Reentrant Softening as Precursor to Reentrant Melting of the Vortex-Lattice in YBCO Single Crystal

C. Hucho¹, J.M. Carter¹, V. Muller¹, A. Petrean², and W.K. Kwok²

¹Paul-Drude-Institut für Festkörperelektronik Hausvogtplatz S-7 10117 Berlin, Universität Augsburg, Institut für Experimentalphysik 111, Universitätsstr. 1, 86135 Augsburg

²Argonne National Laboratory, Argonne, IL 60439 USA

RECEIVED
JAN 18 2000
OSTI

Submitted to the Vortex Conference, Crete, Sept. 18-24, 1999 for publication in Physica C

The submitted manuscript has been created by the University of Chicago as Operator of Argonne National Laboratory ("Argonne") under Contract No. W-31-109-ENG-38 with the U.S. Department of Energy. The U.S. Government retains for itself, and others acting on its behalf, a paid-up, nonexclusive, irrevocable worldwide license in said article to reproduce, prepare derivative works, distribute copies to the public, and perform publicly and display publicly, by or on behalf of the Government.

This work was supported by the U.S. Department of Energy, Basic Energy Sciences—Material Sciences Division Under Contract No. W31-109-ENG-38.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Reentrant Softening as Precursor to Reentrant Melting of the Vortex-Lattice in YBCO Single Crystal

C. Hucho, J.M. Carter*, V. Müller*, A. Petrean**, and W.K. Kwok**

Paul-Drude-Institut für Festkörperelektronik, Hausvogtplatz 5-7, 10117 Berlin, *Universität Augsburg, Institut für Experimentalphysik III, Universitätsstr. 1, 86135 Augsburg, **Argonne National Lab

Abstract

A vibrating sample technique was used to study the elastic behavior of the magnetic vortex system in $\text{YBa}_2\text{Cu}_3\text{O}_7$ single crystals. The setup consists of a system of two weakly coupled mechanical oscillators (transducer, sample), the frequency and Q of which depends sensitively on the frequencies of the two subsystems as well as the coupling between both. By sweeping a magnetic field at temperatures below the superconducting transition temperature T_c we observe pronounced attenuation peaks at temperature-dependent characteristic field strengths H_1 and H_2 . These fields mark temperature-dependent points of constant elasticity of the vortex-ensemble. Since softening precedes the melting of the vortex-lattice by approaching H_{c1} as well as H_{c2} , the observed angular dependence of H_1 and H_2 is interpreted as due to reentrant softening as precursor to reentrant melting.

1. Introduction

The vortex-ensemble in high- T_c superconductors exhibits a phase-diagram of much higher complexity than conventional bulk type-II superconductors. This is due to a combination of intrinsic features such as high anisotropy, high thermal excitation energy and the possibility of a large amount of static disorder induced by a variety of defects. Recently, a number of vortex-phases has been proposed as explanation for experimental findings in the extremely anisotropic superconductor $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (e.g. [1]). Despite increasing effort to map out the complete phase-diagram of magnetic vortices in high- T_c superconductors, however, one of the more prominent theoretical predictions for 2-dimensional type-II superconductors has not been observed

directly: the *reentrant* transition from a vortex-liquid to a crystalline vortex-solid and back to the vortex-liquid phase upon raising the magnetic field from 0 to H_{c2} , the upper critical field. While the upper melting transition (close to H_{c2}) is well established, the lower transition escapes experimental verification due to its close proximity to the lower critical field H_{c1} . An experimental separation of these two phase-transitions will be an extremely difficult if not impossible task. Since a necessary precursor to melting of the vortex-ensemble, however, is the softening of its shear modulus C_{66} [2], we attempted to detect the reentrant softening of the vortex-lattice as precursor to reentrant melting. Ultrasonic techniques, measuring the elastic moduli of the samples under investigation directly, appear to be the natural tool for identification of the temperature- and field-

dependent elastic properties of the vortex-system. Investigation of the vortex-ensemble with ultrasound, however, requires coupling of the ultrasonic strain-field in the ionic crystal-lattice to the vortices. In conventional ultrasound experiments the strain-field couples to the magnetic flux-lines predominantly via the vortex-pinsite interaction (strain-coupling). The contribution of the sound-induced motion of charge carriers relative to the vortex-ensemble (Lorentz-coupling) is usually negligibly small. Conventional ultrasound experiments, therefore, are best suited to study the temperature- and field-dependent depinning transition in defect-rich superconductors – rather than the elastic behavior of the free, unpinned vortex-lattice. While J. Pankert, P. Lemmens and coworkers [3] were successful in identifying thermally assisted flux flow as essential loss-mechanism in high- T_c superconductors, a phase-transition in the vortex ensemble was not detected in ultrasound experiments. Conventional ultrasonic experiments appear to be of little help in determining the properties of the free vortex-ensemble.

2. Experimental approach

Fig.1: The difference between ultrasonic experiments and 'accelerated sample' experiments (schematic). In conventional ultrasound experiments (a) a strain-field with wavelength shorter than sample-length is excited and detected with a transducer. If the sample is driven by mechanical oscillations with wavelengths longer than the sample dimensions, the loosely coupled sample is essentially moving back and forth with the frequency impressed by the transducer (b).

The crystal-lattice and electronic contribution to dispersion and absorption of the sound-wave travelling through the sample, dominate the experimentally observable quantities in ultrasound experiments. The experiments presented here aimed

at reducing the contribution from the crystal-lattice and focusing on the Lorentz-coupling to the vortex-system.

In order to reduce the strain-field in the sample we modified the conventional ultrasound-approach in two aspects: a) The transducer was driven by relatively low frequencies. With the transducer's resonance-frequency at only a few MHz and samples with thickness less than 200 μm , the wavelength of the mechanical oscillations was much larger than the sample dimensions. The sample was essentially moving back and forth, unstrained, with the frequency impressed by the transducer. The aim of producing a linear motion of the sample sets this 'accelerated sample technique' (ast)[4] apart from experiments with high-Q oscillators operated in a tilting mode [5]. b) the sample was attached only loosely to the transducer surface. The setup constitutes a system of weakly coupled mechanical oscillators in which the sample is moving with a phase-lag relative to the driving motion of the transducer-surface. The phase is influenced by the coupling-strength and by the viscous losses of the sample moving in the background of the magnetic vortex-system. While at frequencies of several MHz and displacements of a few nm the acceleration of the sample is of the order of 10^6 m/s^2 , it was argued that in a sample which is accelerated in a homogeneous magnetic field, the motion of the bound charge-carriers and the conduction charge-carriers is strictly in phase and not leading to an alternating net current that would interact with the free vortex system [6,7]. In a superconductor accelerated in a homogeneous magnetic field the vortices would rest in the frame of the superconductor. It was conjectured [7] that periodic tilting of the sample due to intrinsic nonvanishing asymmetries in the setup would more easily explain the observed temperature- and field-dependent losses. While this mechanism does play an important role in vibrating reed experiments, we would like to draw attention to experiments by R.C. Tolman and T.D. Stewart [8], who were among the first to determine the inertia of conduction electrons in metals by measuring the voltage-drop across accelerated metals in the absence of a magnetic field. The acceleration of their samples was 2-3 orders of magnitude lower than in the experiments

presented here. In these experiments we find justification for our assumption that an acceleration-induced ac-net-current could provide for a coupling mechanism between the mechanical oscillations of the sample and the free, unplanned vortex-ensemble. In this case the vortices would not be at rest inside the superconductor. If the induced net current interacts with the vortices, losses in the mechanically oscillating system could be interpreted similar to conventional electrical transport experiments, albeit at very low current densities. The origin of the attenuation-peaks observed in our experiments is depicted qualitatively in fig.2.

Fig.2: Due to the weak coupling between driving oscillator (transducer) and sample the energy-transfer from the driving into the coupled subsystem depends on coupling strength and the viscosity η of the background. The field-dependence of η is sketched as solid line in the upper graph. At a characteristic value η^* the acoustic impedance of the coupled oscillator is matched, the energy-transfer is maximized and, therefore, the decay-rate for the quasi-freely oscillating transducer is increased - leading to the observed attenuation maxima as shown in the lower graph. If the field-dependent viscosity of the vortex-system crosses the characteristic value η^* twice, two attenuation peaks are observed (B1 and B2).

3. Results

The sample was the same detwinned YBCO single crystal ($T_c \sim 93K$) that was used in ref[3]. The sample was mounted to the transducer so that the crystal was oscillating back and forth parallel to the c-axis. The sample thickness was ~ 0.15 mm. The transducer was excited with a rf-electromagnetic pulse of 3 MHz and 5ms duration. The decaying signal after switching off the pulse was monitored with a digital oscilloscope. From the envelope of the decaying signal the attenuation was determined. After cooling the sample to 80 K in zero magnetic field, the temperature was stabilized and data were recorded on increasing field. The main results are presented in fig.3. On increasing field a pronounced attenuation peak appears at a characteristic flux-density B_1 . The attenuation peak moves to lower fields with decreasing angle Θ between field and c-axis of the crystal. With further reduction of Θ a second attenuation peak appears at higher fields (corresponding to B_2 in fig.2). The two peaks finally move together, merge and disappear. These attenuation peaks originate in (acoustic) impedance-matching between the transducer and the oscillating sample at a fixed value of the angular dependent shear modulus $C_{66}(B, \Theta)$. Since $C_{66} \sim H/H_{c2}$ at low fields and $(1-H/H_{c2})^2$ at high fields [11], the matching conditions are fulfilled twice in one field-sweep from 0 to H_{c2} , leading to the observed double-peak structure. This interpretation is corroborated by the observation that the angular dependence of the attenuation-peaks is consistent with the angular-dependence of C_{66} at constant field: $C_{66}(\Theta) \sim 1/\epsilon$ for motion perpendicular to the CuO planes (the angle-dependent anisotropy parameter ϵ is defined as $\epsilon^2 = 1/50 * \sin^2 \Theta + \cos^2 \Theta$) [2].

Fig.3: Field-dependence of the attenuation at 80K after zero-field cooling for different angles between c -axis and magnetic field. Starting with the magnetic field nearly in the a,b -plane of the sample, the attenuation-peak moves to lower characteristic flux-densities B_1 on reducing the angle between field and c -axis. Since the attenuation-peak marks a fixed value of $\eta = C_{44}$ (see fig.2), the angle-dependence of the peak-positions can be interpreted as consequence of the angle-dependence of the elasticity of the vortex-system. By reducing the angle even further, a second attenuation peak appears (see text).

4. Conclusions

In summary, we have shown that a modification of ultrasound experiments, the accelerated sample technique, is a powerful technique to gain insight into the field- and angle-dependence of the shear-modulus of the free, unpinned vortex-system. From the discussion given above, the observed attenuation-peaks could in principle have their origin in a second effect: a field-induced change in the coupling-strength between sample and transducer, originating in a torque acting on the sample. The observed angle-dependence of B_1 and B_2 , however is not consistent with this mechanism [10]. The observed reentrant softening of the vortex-lattice is the origin for a number of reentrant secondary effects, such as e.g. the reentrant irreversibility-line as observed in modified torque experiments [12].

By using different symmetries in the setup we are actually able to observe both effects separately. As will be presented elsewhere [9], a setup similar to the one described here, but with asymmetrically mounted sample, showed an angular dependence of the characteristic field B_1 , that can be explained directly by the angular dependence of the torque in YBCO [10].

5. References

- [1] D.T. Fuchs, E. Zeldov et al., *Phys.Rev.Lett.* 80 (22), 4971 (1998)
- [2] G. Blatter et al., *Rev. Mod. Phys.* 66, 1125 (1994)
- [3] J. Pankert, P. Lemmens et al., *Phys.Rev.Lett.* 65, 3052 (1990)
- [4] C. Huch and M. Levy, *Phys.Rev.Lett.* 77 (7), 1370, (1996)
- [5] C.A. Bollo et al., *Nature*, 399, 43 (1999)
- [6] B. Sonin, private communication
- [7] E.H. Brandt, private communication
- [8] R.C. Tolman and T.D. Stewart, *Phys. Rev.* 8, 97 (1916)
- [9] C. Huch et al., in preparation
- [10] V.G. Kogan, *Phys.Rev.B*, 38 (10), 7049 (1988)
- [11] E.H. Brandt, *Phys.Rev.Lett.* 78, 2208 (1997)
- [12] M. Willemin et al., *Phys.Rev.B*, 58, R5940 (1998)