measurements since the microwave excitation induces a current which is smaller than the critical current of the superconductor. From our observation we also conclude that the depinning frequency is ~10 GHz which matches reasonably well with earlier estimates of depinning frequency in YBCO.[10]

[1] M. J. Higgins and S. Bhattacharya, Physica C **257**, 232 (1996).
[2] G. Ravikumar, P. K. Mishra, V. C. Sahni, S. S. Banerjee, A. K. Grover, S. Ramakrishnan, P. L. Gammel, D. J. Bishop, E. Bucher, M. J. Higgins, and S. Bhattacharya, Phys. Rev. B **61**, 12490 (2000).
[3] S. S. Banerjee, N. G. Patil, S. Saha, S. Ramakrishnan, A. K. Grover, S. Bhattacharya, G. Ravikumar, P. K. Mishra, T. V. Chandrasekhar Rao, V. C. Sahni, M. J. Higgins, E. Yamamoto, Y. Haga, M. Hedo, Y. Inada, and Y. Onuki, Phys. Rev. B **58**, 995 (1998).
[4] A. I. Larkin and Yu. N. Ovchinnikov, J. Low Temp. Phys. **34**, 409 (1979).
[5] P. L. Gammel, U. Yaron, A. P. Ramirez, D. J. Bishop, A. M. Chang, R. Ruel, L. N. Pfeiffer, E. Bucher, G. D'Anna, D. A. Huse, K. Mortensen, M. R. Eskildsen, and P. H. Kes, Phys. Rev. Lett. **80**, 833 (1998).
[6] S. S. Banergee, S. Ramakrishnan, D. Pal, S. Sarkar, A. K. Grover, G. Ravikumar, P. K. Mishra, T. Chandrashekher Rao, V. C. Sahni, C. V. Tomy, M. J. Higgins, and S. Bhattacharya, Suppl. A J. Phys. Soc. Jpn. **69**, 262 (2000).
[7] J. Shi, X. S. Ling, R. Liang, D. A. Bonn, and W. N. Hardy, Phys. Rev. B **60**, 12593 (1999).
[8] A. R. Bhangale, P. Raychaudhuri, S. Sarkar, T. Banerjee, S. S. Bhagwat, R. Pinto, and V. S. Shirodkar, Phys. Rev. B (to be published).
[9] J. I. Gittleman and B. Rosenblum, Phys. Rev. Lett. **16**, 734 (1966).
[10] M. Golosovsky, M. Tsindlekht, and D. Davidov, Phys. Rev. B **56**, 470 (1997).
[11] R. Pinto, N. Goyal, S. P. Pai, P. R. Apte, L. C. Gupta, and R. Vijayraghvan, J. Appl. Phys. **73**, 5105 (1993).