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Quantum Design of Superconducting Critical Parameters: Fundamental Aspects

V.V. Moshchalkov, M. Baert, V.V. Metlushko, E. Rosseel, M.J. Van Bael, K. Temst, Y. Bruynseraede and R. Jonckheere*

Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, Celestijnenlaan 200 D, 3001 Leuven, Belgium

** Interuniversity Micro-Electronics Center, Kapeldreef 75, 3001 Leuven, Belgium*

Abstract. The mixed state in homogeneous type-II superconductors is characterized by the formation of a lattice consisting of flux lines (FL) each carrying one flux quantum ϕ_0 . To make the penetration of these quantized FL into a superconductor possible, normal vortex cores must be created. At the upper critical field $H_{c2}(T)$ the total area of the normal cores formally coincides with the sample area and the superconductivity is completely destroyed. To reduce the destructive action of magnetic field on superconductivity, one should separate the areas where flux penetrates from these where the superconducting order parameter ψ nucleates. Using nanostructuring and fabricating a lattice of microholes ("antidots") to let flux go through antidots, we are thus helping the order parameter between the antidots to sustain much higher currents and magnetic fields. This is the main idea of "quantum design" of the two important superconducting parameters: the critical current $j_c(T, H)$ and the critical field $H_{c2}(T)$. By optimizing the parameters of the antidot lattices, we have stabilized multi-quanta vortex lattices and we have dramatically increased $j_c(T, H)$, up to values limited by the depairing current, and strongly enhanced the critical field, which can eventually be much higher than $H_{c2}(T)$ of the bulk reference superconducting material.

1. INTRODUCTION

In 1957 Abrikosov [1] predicted the existence of a novel quantum state in homogeneous type-II superconductors. This so-called mixed state is characterized by the formation of a lattice consisting of flux lines (FL) each carrying *one flux quantum* ϕ_0 . To allow the penetration of these quantized FL, normal vortex cores, with a size given by the temperature dependent coherence length $\xi(T)$, must be created. Later on, the existence of a single- ϕ_0 FL lattice in type-II superconductors has been convincingly demonstrated in magnetic decoration [2], neutron scattering [3] and recently in scanning tunneling microscope [4] (STM) experiments.

In homogeneous superconductors the formation of a FL lattice consisting of *multi-quanta* vortices is energetically unfavorable [5]. Contrary to this, *relatively large artificial pinning centers can stabilize multi-quanta vortices*. For regular arrays of artificial pinning centers the vortex-vortex interactions complicate the situation, but multi-quanta FL lattices can still exist, provided that their radius r is sufficiently large [6].

Following the pioneering work of Hebard et al.[7], we showed recently [8-10] that a *regular array of submicron holes* or "antidots" (a definition borrowed from similar nanostructured semiconducting films [11-12]) can be successfully used to stabilize *multi-quanta and interstitial vortices* in superconducting films.

In this paper we focus on the fundamental aspects of flux confinement phenomena in superconducting films and multilayers with antidot lattices.

2. MULTIQUANTA VORTEX LATTICES

A typical magnetization loop $M(H)$ at a temperature close to T_c of a Pb/Ge multilayer with a triangular antidot lattice (period $d = 1 \mu\text{m}$) is shown in Fig. 1(a). The $M(H)$ curve is also measured for the reference Pb/Ge multilayer without antidots. The width ΔM of the $M(H)$ loops in perforated films is strongly increased due to the efficiency of antidots as artificial pinning centers.

Figure 1: (a) Magnetization loop $M(H)$ at $T = 6 \text{ K}$ of a $[\text{Pb}(100\text{\AA})/\text{Ge}(50\text{\AA})]_2$ multilayer with and without a triangular antidot lattice. The dashed line shows the linear behavior of $M(H_m)$ (Eq. (1) see text). The solid line is a fit with Eq. (2) (see text). The loops were measured for $M > 0$ and symmetrized for clarity for $M < 0$. (b) The magnetization M versus $\ln(H-H_m)$ at $T = 6 \text{ K}$. The different slopes of the solid lines for the different periods are used to determine the effective flux $\tilde{\phi}_{om}$ in Eq. (2).

Besides an overall enhancement of ΔM , distinct cusp-like $M(H)$ anomalies are clearly seen exactly at the expected matching fields where the number of FL corresponds to an integer multiple of the number of antidots, $H_m = m \times 23.9 \text{ G}$ for triangular antidot lattices. The radii r of the antidots are sufficiently large to trap multiquanta FL. The maximum possible number of FL trapped by a single insulating inclusion with radius r is determined by the saturation number [13] $n_s \equiv r/(2\xi(T))$. In this case, at $T = 6 \text{ K}$, $n_s \approx 3$ and we can therefore assume that the cusp-like $M(H)$ anomalies are related to the formation of multiquanta vortex lattices. We will now attempt to give a quantitative description of the $M(H)$ behavior, first for the matching fields and secondly for field values between the matching fields.

An estimate of the temperature dependent penetration length for thin films $\Lambda = 2\lambda^2/t$ (where λ is the penetration depth and t the total thickness of the film) shows that in our case $\Lambda(T = 6 \text{ K}) \approx 5.8 \mu\text{m} \gg d = 1 \mu\text{m}$. This Λ value can be even further increased due to the renormalization of the penetration depth in perforated films, where superconducting volume corrections have to be taken into account [14].

Figure 2: Schematic drawing of the profile of the magnetic induction B for (a) the classical Bean critical state, (b) the multi-terrace critical state [15], and (c) the single-terrace critical state.

Figure 3: Profile of the superconducting order parameter at different temperatures along a row of vortices (a) in a homogeneous superconductor and (b) trapped by antidots.

Since $\Lambda \gg d$, the average magnetic induction in the sample is constant ("single-terrace" critical state, see Fig. 2(c)) and the superconducting order parameter $|\psi|$ is constant (see Fig. 3(b)), therefore we can use the textbook expression for the magnetization [5] with a simple substitution $\xi(T) \rightarrow r$ for the core size:

$$M(H) = -\frac{\phi_0}{16\pi^2 \Lambda^2} \ln\left(\frac{\beta a_v}{\sqrt{er}}\right) \quad (1)$$

where a_v is the distance between ϕ_0 -vortices, e the electron charge, β a numerical constant (for a triangular vortex lattice in unperforated films [5] $\beta = 0.381$).

Let us first consider the situation which occurs *exactly at the matching fields* $H = H_m$, where we expect that the FL lattice consists of only one type of vortices, namely of $m\phi_0$ -vortices forming a regular array coinciding with the antidot lattice. In this case in Eq. (1) $m\phi_0$ should be used instead of ϕ_0 and $a_v = d$ and we have $M(H_m) \propto -m\phi_0 / \Lambda^2$. The difference $M(H_m) - M(H_{m-1}) \propto -1/\Lambda^2$ is independent of m and is determined only by Λ while all other parameters in Eq. (1) are known. Therefore, at $H = H_m$ a linear behavior of $M(H_m)$ as a function of the integer m should be seen. This behavior is in very good agreement with the observed $M(H_m)$ variation at different temperatures (see the dashed lines in Fig. 4). The slope $\Delta M/\Delta H$ of the dashed lines nicely follows the temperature variation $1/\Lambda^2 \propto (1-T/T_c)^2$ (insert of Fig. 4) given by the Ginzburg-Landau theory.

Figure 4: The upper right parts of the magnetization loops $M(H)$ at different temperatures for a $[\text{Pb}(100\text{\AA})/\text{Ge}(50\text{\AA})]_2$ multilayer with a square antidot lattice. The dashed lines, at different temperatures, clearly indicate the linear behavior of $M(H_m)$ as a function of the integer m . The insert presents the slopes $\Delta M/\Delta H$ of the dashed lines, as a function of $(1-T/T_c)^2$. According to Eq. (1) these slopes follow the temperature dependence of $1/\Lambda^2$. The solid line presents the linear fit.

In the following, we will describe the $M(H)$ behavior in the field intervals between the matching fields. The cusp appearing in $M(H)$ at each matching field H_m will be considered as the onset of the formation of $(m+1)\phi_0$ multiquanta vortices, in the same way as in a homogeneous sample without pinning centers the $M(H)$ maximum at H_{c1} indicates the onset of the penetration of FL. We can calculate an analogue of H_{c1} in each field interval $H_{m-1} < H < H_m$ for the onset of formation of $m\phi_0$ FL by inserting $m\phi_0$ instead of ϕ_0 in the expression for H_{c1} , resulting in $H_{c1}(m\phi_0) = (m\phi_0/4\pi\Lambda^2)\ln(\Lambda/r)$. An estimate based on this equation gives very low fields $H_{c1}(m\phi_0) \sim 10^{-2} \text{ G} \ll H - H_m$. This implies that the difference between $H - H_m - H_{c1}((m+1)\phi_0)$ and $H - H_m$ can be neglected and therefore one should see the logarithmic behavior $M(H) \propto -\ln(H - H_m)$ for magnetic fields between the matching fields, $H_m < H < H_{m+1}$. Such behavior is confirmed by our experimental data (see Fig. 1(b)), and is a result of inserting the relation $a_v \equiv (\phi_0/(H - H_m))^{1/2}$ into Eq. (1), which is a good approximation in fields $H_m < H < H_{m+1}$ for a $(m+1)\phi_0$ vortex-vortex distance in a superconductor with an antidot lattice. In this interval the vortex-vortex interaction terms U_{ij} in the Gibbs potential are represented by different contributions arising from the presence of two types of vortices $m\phi_0$ and $(m+1)\phi_0$. These terms will contain instead of a usual $\phi_0 \times \phi_0$ product [5], other products $m\phi_0 \times m\phi_0$, $m\phi_0 \times (m+1)\phi_0$ and $(m+1)\phi_0 \times (m+1)\phi_0$. Due to that, in the interval between the matching fields H_m and H_{m+1} , the magnetization of the superconducting films with an antidot lattice should follow the logarithmic dependence:

$$M(H_m < H < H_{m+1}) \cong -\frac{\tilde{\phi}_{om}}{16\pi^2\Lambda^2} \ln\left(\frac{\beta_{\text{eff}}}{\sqrt{er}}\left(\frac{\phi_o}{H - H_m}\right)^{1/2}\right) \quad (2)$$

Here $\tilde{\phi}_{om}$ is an effective flux for $H_m < H < H_{m+1}$ and β_{eff} an effective parameter appearing due to the summation of different terms in the vortex-vortex interactions U_{ij} over vortex positions i and j on the antidot lattice. For H not far from H_m we may approximate $\tilde{\phi}_{om}$ by $\sqrt{m(m+1)}\phi_0$. We determined the slopes of the M versus $\ln(H - H_m)$ lines (Fig. 1(b)) which give us the effective flux $\tilde{\phi}_{om}$. For a triangular antidot lattice we have $\phi_{om}/\phi_0 = 1, 1.79, 2.45$ and 2.72 for $m = 0, \dots, 3$, which have to be compared with $1, 1.41, 2.45$ and 3.46 respectively, estimated from $(\sqrt{m(m+1)}\phi_0)/\phi_0$. Therefore, besides a logarithmic dependence itself, we see also a very reasonable agreement of the parameter $\tilde{\phi}_{om}$ in different field intervals ($H_m < H < H_{m+1}$). At higher temperature the simple argument that $\tilde{\phi}_{om}$ should scale as $\sqrt{m(m+1)}\phi_0$ fails, since $\Lambda(T)$ is spread over many periods and U_{ij} terms, corresponding to $m\phi_0 \times (m+1)\phi_0$ and $(m+1)\phi_0 \times (m+1)\phi_0$ should be taken into account in order to minimize the energy. Such an optimization procedure should be performed numerically [16].

We note that the stabilization of the FL by the antidot lattice has resulted in a remarkable collective behavior of $M(H)$, typical for the presence of a $m\phi_0$ -FL lattice at $H = H_m$ and a mixture of $m\phi_0$ - and $(m+1)\phi_0$ -vortices between the matching fields $H_m < H < H_{m+1}$. Due to the introduction of a regular pinning potential, we were able to obtain in a multiple-connected superconductor with an antidot lattice a *logarithmic irreversible magnetization behavior* which is normally observed as a *reversible magnetization of the Abrikosov FL lattice* in homogeneous superconductors in fields $H > H_{c1}$. The pronounced $M(H)$ cusps at $H = H_m$ have been interpreted as analogues of the usual H_{c1} cusps, but for the onset of the formation of multi-quanta vortices.

Besides the strong increase in critical current, the formation of the multi-quanta vortex lattices results also in a dramatic modification of the critical field $H_{c2}(T)$ (Fig. 5). Comparing $H_{c2}(T)$ curves for the film with and without antidot lattice, we clearly see a strong enhancement of $H_{c2}(T)$ and also the appearance of the pronounced cusp-like anomalies at the matching fields $H = H_m$. Assuming again that the London limit $|\psi| = \text{constant}$ (Fig. 3(b)) and the single-terrace critical state $B = \text{constant}$ (Fig. 2(c)) are still relevant, we can easily interpret the $H_{c2}(T)$ anomalies in the following way.

The critical field $H_{c2}(T)$ exactly at the matching fields may be found from the condition

$$\frac{\hbar^2}{2m\xi^2(T)} = \frac{H_m^2}{8\pi} + \frac{H_m}{4\pi} H_{c1}(H_m) \frac{\ln(\beta a_v/r)}{\ln(\lambda/r)} \quad (3)$$

As it was already shown before, $H_{c1}(H_m) \ll H_m$ and the second term in Eq. (3) can be neglected. Therefore $T_c(H_m) \propto H_1 \times m^2$, which is in a good agreement with the experimental data (see the dashed line in Fig. 5)

Between the matching fields, the cusp-like anomalies are arising from the second term in Eq. (3) and they will give also the logarithmic shift of $T_c(H_m < H < H_{m+1}) \propto \ln(H - H_m)$, in a similar way as for the formation of the logarithmic cusps in the magnetization curve (see Fig. 1).

Figure 5: H - T Phase diagram of a $W_{0.67}Ge_{0.33}$ film with and without a square antidot lattice ($r = 0.5 \mu m$). The dashed line demonstrates the parabolic dependence $T_c(H_m) \propto H_1 \times m^2$ of T_c at the matching fields.

3. VORTICES PINNED BY ANTIDOTS AND INTERSTICES

In order to study the vortex pinning by antidots and interstices (interstitial positions between the antidots), we have performed magnetoresistance $R(H)$ and voltage-current $V(I)$ measurements in superconducting amorphous $W_{0.67}Ge_{0.33}$ films with a square lattice (period $d = 1 \mu m$) of relatively small antidots with radius $r \approx 0.12 \mu m$. The amorphous WGe films behave as extreme type II superconductors ($\xi_{GL}(0) = 60 \text{ \AA}$, $\lambda(0) \approx 4920 \text{ \AA}$), having a very moderate pinning strength. In that way, a large pinning contrast can be obtained between the perforated and the non perforated reference films and the influence of the defect array on the transport properties can be clearly observed.

In Fig. 6, the magnetoresistance of the $W_{0.67}Ge_{0.33}$ film with an antidot lattice (AL) is compared with the behaviour of the reference film without antidots measured at three different temperatures near $T_c = 4.725 K$ and with a fixed ac current density of $41 A/cm^2$. The reference film has a linear field dependence typical for the classical flux flow [17]. In the case of the film with an AL, the resistance is strongly suppressed when the number of flux lines is less than the number of antidots ($H < H_1 = 20.7 G$) due to strong pinning of the flux lines by the antidots. Above the first matching field H_1 , the resistance increases linearly with increasing field and shows pronounced dips at the second matching field $H = H_2$ where there are exactly two flux lines per antidot. This remarkable increase of the dissipation, $V \propto H - H_1$ can be attributed to the generation of vortices at interstices between the holes, which are easily channeled through the rows of antidots due to the Lorenz force, $F_L \propto J \phi_0$. As more interstitial vortices are added,

the interaction between them becomes stronger and a deviation from the linear dependence can be observed. At the second matching field, the interstitial flux lines are commensurate with the underlying AL, occupying hereby the positions of the squares with the antidots at the corners, which enhances the energy barrier for the motion of the interstitial flux lines.

Figure 6: Comparison of the normalized resistance R/R_n (R_n the resistance at 5 K) for a $W_{0.67}Ge_{0.33}$ film with a lattice of antidots (open symbols) and the film without antidots (filled symbols and straight guide-to-the-eye lines) measured at different temperatures: $\square$ $T=4.710$ K, $\bullet$ $T=4.705$ K, $\triangle$ $T=4.700$ K.

In Fig. 7, E - J plots with E the electric field and J the current density are shown in different magnetic fields ranging from 10 to 100 G at a fixed temperature $T = 4.69$ K. At fields below H_1 , J_c (shown in the insert) seems to be rather independent of the field and the $\log E - \log J$ plots are reasonably well approximated by a straight line corresponding to a power law relation $E \propto J^\alpha$. As the field exceeds H_1 , a kink appears in the E - J curve. This kink is preceded by a tail which can also be described by a power law but with a much smaller exponent α . Again, as for the case $H < H_1$, the slope of the curve is the same for the different fields. From the above observations it is clear that at $H > H_1$ we have to distinguish between two types of dissipative processes related to vortices with a different mobility. At low currents $J < J_{cr}$ and $H > H_1$, the vortices at the holes are pinned while the interstitial vortices are easily swept giving rise to a dissipation E_i . When a certain threshold current is reached, the vortices at the antidots are delocalized and their motion creates an electrical field E_a . As a result the total field is given by $E = E_i + E_a$ and a kink is visible in the E - J curve at the moment when the additional dissipation process, related to the motion of the vortices trapped by the antidots, is initiated.

Figure 7: $E(J)$ sweeps for different magnetic fields between 10 G and 30 G at temperature $T = 4.690$ K. The corresponding $J_c(H)$ curve, determined using a $5 \mu\text{V}/\text{cm}$ criterion (dashed line in the $E(J)$ plot) is shown in the inset.

4. CONCLUSIONS

We have studied flux confinement phenomena in superconducting films and multilayers with an artificial periodic pinning array. The presence of the lattice of artificial pinning centers leads to an overall enhancement of the critical current density and to cusp-like $M(H)$ anomalies due to a matching of the flux line lattice with the antidot array.

For relatively large antidots we encounter multiple flux quanta in each hole. Assuming the existence of multiple-flux-quanta lattices, we constructed a theoretical description of the magnetization loops. This equation yields a convincing quantitative agreement with the experimental magnetization loops, including the linear behavior of $M(H)$ at matching fields $M(H_m) \propto -m\phi_0/\Lambda^2$ and logarithmic behavior elsewhere: $M(H_m < H < H_{m+1}) \propto -\ln(H-H_m)$. Similar approach has been also developed to interpret the strong enhancement of the critical fields due to the formation of the multi-quanta vortex lattices. For the superconducting films with relatively small antidots, the holes can only pin one flux quantum and, as the field is increased, additional flux lines have to occupy interstitial sites between the holes, leading to a coexistence of weakly pinned interstitial vortices and a strongly pinned vortex lattice at the antidots. This explains the observed drop in the critical current density for fields exceeding the first matching field H_1 . The presence of mobile interstitial vortices leads to a crossover in the E - J characteristics.

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