Intrinsic pinning, commensurability, and reentrant behavior on superconducting Mo/Si multilayers

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A reentrance phenomenon is found on Mo/Si multilayers which occurs in parallel to the layers and slightly inclined magnetic fields. This effect may be explained in terms of the intrinsic pinning and vortex lattice (VL) commensurability with the underlying layered structure. The locations of the zero-resistance regions correspond to stable VL configurations or to the transitions between two commensurate lattices. It is suggested that this resistive method may be used as a tool to study VL structure in layered superconductors.
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The vortex lattice (VL) structure in layered superconductors differs essentially from the simple triangular one observed in homogeneous type-II superconductors, unless the magnetic field $\vec{H}$ is parallel to the $\vec{c}$ axis. Different types of arrangements of VL are predicted theoretically for the cases when the magnetic field is parallel or tilted with respect to the layer planes. Ami and Maki[1] studied the stability of different VL configurations for a parallel magnetic field $H_{\parallel}$ taking into account that the ''resonance condition,'' i.e., the commensurability between the VL parameter and the period of the layered structure, plays an important role. The outburst of activity in the study of the VL structure in layered superconductors occurred after discovery of high-T_c compounds. Different theoretical approaches including anisotropic three-dimensional London and Ginzburg-Landau (GL) models, as well as the Lawrence-Doniach (LD) model, were used. According to the results of Ref. 2 obtained within the London approximation, the unit cell of the VL should be strongly distorted with respect to the equilateral triangle and VL parameters should depend intrinsically on the anisotropy parameter $\gamma=(M/m)^{1/2}$ and the angle between $\vec{H}$ and the anisotropy axis. Here M is the effective mass along $\vec{c}$, and m is the in-plane mass. The commensurability effect is outside the scope of this work. The latter was considered in the paper of Ivlev, Kopnin, and Pokrovsky[3] (IKP). It was shown that in the case of $H_{\parallel}$, when the intrinsic pinning energy E_p exceeds the elastic energy of a VL shear deformation E_{el}, the vortices cannot cross the layers, the period Z_0 along $\vec{c}$ is fixed, and it is determined by the initial conditions under which the VL was formed. This means that the VL should always be commensurable with the layered structure period s (the distance between vortices in the direction normal to the layers $Z_0=Ns$, where N is an integer), and independent of the external field, while the unit cell area varies with a field only due to the vortex displacements along the layers. In the opposite limit case the VL parameters are determined by the applied magnetic field. It was shown that the free energy of the rhombic lattice in the commensurate state as a function of H displays two minima corresponding to the different orientations of the unit cell vectors with respect to the layer planes. In the instability region there are many metastable states corresponding to the different displacements of the vortex rows relative to each other in the neighboring interlayers.[3–5] They can be dynamically accessible at the H variation.[4] In the framework of the LD approach for relatively high parallel magnetic fields a sequence of first-order phase transitions between VLs with different N is predicted.[6] For the tilted fields many versions of the vortex arrangement are suggested.[7–9] The idea of an independent response of the layered superconductor to the parallel and perpendicular components of a magnetic field[10] is exploited in many works. The most exotic among possible VL configurations in the tilted magnetic fields is the so-called combined lattice consisting of two vortex ''species'' oriented in different directions.[7–9] Obviously, due to the nonstandard VL structure and intrinsic pinning, many unusual effects can arise in layered superconductors. In the tilted fields the direction of the magnetization vector $\vec{M}$ in many cases does not coincide with the external field direction.[2,11,12] In parallel magnetic fields the critical current should be an oscillating function of magnetic field.[1] This was observed experimentally as well.[13–15]

Here we report on the effect observed on Mo/Si artificial superlattices whose origin may be connected with intrinsic pinning, the commensurability phenomenon, and the specifics of VL structure in layered superconductors. In a parallel magnetic field and in tilted fields at relatively small tilting angles the reentrance of superconductivity with an increase of the magnetic field is observed. Resistivity vs magnetic field H dependences below a definite temperature T_0 became nonmonotonic. At some value of H the resistance minimum appears which becomes more pronounced with temperature lowering and transforms into a large zero-resistance region (ZRR) at still lower temperatures. After the ZRR the resistance appears again. The critical current I_c dependence on H is also nonmonotonous, and all features of R vs H and I_c vs H curves correlate. These effects are very sensitive to the magnetic field orientation and depend essentially on the magnetic history. It is shown that all features of the reentrance behavior may be explained quantitatively if one takes into account different possible realizations of VL structure in layered superconductors. It is suggested that the reentrance phenomenon discovered may be used as an instrument for VL structure investigations.

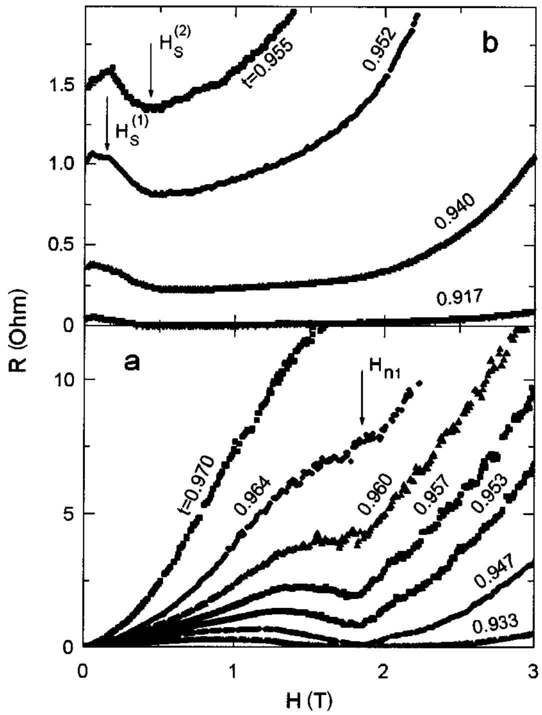

FIG. 1. Resistance as a function of parallel magnetic field at different reduced temperatures $t=T/T_c$ for sample A (a) and sample B (b). T_c for both samples is about 3.7 K. The arrows show values of H_s and H_n (see the text).

The experiments have been carried out on two Mo/Si multilayered samples: sample A with Mo layer thickness $d_{\mathrm{Mo}}=22$ Å and Si layer thickness $d_{\mathrm{Si}}=34$ Å, and sample B with the same d_{Mo} value and d_{Si} value of 44 Å. The number of bilayers in both samples is 50. The sample preparation is described in Refs. 16 and 17. The sample wavelength and individual layer thicknesses are determined from small-angle x-ray diffractometry with an accuracy of 0.1 Å. The number of satellite lines on diffractograms for the samples investigated is 4, while for multilayers with wavelengths equal or exceeding 100 Å this number is about 10 or greater. These data testify about the high regularity of the layering. The same conclusion follows from an electron microscopy investigation of the sample cross section. The latter shows as well that the roughness of the interfaces does not exceed 7–8 Å. The measurements were performed with a 5 T superconducting magnet. At all orientations of $\vec{H}$ with respect to the layers the transport current $\vec{I}$ directed along the layers was always perpendicular to $\vec{H}$. The precision of the $\vec{H}$ alignment with the layer planes was about 0.2°. The stabilization of the temperature during a field sweep was no worse than 10^{-3} K.

In Fig. 1(a) the resistance as a function of H at different temperatures for the angle $\Theta=0°$ is shown for sample A ($\Theta=0°$ for $\vec{H}$ parallel to the layers). Beginning from some reduced temperature ($t=0.96$) on an R vs H curve a step appears which develops at lower temperatures into a minimum. At further T diminishing instead of R minimum the zero-resistance region appears which manifests the reentrance of superconductivity. After the ZRR at still larger fields the resistance appears again. As we keep going down in temperature, the ZRR becomes wider, and in the low-

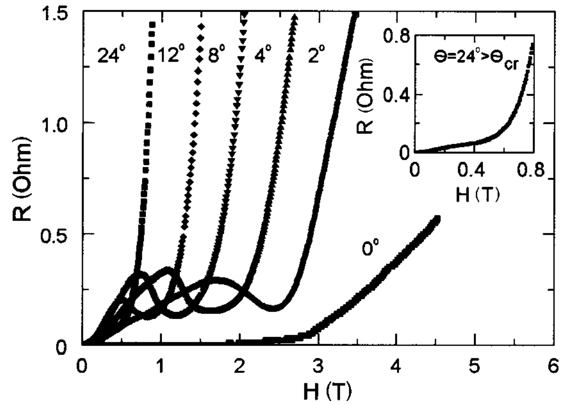

FIG. 2. Resistance as a function of magnetic field for different orientations with respect to the layer planes for sample A.

temperature limit the R maximum below $H=1.8$ T disappears. Thus, reentrance behavior exists in a range between T_0 and some lower temperature T'. For understanding the reentrance phenomenon scale it should be mentioned that the normal resistance of sample A is 42.4 Ω. The resistance as a function of $H_\parallel$ for another sample is shown in Fig. 1(b).

The reentrance behavior is very sensitive to the deviation of the $\vec{H}$ orientation from parallel to the layer planes (Fig. 2). Already at a slight deviation the radical change in the R vs H behavior appears. If measurements are made at a temperature where ZRR states in the field $H_\parallel$ are observed, at $\Theta\neq 0°$ instead of the reentrance behavior only steps are seen on R vs H curves. If $T<T'$, like in Fig. 2, in the tilted fields the R minima are observed until some critical angle Θ_{cr}. Thus, the field rotation appears equivalent to the ''effective temperature'' change.

The reentrance phenomenon is also very sensitive to the magnetic history. When one begins measurements with the first switching on of the H sweep at sufficiently low temperature, another realization of R vs H curves at $\Theta=0°$ in the same t range may be obtained. Such another realization for sample A is shown in Fig. 3. In this case two ranges of ZRRs are observed; i.e., the reentrance of superconductivity arises twice during one magnetic field sweep.

The natural assumption explaining the appearance of ZRR states is connected with the nonmonotonic dependence of the

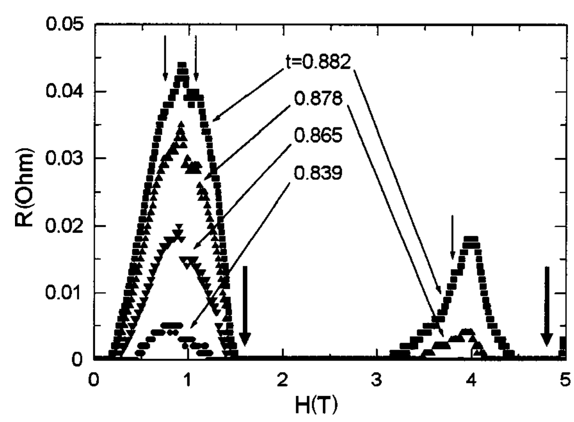

FIG. 3. Resistance as a function of $H_\parallel$ at the different temperatures for sample A for a case when at $t=0.882$ the sample was in a virgin state. Thick arrows show values of H_s; thin vertical ones mark additional features of R vs H curves described in the text.

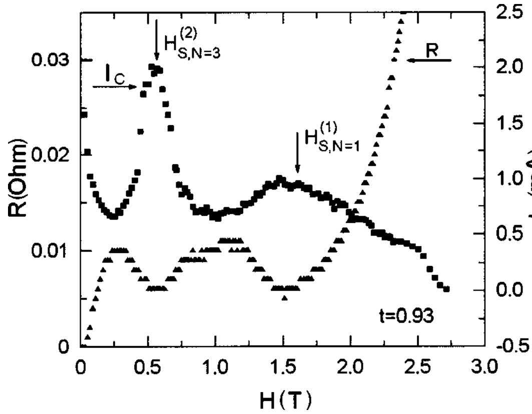

FIG. 4. I_c and R as a function of magnetic field for sample A ($\Theta = 0$ °). The critical current was determined by criterion 1 μV.

critical current I_c on magnetic field. Provided there are oscillations in I_c vs H curves, one may expect that for the fields around the I_c maximum the fixed transport current appears to be less than I_c, and correspondingly the resistance is absent (ZRR state). In the meantime, in the fields around the I_c minimum the condition $I > I_c$ may be satisfied, and a nonzero resistance should be observed. The measurements of I_c vs H dependences confirm this supposition as Fig. 4 shows. Here for the sake of clarity we have chosen the situation with the resistance minimum instead of one with the ZRR. The I_c dependences on H are indeed nonmonotonic. Positions of the minima on the R vs H curve coincide with the locations of the maxima on the I_c vs H curve and vice versa. Figure 4 shows the third realization, characteristic for sample A.

For the interpretation of the data obtained let us, first of all, determine the physical meaning of the temperature T_0 where the signs of developing ZRR states appear. It follows from the experimental data that at this temperature the transverse coherence length $\xi_\perp(T)$ becomes equal to or less than $s/2$; i.e., beginning from T_0 the confinement of the vortex cores between superconducting layers starts to develop. For sample A the value $\xi_\parallel(0) = 63$ Å, $\gamma = 11.8$, $\xi_\perp(0) = 5.5$ Å. At $T_0 = 3.52$ K the value $\xi_\perp(T_0) = 27$ Å, $2\xi_\perp(T_0) \lesssim s = 56$ Å. When the vortex cores fit into the insulating interlayers, intrinsic pinning should become more pronounced, and a transition to the limit $E_p > E_{el}$ may be expected. Thus, T_0 manifests by itself the transition to the regime of strong layering.[3] The same situation is observed for sample B.

A large variety of possible VL configurations is proposed as follows from the papers cited above. Among them there are VL arrangements corresponding to the commensurate lattices. When the intrinsic pinning energy is larger than the elastic energy of a shear deformation of the VL, the latter should be commensurate with the multilayer wavelength at all magnetic field values.[3] According to IKP the stable states of the commensurate lattices correspond to a rhombic lattice with rational values of the apex angle $\pi/3$ and $2\pi/3$ [in the frame of reduced coordinates $x, z\sqrt{(M/m)}$; x is a direction along the layers, and z is along c axis]. The conditions of stability look as follows:

$$p = \pi/\sqrt{3}, \quad p = \pi\sqrt{3}. \tag{1}$$

Here p is a reduced magnetic field:

$$p = 2\pi N^2 s^2 \gamma H/\Phi_0. \tag{2}$$

Using formulas (1) and (2) one can define H_s values corresponding to the stable states (i.e. to the free energy minima) for different commensurability orders. The anisotropy parameter γ is equal to 11.8 and 23.5 for samples A and B, respectively. For sample A at $N = 1$ we have the following values of the magnetic field H_s at two stable states: 4.77 T and 1.59 T. At $N = 2$ the H_s values are 1.19 T and 0.4 T, and for $N = 3$ they are 0.53 T and 0.18 T. Because of the relatively large wavelengths in our multilayers the H_s values corresponding to the low orders of commensurability are in the accessible range of magnetic fields in contrast to high-T_c compounds with small s values. It appears that two values of H_s for $N = 1$ are in both ZRR ranges for sample A (these values are shown by thick arrows in Fig. 3). Such a situation when Z_0 stays the same during the variation of H corresponds to the strong pinning limit. The two R minima in Fig. 4 may be identified as IKP stable states for $N = 1$ and $N = 3$. The difference in the data of Fig. 3 and 4 may be attributed to the variation of the initial state when the VL was first formed.

As was mentioned above, beside the stable VL configurations considered by IKP rather different VL states may exist which are dynamically accessible at the magnetic field variation.[3–5] Under the conditions of strong pinning and relatively small magnetic fields, the shear instability of the commensurate lattice leads to the breaking of symmetry: neighboring vortex chains locked between superconducting layers may be shifted one relative to the other.[4] A lot of these ''shifted'' lattices correspond to the metastable states, i.e., to the local minima of free energy. The trajectory of the dynamically accessible minimum which starts from symmetric VL goes through a sequence of bifurcation and quasibifurcation points, and this trajectory is not uniquely defined. When the magnetic field varies, the trace of the absolute minimum jumps randomly between different metastable states.[4] One may believe that the metastable states of the VL may be probed in dynamic experiments, i.e., by resistive or critical current measurements. We suggest that a number of additional features observed on R vs H curves (like steps, kinks, or abrupt changes of curvature; see thin arrows in Fig. 3), along with the main minima, may be evidence of the above-discussed dynamically accessible metastable states.

As is expected,[3] all the data are sensitive to the magnetic history. The dependences R vs H and I_c vs H are hysteretic. The hysteretic behavior of the phenomena observed and the data obtained in the tilted fields will be discussed elsewhere.

The predictions about the VL structure in layered superconductors obtained in the paper of Bulaevskii and Clem[6] (BC) in the framework of the LD model which takes into account the Josephson nature of the interlayer coupling are rather different from those obtained on the base of a three-dimensional anisotropic London or GL approach. The series of the phase transitions between different commensurate phases should occur at definite magnetic field values H_n which depend on γ and the multilayer wavelength. For this effect the value of the characteristic field $H_0 = \Phi_0/\gamma s^2$ where Josephson cores of the vortices begin to overlap is essential. For sample A this characteristic field H_0 is equal to 5.51 T. The transition between commensurate phases corresponding to $Z_0 = s$ and $Z_0 = 2s$ should occur in the field $H_1 \approx H_0/3 = 1.84$ T, while another transition (between the phases with $Z_0 = 2s$ and $Z_0 = 3s$) in the field $H_2 \approx H_0/8 = 0.69$ T. The position of the minima in Fig. 1(a) is just consistent with the field H_1 estimated above on the base of the LD model results of BC. However, at the field close to $H_2 = 0.69$ T there is only a peculiarity on the derivative dR/dH (the latter becomes zero at sufficiently low t).

It is rather puzzling that in spite of the differences in the approach and predictions of GL and LD models, one can find on the same sample patterns corresponding to both scenarios in the same range of magnetic fields. Nevertheless, it is obvious that the location of the minima in Fig. 1(a) cannot be explained in the IKP GL model, while they are in agreement with the results of the LD model of BC. Meanwhile the data of Figs. 3 and 4 are consistent only with IKP theory predictions. As for sample B, the positions of the R minima estimated from IKP theory for $N = 1$ [Fig. 1(b)] are consistent with experimental data.

In summary, a reentrance phenomenon has been found in Mo/Si multilayers which occurs if the magnetic field is aligned along the layers or slightly tilted with respect to the layer planes. The reentrance behavior is related to the effect of intrinsic pinning and to the specifics of VL structure in layered superconductors. Locations of the R vs H minima and ZRR correspond either to the stable states of the commensurate VL or to the transitions between two commensurate lattices with different Z_0. The results obtained allow one to conclude that the investigation of the reentrance behavior may be used as a tool to study the VL arrangement in layered superconductors.

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