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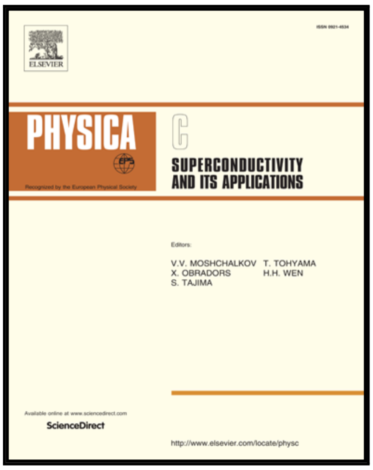

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Negative magnetoresistance in thin superconducting films with parallel orientation of current and magnetic field

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(Dated: July 19, 2018)

Thin superconducting films can exhibit negative magnetoresistance when an in-plane external magnetic field is aligned *parallel* with the transport current. We explain this effect as due to appearance of parallel vortices in the plain of the film at the first critical magnetic field H_{c1} which leads to an enhancement of the superconducting properties and impedes the motion of the current induced perpendicular vortices. Our theoretical results are based on a numerical solution of the time-dependent and stationary 3D Ginzburg-Landau equations.

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It is well-known that thin superconducting films with width $2\xi \lesssim w < \Lambda = 2\lambda^2/d$ (ξ is the coherence length, λ is the London penetration depth) and thickness $2\xi \lesssim d < \lambda$ may exhibit a nonmonotonous dependence of the critical current I_c and resistance R on an external magnetic field H when it is perpendicular to the transport current I. This effect was predicted by Shmidt in 1969 [1] for thin film with thickness $d \gtrsim 2\xi$ placed in parallel magnetic field (magnetic field in plane of the film). Shmidt noted, that the entrance of the vortex chain to the film prevents the penetration of the next vortices and results in an enhancement of the critical current. Subsequently, it was found [2, 3] that the entrance of the second and next vortex chains leads to the appearance of additional maxima in the $I_c(H)$ curve. The effect is similar to the oscillations of I_c in the Josephson junction when Josephson vortices enters the junction one by one with increasing external magnetic field (so called Fraunhofer oscillations). In this case the entrance of the vortex chain in the thin film qualitatively plays the same role as the entrance of a single vortex in the Josephson junction [4].

Because the critical current oscillates as function of the magnetic field one can also expect, that the resistance of the film (at fixed current) also oscillate. Such oscillations were theoretically found in narrow thin films in Ref. [5] in the regime of permanent vortex flow (using time-dependent Ginzburg-Landau equation) and in Ref. [4] in the regime of thermoactivated vortex hopping (using the calculated field dependent energy barrier for vortex entrance).

Experimentally, nonmonotonous dependence of $I_c(H)$ was observed for thin films both in parallel [6, 7] and in perpendicular (to the plane of the film) [8, 9] magnetic fields which was orthogonal to the transport current. Oscillations of the magnetoresistance (which could be related to vortex motion in the presence of the vortex chains [4]) was observed only in the perpendicular geometry in several works [5, 10–15]. Relation of these experiments with the theoretical predictions is confirmed by the correct prediction of the position of the dip in $I_c(H)$ at $H = H_{dip}$ (according to the theory $H_{dip} \sim \Phi_0/w\xi$ or $H_{dip} \sim \Phi_0/d\xi$ [1–3, 9] for perpendicular and parallel geometries, respectively) and the position of the peak in $R(H)$ at $H_{peak} = H_{c1}$ [4] ($H_{c1} \sim \Phi_0/w^2$ or $H_{c1} \sim \Phi_0/d^2$ [16, 17]).

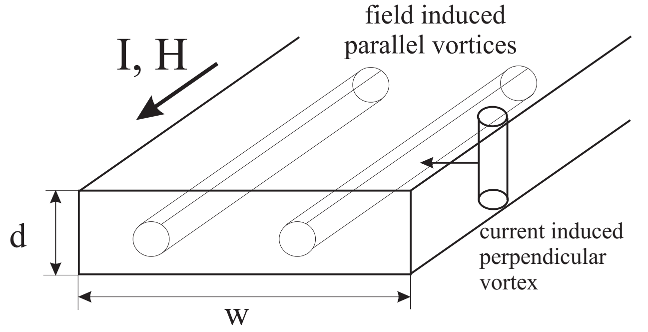

FIG. 1: Sketch of the studied geometry. The resistance appears due to motion of current induced perpendicular vortices.

Here we show theoretically that very similar oscillations of the magnetoresistance appear even if the external magnetic field is applied *parallel* to the transport current (see Fig. 1). In such a geometry one cannot expect that the magnetic field induced vortices are moved by the applied current. Instead, the resistance is now realized by the motion of current induced perpendicular vortices (see Fig. 1) which are nucleated at the edges if current exceeds $I_c(H)$ or which may appear in the film due to thermo-fluctuations for $I < I_c(H)$. Parallel magnetic field creates parallel vortices in the film and it changes the condition for the appearance of the perpendicular vortices and their motion.

To support the above idea we performed numerical simulations of the vortex dynamics within the framework of 3D time-dependent Ginzburg-Landau equation (for details of the calculations see Ref. [18]). In Fig. 2 we present the dependence of the time-averaged voltage (found at fixed current, which is larger than $I_c(H)$ at $H > 0.1H_{c2}$) on the parallel magnetic field. The resistive state is realized via the entrance and motion of the perpendicular vortices (see bottom panels in Fig. 2). At $H \gtrsim 0.45H_{c2}$ parallel vortices exist in the film (see panels 2-4) and when their density is relatively low they impede the motion of perpendicular vortices (voltage decreases). At large fields ($H \gtrsim 0.8H_{c2}$) the density of parallel vortices becomes so large that the order parameter is strongly suppressed such that the perpendicular vortices move more easily (voltage increases).

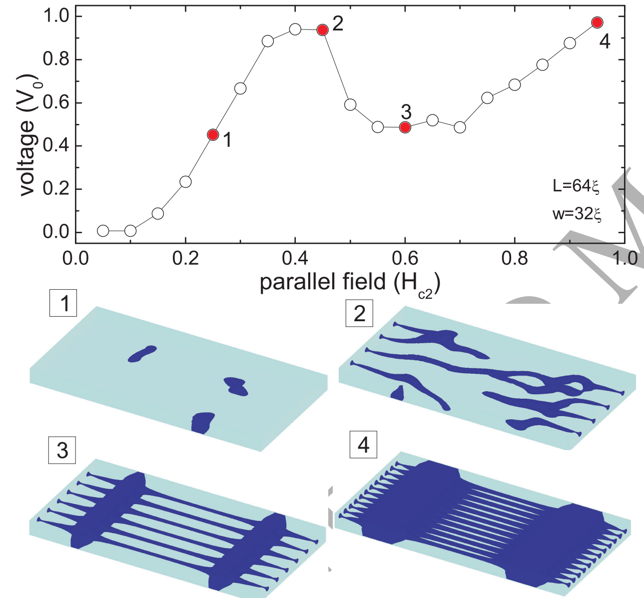

FIG. 2: Dependence of the voltage (top panel) on the parallel magnetic field in the film with thickness $d = 4\xi$, width $w = 32\xi$ and length $L = 64\xi$. The voltage is normalized in units of $V_0 = c\Phi_0\rho_n/8\pi^2\lambda\xi$ (Φ_0 is the magnetic flux quantum, λ is the London penetration depth and ρ_n is the normal state resistivity), the magnetic field is in units of the second critical field H_{c2} and the current is equal to 52 % of the depairing current. At the bottom panels we present 3D snapshots of the dynamics of the superconducting order parameter at the different magnetic fields marked by numbers in the top panel.

Above calculations predict negative magnetoresistance when applied current is larger than $I_c(H)$. But what will happen when $I < I_c(H)$? We assume that the finite resistance at low currents $I \ll I_c(H)$ could be connected with thermo-activated vortex entry and $R \sim exp(-\delta F(H)/k_BT)$ where $\delta F(H)$ is a field dependent energy barrier for perpendicular vortex entry. To find $\delta F(H)$ we use the 3D stationary Ginzburg-Landau equation and the numerical method from Ref. [19] for finding saddle point states. At all magnetic fields and for $I \to 0$ the maximal energy barrier corresponds to a perpendicular vortex sitting in the center of the film. In Fig. 3 we present calculated field dependence of the energy barrier δF. One can see that at $H > 0.45H_{c2}$ the energy barrier increases, which indicates an enhancement of the superconducting properties in the space between the parallel vortices. At larger fields the increased number of vortices in the chain already cannot compensate the pair-breaking effect of screening currents and δF decreases with increasing H. In the experiment it should result in an increasing fluctuation induced finite resistance.

Above we considered two limiting cases: $I > I_c(H)$ and $I \ll I_c(H)$. In both cases the magnetoresistance is negative at fields $H \gtrsim H_{c1}$. Therefore, we believe that at intermediate currents the magnetoresistance also will be negative in the same field range.

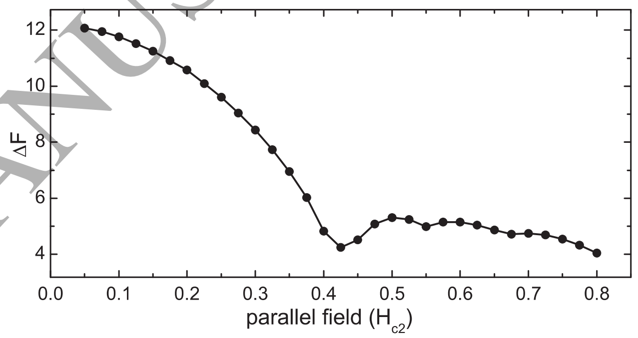

FIG. 3: Field-dependent energy barrier for perpendicular vortex hopping to the center of the film. The barrier is scaled in units of $F_0 = \Phi_0^2 d/16\pi^2\lambda^2$. The geometrical parameters of the film are the same as in Fig. 2.

Recently [20], the magnetoresistance of MoGe thin film (with $d = 50nm$) in parallel magnetic field was studied but no signs of negative $R(H)$ were found. In such a thin film $H_{c1} \simeq 1.4\Phi_0/d^2 \sim 11.6kOe$ (using results of calculations in Ginzburg-Landau theory with $d = 3-5\xi$ - see Fig. 8 in Ref. [4]) which is close to the maximal field used in that work.

In a very recent experiment [21] a two times thicker MoGe film ($d = 100nm$) was studied and negative magnetoresistance was observed in the temperature interval $T = 5.8-5.95K$ near $T_c \simeq 6.1K$. Note that the effect was absent at $T = 6K$ when the thickness of the film approached $2\xi(T)$ ($\xi(0) = 6nm$ in this experiment). The position of the peak at $H_{peak} \sim 3.2kOe$ in $R(H)$ curve varied weakly with temperature and this value is close to the first critical field $H_{c1} \simeq 3.2kOe$ for films with thickness $3-5\xi$.

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A more close quantitative comparison of theory and experiment is difficult because of limitations of the time dependent Ginzburg-Landau equation that gives only qualitatively correct result for the voltage (resistance) even at $T \sim T_c$. The calculations of δF are done only in the limit $I \ll I_c(H)$ while in the experiment of Ref. [21] the current could approach $I_c(H)$ (in this case $\delta F \to 0$).

To conclude, we showed theoretically that a magnetic field aligned parallel with the transport current may provide both positive and negative magnetoresistance in thin superconducting film with thickness exceeding $\gtrsim 2\xi(T)$. Positive magnetoresistance comes from the pair-breaking effect of the screening current, while negative magnetoresistance is connected with the existence of parallel vortices in the film. The presence of these vortices changes the entrance and the motion of the perpendicular vortices leading to a decreasing magnetoresistance at fields close to H_{c1}. Our theory is able to explain qualitatively recent experimental results [21] without assumption about existence of defects inside the superconducting film [21].

Acknowledgments

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