Depinning of caged interstitial vortices in superconducting *a*-WGe films with an antidot lattice

E. Rosseel, M. Van Bael, and M. Baert
Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium

R. Jonckheere
Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium and Interuniversity Micro-Electronics Center, Kapeldreef 75, B-3001 Leuven, Belgium

V. V. Moshchalkov and Y. Bruynseraede
Laboratorium voor Vaste-Stoffysica en Magnetisme, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium
(Received 31 October 1995; revised manuscript received 8 December 1995)

The magnetoresistance, critical currents, and voltage-current (V-I) characteristics have been studied in superconducting *a*-WGe films with a square lattice of cylindrical microholes (antidots). Besides a strong enhancement of the critical current caused by matching of the flux lines with the antidot lattice having a period d, two different dissipative regimes have been observed giving rise to a crossover in the [log(V)-log(I)] characteristics for magnetic fields above the first matching field $B_1=B_\phi\equiv\Phi_0 d^{-2}$. This V-I behavior is caused by the coexistence of a weakly pinned interstitial vortex fluid and a strongly pinned vortex lattice at the antidots.

The introduction of artifical pinning centers into low[1–3] and high-T_c superconductors[4,5] leads to a considerable modification and enhancement of the flux line (FL) pinning. In the case of high-T_c superconductors, the standard option now is to consider the influence of correlated disorder created by columnar defects (CD's) on the FL pinning in the framework of the Bose-Glass theory[6] for $B\leqslant B_1$ (with $B_1\equiv\Phi_0 d^{-2}$, the matching field, corresponding to one flux line per CD). For fields above B_1, however, it has recently been argued[7] that the presence of weakly pinned interstitial FL's strongly reduces the pinning strength of the system, leading to a downward shift of the irreversibility line in the B-T phase diagram for $B>B_1$. This prediction can be experimentally verified by using artificial pinning centers with a well-controlled distribution and size. Evidently, such centers are extremely difficult to make by heavy-ion irradiation. At the same time, modern *e*-beam lithography makes it possible to fabricate regular arrays of identical microholes (antidots) which are small enough to be used as efficient pinning centers.[2,3]

In this paper we demonstrate that in a low-T_c $W_{1-x}Ge_x$ film with an antidot lattice (AL) the formation of interstitial FL's can be observed in the voltage-current (V-I) characteristics where it leads to a strong reduction of the critical current. Although a typical Bose-Glass behavior has not been found in our system with the FL periodicity enforced due to the presence of the lattice of regular antidots we do believe that our experimental findings bare a strong resemblance with some of the predictions made in Ref. 7: (a) above B_1 a coexistence of strongly pinned vortices at the defects and weakly pinned vortices at interstices gives rise to a drastic reduction of the critical current; (b) the difference in depinning strengths needed for vortices at interstitials and at antidots leads to an appearance of a kink in the V-I characteristics.

The amorphous $W_{1-x}Ge_x$ ($x\approx0.33$) samples were prepared in a molecular beam epitaxy apparatus by electron beam coevaporation of W and Ge onto liquid-nitrogen cooled SiO_2 substrates with a predefined lattice of resist dots. At the same time, bare SiO_2 substrates without any resist pattern were added for comparison. After evaporation of a film with thickness $t\approx73$ nm, a standard lift-off procedure was followed, finally yielding a well-defined lattice of holes with a spacing d between the holes of 1 μm and a radius $r_a\approx0.12$ μm [see the inset of Fig. 1(b)]. For details of the preparation procedure, see Refs. 2 and 3.

After a structural characterization (with x-rays, atomic force microscopy, Rutherford backscattering spectroscopy), the samples were patterned into a four probe configuration with typical dimensions 1×3 mm and a distance between the voltage contacts of 1 mm. The electrical transport measurements were performed in a helium-3 cryostat equipped with a 7 T superconducting coil and a temperature stability of approximately 0.5 mK. The magnetic field was applied perpendicular to the film plane or in other words, parallel to the symmetry axis of the cylindrical antidots. The sample resistances were measured using a commercial four terminal ac resistance bridge (linear research) and the $J_c(B)$ curves were obtained from the E-J sweeps using a 5 μV/cm criterion.

The studied $W_{0.67}Ge_{0.33}$ films behave as type-II superconductors in the extreme dirty limit. From the midpoint of the zero field resistive transition a critical temperature, T_c, of 4.725 K was obtained. Using the Ginsburg-Landau (GL) expression for the measured upper critical field $B_{c2\perp}(T)$, a coherence length $\xi(0)$ of 60 Å is determined. For the calculation of the GL parameter κ we rely on the dirty limit expression[8] $\kappa=3.54\times10^4[\rho_0|S|]^{1/2}$ (with ρ_0 the normal state resistivity ≈2.77 $\mu\Omega$ m for $T\rightarrow0$ K and $S=-1.94$ T/K the critical field slope at T_c) and we get a reasonable estimate $\kappa\approx82$ which is in good agreement with the typical values obtained for other amorphous transition-metal-based superconductors such as $Nb_{1-x}Ge_x$ (Ref. 9) and $Mo_{1-x}Ge_x$.[10] Based on the previous results, we can derive a value for the

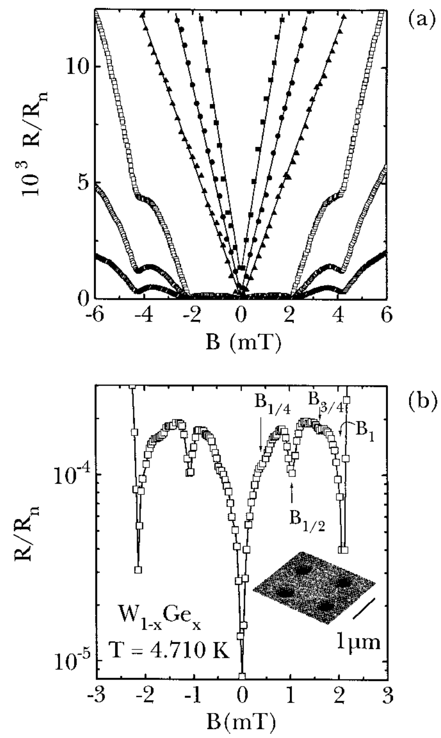

FIG. 1. (a) Comparison of the normalized resistance R/R_n (with $R_n \equiv$ the resistance at 5 K) for a film with a lattice of antidots (open symbols) and the film without antidots (filled symbols and straight guide-to-the-eye lines) at different temperatures: squares, $T=4.710$ K; circles, $T=4.705$ K; triangles, $T=4.700$ K and at an ac current density of 41 A/cm^2. (b) Magnification of the curve at 4.710 K (film with antidots) in a logarithmic scale. The dips in the resistance at rational field values are marked with $B_{p/q}=(p/q)B_1$. The small inset shows an AFM picture of the unit of the lattice.

penetration depth $\lambda(0)$ of $\approx$492 nm. Since the film thickness $t \ll \lambda(0)$, the effective transverse penetration depth $\Lambda(0) = 2\lambda^2(0)/t \approx 6.6$ μm should be used. The latter is much larger than the antidot lattice period d, which indicates that for $B \approx B_1$ the magnetic field lines of the vortices strongly overlap and as a consequence the induction profile can be considered as homogeneous in the whole temperature interval.

A straightforward way to obtain information about the dissipation processes in our perforated $W_{0.67}Ge_{0.33}$ films is to perform low-field magnetoresistance measurements. Since flux motion leads to dissipation, the presence of the AL is expected to reduce it due to trapping of the FL's by the antidots and hence to diminish the voltage drop over the sample. In Fig. 1(a), a comparison is made between a film with antidots and the reference film without antidots at three different temperatures near T_c (=4.725 K) and with a fixed ac current density of 41 A/cm^2. For the reference film, a linear field dependence is measured with a slope which diverges near T_c as $(T_c - T)^{-\nu}$ $(\nu \approx 1)$. This behavior is typical[11] for high-κ superconductors in the presence of small fields $(B/B_{c2} < 0.1)$ where the Bardeen-Stephen limit[12] $R = \beta(T)B/B_{c2}(0)$ [with $\beta(T)$ the temperature dependent prefactor] is valid. In the case of the film with an AL, the resistance is clearly strongly suppressed when the number of FL's is less than that of available antidots ($B < B_1 = 2.07$ mT). The strong reduction with respect to the unperforated film's response is due to the efficient pinning of the FL's by the AL.

A closer look at the $R(B)$ curves for the film with the AL [see Fig. 1(b)] shows that there is even an additional structure present at the low dissipation level. Besides the clear dips at $B=0$ and $B=B_1$, less pronounced but still clearly visible R/R_n suppressions can also be found at $B=B_{p/q} = (p/q)B_1$ with p/q=1/4, 1/2 and 3/4. The rational dips in $R(B)$ at $B < B_1$ are reminiscent of energetically stable rational flux phases[13] (such as, for example, the well-known checkerboard configuration[14] at $B=B_{1/2}$, etc.) Above B_1, all the antidots forming a lattice are filled with one flux quantum. Since the coherence length $\xi(4.71\text{ K}) \approx 0.11$ μm is quite large, the saturation number[15] $n_s \propto r_a/2\xi \leqslant 1$ is too small for the formation of two-quanta vortices at the antidots. Moreover, from a crossover in the $J_c(T)$ dependence at fixed field $B \approx B_2$ (see the inset of Fig. 3), the temperature, T_{2Q}, where two-quanta formation becomes energetically favorable is estimated to be about $T \approx 4.660$ K. As a result, at $T=4.710$ K the extra FL's cannot be accommodated by the AL and the FL's are forced to occupy the interstices between the holes. In this way the interstitial FL's are caged by surrounding FL's strongly pinned by the antidots. Under the action of the Lorentz force, $F_L \propto J\Phi_0$, perpendicular to the transport current density J, these interstitial caged vortices are easily channeled through the rows of the FL's at the holes, leading to a dissipation $V \propto (B - B_1)$. 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, $B_2 \equiv 2B_1 = 4.14$ mT, the interstitial lines are commensurate with the underlying AL, occupying hereby the positions in the center of the squares with the antidots at the corners, which enhances the energy barrier for the motion of the interstitial FL's.

In Fig. 2, E-J plots (with E the electric field and J the current density) are shown in different magnetic fields ranging from 1 to 3 mT at a fixed temperature $T=4.690$ K. The horizontal dashed line corresponds to a voltage criterion of 5 μV/cm for the determination of the critical currents $J_c(B)$ shown in the inset of Fig. 2(a). For fields just below B_1, J_c seems to be rather independent of the field and the curves are reasonably well approximated by a straight line in the log(E)-log(J) plot, which corresponds to a power-law relation $E \propto J^\alpha$. As the field exceeds the first matching field, 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 $B < B_1$, the slope of the curve is the same for the different fields. From the above observations it is clear that at $B > B_1$ we have to distinguish between two types of dissipative processes related to vortices with a different mobility. At low currents $J < J_{cr}$ and $B > B_1$, the vortices at the holes are pinned while the interstitial vortices are easily swept, giving rise to a dissipation:

$$E_i \propto (J - J_{ci})^{\alpha_i(T)} n_i(B). \quad (1)$$

Here J_{ci} is the critical current density for interstitial FL's motion, $\alpha_i(T)$ the temperature dependent exponent and

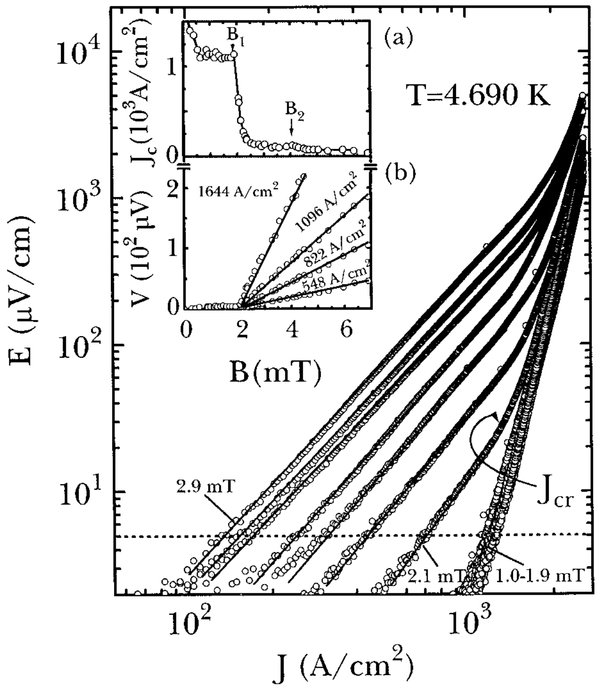

FIG. 2. $E(J)$ sweeps for different magnetic fields between 1 and 3 mT at a fixed temperature of 4.690 K. The corresponding $J_c(B)$ curve, determined using a 5 μV/cm criterion [dashed line in the $E(J)$ plot], is shown in inset (a). Inset (b) shows the generated voltage as a function of the magnetic field for different values of the current density at a fixed temperature of 4.690 K.

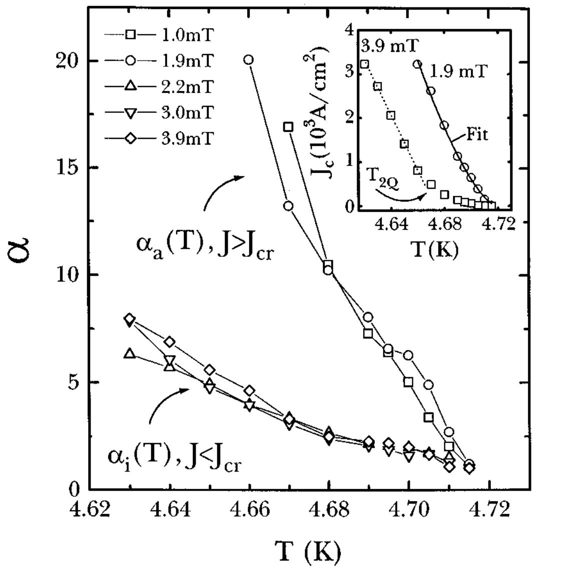

FIG. 3. Temperature dependence of the $E(J)$ exponents α for different fields. The subscript a refers to the vortices pinned at the antidots and i refers to the interstitials. The inset shows the $J_c(T)$ dependence at fields $B=1.9$ mT ($\sim B_1$) and $B=3.9$ mT ($\sim B_2$). The solid line in the inset is a fit of the $B=1.9$ mT data using the GL expression for the depairing current density with parameters: $\lambda(0)=0.84$ μm and $T_c=4.719$ K. The dashed line is a guide to the eye which emphasizes the fast J_c increase below T_{2Q}.

$n_i(B)$ the average number of interstitial FL's taking part in the motion, per interstitial position).

From inset (b) in Fig. 2, we can see that for $B>B_1$, E varies linearly with B and hence we can approximate $n_i(B)$ in Eq. (1) with $(B-B_1)/B_1$. This clearly demonstrates that an increase of the magnetic field above B_1 at $T=4.690$ K gives immediately rise to an increase of the number of FL's at interstices. When a certain current threshold is reached ($J\equiv J_{cr}\approx J_{ca}$) the vortices at the antidots are delocalized and their motion produces an electric field:

$$E_a \propto (J-J_{ca})^{\alpha_a(T)} A(B)$$

with J_{ca} being the critical current density for the vortices at the holes, $\alpha_a(T)$ the exponent determined from the $E(J)$ curves at $B<B_1$ and $A(B)$ a factor which is weakly dependent upon field. 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.

In Fig. 3, the temperature dependence of the $E(J)$ exponents α is shown for fields below and above B_1. For $B>B_1$ and $J<J_{cr}(T,B)$, only the part of the $E(J)$ curve which is associated with the interstitial motion is taken into account for the determination of α and hence labeled α_i. When the current density exceeds $J_{cr}(T,B)$, the value of the exponent increases rapidly from $\alpha_i(T)$ to $\alpha_a(T)$. Since both the exponent and the depinning threshold are much larger for the vortices at the antidots than at the interstices, it seems that there exists a correlation between the exponents and the different pinning potentials at the antidots (U_a) and at the interstices (U_i).

From a calculation based on electromagnetic pinning,[16,17] $U_a(T)$ is found to be much larger than $U_i(T)$ and both are seen to increase smoothly with decreasing temperature, which is also the case for $\alpha_i(T)$ and $\alpha_a(T)$. The relation between α and U is however not straightforward, though, of course one can assume that the pinning potentials are logarithmically dependent upon the applied current, $U_{i,a}(J)=U^0_{i,a}\ln(J_{i,a}/J)$, leading to $\alpha_{i,a}=U^0_{i,a}/k_BT$.

On the other hand, if we consider the different magnitudes for $\alpha_i(T)$ and $\alpha_a(T)$ and the fact that the generated electric field for $B<B_1$ does not scale with B as it does for FL's at interstices [see inset (b) in Fig. 2], it is possible that the vortex delocalization at the interstitials and at the antidots has to be treated differently. A fit of the $J_c(T)$ dependence for $B<B_1$ with the simple GL expression for the depairing current density[18] (see the inset of Fig. 3) gives actually a fairly good result, both for the order of magnitude and for the typical $(T_c-T)^{3/2}$ dependence. Although the GL formula is probably too simple for samples with antidots, the fit may nevertheless indicate that current induced depairing (often observed in strongly coupled wire networks[19]) is quite substantial, which might explain the steep V-I curves for $B<B_1$. If we compare the V-I behavior related to the motion of the interstitial vortices with the one observed in reference films without AL at a comparable field $\tilde{B}=B-B_1$, it turns out that the temperature region where flux flow occurs ($\alpha=1$) is much more extended in the latter case. Since it has been shown that in similar two-dimensional a-Nb_3Ge films[20] the pure flux flow region is a consequence of a Kosterlitz-

Thouless type melting of the vortex lattice, it seems that the presence of the vortices at the antidots increases the shear strength of the interstitial fluid and delays the melting of the interstitial lattice with respect to the vortex lattice in the reference film. As a consequence, a peculiar V-I behavior is found for the interstitial vortices.

In conclusion, we have studied flux motion in the presence of well-defined artifical periodic pinning arrays. A drastic reduction of the critical current for fields exceeding the first matching field B_1 has been found. From a crossover in the voltage-current [log(V)-log(I)] characteristics it is clear that this reduction is caused by the coexistence of a weakly pinned interstitial fluid and a strongly pinned vortex lattice at the antidots.

This work was supported by the Belgian National Fund for Scientific Research (NFWO) and Flemish Concerted Action (GOA) Programs. We would like to acknowledge useful discussions with Dr. V. V. Metlushko and Dr. T. Puig. E.R. was supported by the Belgian Interuniversity Institute for Nuclear Sciences (IIKW) M.V.B. by the NFWO, and M.B. by the Research Counsil at K. U. Leuven.

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