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Angular Dependence of Ultrasonic Attenuation at H_{c1} in $\text{YBa}_2\text{Cu}_3\text{O}_7$ Single Crystal

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Abstract. The resistive behavior of type-II superconductors in the superconducting state is largely influenced by the materials' ability to pin magnetic flux lines. While an externally applied magnetic field leads to an ordered flux-lattice in defect-free superconductors, spatial variations in the superconducting order parameter tend to deform the vortex system. This has immediate implications for the temperature- and field-dependence of the critical current density. Simple estimates of the balance between the intervortex interaction and the vortex-pinsite interaction allow for qualitative predictions of the temperature- and field-dependent resistive behavior of type-II superconductors. A low frequency ultrasonic technique was developed, which was used to study the viscous properties of the vortex system.

1. INTRODUCTION

Magnetic vortices in conventional, isotropic, defect-free type-II superconductors order due to their repulsive interaction and form a hexagonal lattice below the superconducting transition temperature[1]. The intrinsically two-dimensional nature of the high- T_c materials, however, together with the high transition temperature into the superconducting state and a high density of defects leads to static and dynamic disorder, which tends to disrupt the long-range correlation of the vortex lattice. This bears consequences for the resistive behavior in the superconducting state. While a perfectly ordered, rigid vortex lattice can easily be collectively pinned by the superconductors' mechanical boundaries, a soft vortex-'lattice' is prone to disruptions and defect motion. The motion of individual vortices or vortex-bundles - driven by the Lorentz-force of a transport current - leads to non-zero resistance in the superconducting state. Since the (collective) pinning behavior of the vortex-system depends strongly on the amount of intervortex interaction, the elastic properties of the vortex-system influence the resistive properties of the superconducting system in the presence of a magnetic field[2]. Conversely, the elastic properties of the vortex system can be deduced from temperature- and field-dependent electrical transport measurements. These experiments, however, probe the flow-properties of the system and the results depend on the electrical current density used. The determination of possible phase-transitions in the vortex-system by means of a transport experiment is indirect[3]. It is obvious that static experiments are most desirable.

Recently much experimental and theoretical effort was aimed at possible phase transitions in the magnetic vortex system of high temperature superconductors[4]. Of considerable interest are in this context transitions from a vortex-lattice to a vortex glass and to a vortex liquid. Since the transition from a vortex-solid to a liquid should be accompanied by the disappearance of the vortex-systems shear modulus, ultrasound is a promising tool to map out the phase diagram of the flux-line system. Pankert showed, however, that the propagation of ultrasound in the mixed state of type-II superconductors is influenced by the vortex-systems' elastic behavior as long as it is pinned to the ionic lattice[5]. Ultrasonic experiments on high- T_c superconductors were consequently successfully used to map the field- and temperature dependence of the *depinning* transition. The much weaker interaction of ultrasound with the depinned system is mediated via the modulation of the system of charge carriers and was rarely studied to date. The goal of the experiments presented here was to investigate the vortex system in the depinned regime at very small disturbances and with only weak modulations of the ionic lattice and the pinsites.

2. EXPERIMENTAL SETUP

In order to probe the vortex system at very small disturbances, we performed ultrasonic experiments at wavelengths which are long compared to the sample thickness. We therefore studied the attenuation of a freely suspended transducer after exciting it with a short electromagnetic pulse at 3MHz. The sample under investigation is mounted on the surface of the x-cut quartz-transducer. No bond is used between the crystal and the transducer. The crystal is pressed to the transducers polished surface by varnish-threads, leaving a microscopic gap between the crystal and the transducer surfaces. The transducer is held by two gold-wires, which serve as ground contact. The experimental setup is described in more detail elsewhere[7]. A 50 μ s rf electromagnetic pulse is applied via a spring loaded contact to the opposite side of the transducer. After the pulse is switched off, the oscillations of the transducer-crystal system decay with a characteristic time which is determined mainly by the mechanical load due to the contacts to the transducer and by the mechanical load due to the small sample under investigation. With the transducer suspended quasi freely, decay times of up to 2ms are obtainable. A twin-free YBCO single crystal (1.4mm*1.3mm, c=0.05mm) was mounted to the transducer with the c-axis parallel to the propagation direction and strain of the soundfield. The wavelength of the soundwave is much larger than the sample thickness. This leads to only small relative displacements of the ions in the crystal which is essentially moving back and forth. In an homogeneous magnetic field oriented parallel to the crystals a-b-plane ($\Theta=0^\circ$), the soundwave interacts with the vortex system via the sound induced motion of charge-carriers in the magnetic field. In a normal conductor the electronic subsystem is essentially clamped to the ionic system, thereby leading to a vanishing total current density at sound-frequencies well below 10¹⁰Hz. E.B. Sonin showed[6], however, that the sound induced modulation of charge carriers can lead to a net force on the vortex system even at low frequencies, if the density of normal- and superconducting charge carriers is taken into account. Consequently, field dependent attenuation changes in the 'freely' oscillating transducer-sample system can be interpreted as due to dissipative interaction of oscillating charge-carriers with the magnetic vortex system. It was shown earlier[7] that at low field strengths (but above H_{c1}), the attenuation is proportional to the applied magnetic field, indicating free motion of individual, only weakly interacting vortices. As the field is raised above a critical value, the field-dependence departs from linearity as the vortices start to interact strongly. It was shown that the field- or temperature-dependence of the elastic behavior of the vortex system can be deduced from the ultrasonic attenuation of the oscillator. In this paper we study the angular dependence of the observed effects in the vicinity of H_{c1} .

3. RESULTS AND DISCUSSION

As a measure for the attenuation we recorded the amplitude of the exponentially decaying rf-signal of the oscillating transducer-sample system. Fig. 1 shows the field dependence of this amplitude for different angles between magnetic field and the crystals a-b-plane. A drop in the amplitude is clearly visible in the vicinity of H_{c1} . This indicates a field dependent increase of losses as fluxlines start to penetrate into the sample. Due to the angular dependence of the demagnetizing factor this penetration field depends on the angle between magnetic field and the sample's a,b-plane as can be seen in fig. 1a. With increasing angle, furthermore, the interaction between the sound field and the vortex lines is expected to decrease. The opposite behavior is observed here. This is due to a different effect that dominates at angles $>0^\circ$. As the magnetic field is tilted out of the a,b-plane of the sample, the crystal experiences a field-dependent torque. This torque appears as consequence of the systems' intrinsic anisotropy and vanishes at fields perpendicular and parallel to the c-axis[8]. A change in the torque changes the load on the transducers' surface and thereby its resonance frequency and the attenuation. The value of the drop in amplitude is plotted for different angles in fig 2b.

Figure 1: Field dependence of the resonator's amplitude for different angles at 82K (left). The maximum amplitude-change versus angle (right)

The amplitude change is minimal at an angle of about 4 degrees. Within the uncertainty in the absolute angle, this corresponds to the field oriented parallel to the crystals *a,b*-plane. The minimal amplitude change appears to be nonzero at all angles (experiments were only possible up to 60°). While the non-vanishing amplitude-change at small angles points at a loss-mechanism that is not related to the torque acting on the sample, it is obvious that the torque dominates the amplitude changes with the field tilted away from the *a,b* plane. The experiment described here can therefore be used in two essentially different ways: a) with the magnetic field oriented parallel to the crystals' *a,b*-plane the collective pinning behavior of the vortex system can be probed at very small disturbances. b) with the magnetic field tilted out of the *a,b*-plane the method probes the torque acting on the sample. The torque is probed at constant angle.

4. CONCLUSIONS

A resonator technique was used to study the penetration of vortices in YBCO. A pronounced amplitude change was observed at low fields. This amplitude change can be related to flux penetration above the lower critical field H_{c1} . The value of the amplitude change as well as the critical field show a pronounced angular dependence. The change in amplitude appears to be minimal with the applied field oriented parallel to the crystals *a,b* plane. While at magnetic fields within the *a,b* plane and longitudinal oscillations of the transducer along *c* changes in the attenuation can be ascribed to viscous losses of the sound induced ac-electric currents interacting with the vortex system, a different mechanism starts to dominate when the field is tilted out of plane. We suspect the attenuation

changes at large angles to be due to the field dependent torque acting on the sample. This torque appears as a result of the intrinsic anisotropy of the system.

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