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Vortex Interactions in 2 x 2 Antidot Clusters

T. Puig, E. Rosseel, L. Van Look, M. Baert, M.J. Van Bael, R. Jonckheere*, V.V. Moshchalkov and Y. Bruynseraede

Laboratorium voor Vaste-Stoffysica en Magnetisme, K.U. Leuven, 3001 Leuven, Belgium
** Interuniversity Micro-Electronics Center, Kapeldreef 75, 3001 Leuven, Belgium*

Abstract. Vortex pinning effects by artificial antidots have been studied in superconducting 2 x 2 antidot clusters of $W_{1-x}Ge_x$ ($x \sim 0.33$) and Pb/Cu. These effects have been observed as several minima appearing in the magnetoresistance close to the transition temperature in magnetic fields between 0 and 100 G. Vortex configurations with one and two flux quanta per antidot and their related half-filling configurations have been found showing that different well controlled stable vortex configurations can be realised by tuning the magnetic field.

1. INTRODUCTION

Experimental studies of low temperature superconducting films and multilayers with a lattice of submicrometer holes or antidot lattice [1-4] have shown pronounced commensurability effects between the lattice of antidots and the vortex lattice. It has been proved that antidots with diameters comparable to the temperature dependent superconducting coherence length are good candidates to pin vortices, leading to a strong enhancement of the critical current in these systems. Studies on Pb and $W_{1-x}Ge_x$ films as well as Pb/Ge multilayers with regular arrays of a huge number of antidots (approximately 10^6) have been reported so far [2-4]. At the same time it is much easier to investigate the vortex-vortex interaction effects using a small number of antidots, i.e. "antidot clusters".

In the present paper we report the results of the investigation of the vortex-vortex interaction effects in 2 x 2 antidot clusters. This is the first attempt to study these antidot clusters which are interesting not only for fundamental science but also as potential elements for new quantum devices. It should also be noted here that a 2 x 2 cluster of a square Josephson network has been used before [5].

For the last few years, intensive efforts have been devoted to single electron tunneling effects in quantum dots [6]. The main interest towards these nanostructures is the possibility to use them to transmit binary information without using conventional microelectronics architectures [7]. Since the repulsion between vortices is similar to that between electrons, the ultimate purpose of studying the interaction between vortices in the 2 x 2 antidot clusters is to analyse the possibility to use them also as elements of a single flux quantum logic. In this case, vortices could be used instead of electrons and antidots instead of quantum dots.

In the same context, also superconducting Josephson junctions [8] and superconducting wire networks [9] have been studied for potential new microelectronic technologies based on quantum-mechanical principles. However, it has been shown [10] that interference effects can also be obtained in superconducting samples without Josephson weak-links, as long as these samples are in the mesoscopic regime. In superconductors, the mesoscopic regime is reached when the temperature dependent coherence length, $\xi(T)$, exceeds the sample size, L , ($\xi(T) > L$). In principle, since $\xi(T)$ diverges at the superconducting transition temperature, the above condition should always be satisfied close enough to T_c .

But, it is only in mesoscopic samples that the temperature interval, where $\xi(T) > L$, is sufficiently broad so that interference and quantization phenomena can be studied experimentally.

In this communication we will show that the quantization and interference effects are certainly present in our mesoscopic antidot clusters and that they give rise to well pronounced characteristic minima in the magnetoresistance. From a comparison between the experimental data and a simple theoretical model it is clear that a bistable state occurs, where two vortices with a higher flux quantum number occupy one of the cluster diagonals and another two vortices with a lower flux quantum number occupy the other diagonal. Due to the symmetry of our system, both diagonal states have the same energy and are thus equally probable. In order to make this structures interesting for applications, one has to be able to lift the degeneracy of these states, for example by introducing an interaction field that breaks the symmetry between the two diagonals. In this respect, the recent work of Davidovic et al. [10], who proved the existence of antiferromagnetic coupling between isolated neighbouring superconducting mesoscopic loops, could be used. Such a bistable state is promising for single flux quantum logic applications, however at the moment we still cannot distinguish experimentally between the two degenerated states.

We have studied antidot clusters made of two materials: $W_{1-x}Ge_x$ films and Pb/Cu bilayers. The choice of these materials was justified by the fact that these materials have been used for an extensive study on the matching phenomena in artificial periodic antidot lattices [2,4]. At the same time, these two materials offer the possibility to study the role of the different superconducting parameters on the magnitude of the observed quantum effects. An important length scale which enters the problem is the superconducting coherence length, $\xi(0)$. In the case of $W_{1-x}Ge_x$, $\xi(0)$ is very small in comparison with the antidot cluster dimensions while it is quite large for the Pb/Cu system. Our results show that the magnitude of the effect is larger in the Pb/Cu clusters thus proving that indeed a large $\xi(0)$ is crucial for the appearance of pronounced quantum phenomena.

2. EXPERIMENTAL

Clusters consisting of squares of $2 \times 2 \mu m^2$ with four antidots (i.e. microholes of $0.45 \times 0.45 \mu m^2$) separated by $0.95 \mu m$ were written in positive PMMA e-beam resist onto SiO_2 substrates. Both the $W_{1-x}Ge_x$ ($x \sim 0.33$) films and the Pb/Cu bilayers were evaporated in an MBE apparatus at a pressure of $\sim 5 \times 10^{-8}$ Torr onto liquid N_2 cooled substrates. After lift-off, the structures were thoroughly characterised by x-ray diffraction, scanning electron microscopy (SEM) and atomic force microscopy (AFM). Figure 1 shows an AFM picture of a 2×2 antidot cluster of Pb/Cu.

Figure 1: Atomic Force Microscopy (AFM) picture of a 2×2 antidot cluster of Pb/Cu.

The co-evaporated $W_{1-x}Ge_x$ samples had a thickness of 500 Å and a roughness of only 0.8 nm which is typical for these amorphous alloys and which is lower than the roughness of 1.4 nm, observed in the textured crystalline Pb/Cu bilayers. In the $W_{1-x}Ge_x$ samples, the Ge concentration was optimised to yield a maximum superconducting critical temperature, of about 4.5 K at a concentration of 33 %.

The Pb/Cu bilayers consisted of a 500 Å thick film of Pb with a layer of 175 Å of Cu on top. The Cu layer was used as a protective layer to prevent Pb oxidation and to enable electrical connection to the experimental apparatus using a wire bonding technique through the $150 \times 150 \mu\text{m}^2$ electrical pads of the sample. Figure 2 shows a SEM picture of the electrical pad layout.

Figure 2: Scanning Electron Microscopy (SEM) picture of the contact pad layout in the 2×2 antidot clusters

Since the Cu is a normal metal in close contact with the superconducting Pb, the Cu layer becomes superconducting due to the proximity effect and this influences the T_c of the system. A study of the Cu influence on the superconducting properties of Pb films showed that the transition temperature could be tuned by changing the thickness of the covering Cu layer. When no Cu was evaporated onto the Pb film a $T_c = 7.2$ K was achieved, while T_c was decreased to 5.3 K with 300 Å of Cu. Remarkably, the relevant superconducting parameter for our study, the in-plane superconducting coherence length, $\xi(0)$, did not change when increasing the Cu thickness up to 300 Å.

The transport properties were measured using an ac resistance bridge (LR400) in a ^3He cryostat equipped with a superconducting coil. The magnetic field was applied perpendicular the film's surface and a temperature stabilisation better than 0.4 mK was achieved. Since the mesoscopic samples are very sensitive and easily destroyed by electrostatic charges, all necessary grounding precautions were taken and 1.2 kΩ resistors were connected in series with each lead to damp parasitic voltage peaks.

The characteristic superconducting parameters were determined for both materials (see table 1).

	WGe	Pb/Cu
T_c	4.5 K	5.8 K
$\rho(5K)$	$280 \mu\Omega\text{cm}$	$25 \mu\Omega\text{cm}$
d	500 Å	500 Å
$\xi(0)$	6 nm	35 nm
$\lambda(0)$	490 nm	150 nm
$\Lambda = \lambda^2(0)/d$	4 μm	0.47 μm
κ	82	4.4

Table 1. Characteristic superconducting parameters for the $W_{1-x}Ge_x$ films and Pb/Cu bilayers

Note that the effective superconducting penetration depth, $\Lambda(T) = \lambda(T)^2/d$ (where d is the sample thickness) is very large in comparison with the antidot cluster dimensions for both systems. Thus the magnetic induction profile through the sample can be considered homogeneous in the temperature interval studied.

The $2 \times 2 \mu\text{m}^2$ reference samples without antidots were also fabricated to study the surface effects coming from the reduced dimensions of the sample and confinement of the superconducting condensate.

3. RESULTS AND DISCUSSION

Figure 3 shows the magnetoresistance of a $\text{W}_{1-x}\text{Ge}_x$ antidot cluster at 60 mK below T_c . The resistance values have been normalised by the resistance at 300 K. Characteristic steps appear at approximately 23 G and 46 G (see the arrows in Fig. 3), which are symmetric with respect to magnetic field reversal. These values of the magnetic field are approximately the ones expected for localisation of vortices with one and two flux quanta per antidot, respectively, for a distance between the antidots of $0.95 \mu\text{m}$. In fact, these features resemble very much the results obtained in $\text{W}_{1-x}\text{Ge}_x$ films with an antidot lattice [4], where clear features were present in the magnetoresistance at integer multiples of the matching field $H_1 = \phi_0/a^2$ (here ϕ_0 is the flux quanta per antidot and a the distance between antidots) corresponding to the formation of multiple quanta per antidot. At rational values of the matching field, $H = (p/q)H_1$ (with $p/q = 1/2, 1/3$ and $3/4$), smaller dips were observed showing that the interaction between vortices could lead to the formation of several energetically stable vortex phases.

Figure 3: Resistance as a function of the magnetic field for a 2×2 antidot cluster of $\text{W}_{1-x}\text{Ge}_x$ (o) at 60 mK below the transition temperature. Also shown (•) is the resistance versus magnetic field of the reference sample without antidots at 60 mK below T_c . The resistance values have been normalised to the resistance at 300 K.

In the $\text{W}_{1-x}\text{Ge}_x$ antidot cluster, the amplitude of the effects is very small. We can distinguish the matching fields H_1 and H_2 , however it is difficult to identify in a reliable way any structure at rational matching fields. The comparison with the reference sample without antidots (see straight line in figure 3) clearly shows that the characteristic features appearing at the matching fields are due to pinning of vortices by the antidots.

Figure 4 shows the magnetoresistance of a Pb/Cu antidot cluster at 20 mK below T_c . In this case, pronounced minima can be observed at the matching fields $H_1 = 24$ G and $H_2 = 48$ G, corresponding to one and two flux quanta per antidot. In addition, minima also appear at $H_{1/2}$ and $H_{3/2}$. The latter fields being related to a half filling configuration, i.e. two antidots have a flux quantum number higher than the other two. Therefore, it is clear that close to the transition temperature, these clusters are able to localise vortices at the antidots and that several stable configurations can be obtained by tuning the magnetic field.

Figure 4: Resistance as a function of the magnetic field for a 2×2 antidot cluster of Pb/Cu at 20 mK below the transition temperature. The resistance values have been normalised to the resistance at 300 K

Note that the vortices pinned by these antidots are not the typical type II Abrikosov vortices. They have cores coinciding with the antidots and consist of screening currents which are induced to maintain fluxoid quantization. Fluxoid quantization is defined as [12]:

$$\phi^* = \int \vec{B} \cdot d\vec{s} + \frac{m}{2e} \oint \vec{v}_s \cdot d\vec{l} = n\phi_0 \quad (1)$$

where v_s is the superconducting velocity, m the electron mass and e the electron charge. The first term in Eq. 1 gives the flux enclosed in the antidot while the second term refers to the screening currents surrounding the antidot. The flux in the antidot continuously increases as the magnetic field is increased and therefore it is not quantised. The second term in Eq. 1 is usually not zero, and only when the first term is equal to $n\phi_0$ the screening currents vanish [13]. This is certainly the case in our mesoscopic antidot clusters where fluxoid quantization leads to the generation of the current to compensate for the non-quantized flux at the antidots.

In addition, since the interaction between the screening currents or vortices is repulsive [14], vortices with an equal quantum number will always occupy diagonals at $H = H_{(2n+1)/2}$. This has also been confirmed by calculations carried out in the London limit $|\psi| \equiv \text{const}$, which is valid close enough to T_c where the dimensions of the cluster are smaller than $\xi(T)$. The calculations show that the “diagonal” vortex configurations are always more stable than the “parallel” states [15]. In figure 4, we have shown the schematic representation of the quantum number in each antidot of the cluster, for each resistance minima obtained from these calculations. Note that the features appearing at 12 G and 36 G allow us to define two

logic states (the two possible diagonal vortex states). In these measurements, the two logic states are still degenerated, however further work is under way to lift this degeneracy.

4. CONCLUSIONS

Studies of transport properties of 2×2 antidot clusters of $W_{1-x}Ge_x$ and Pb/Cu as a function of the magnetic field have revealed pronounced interference effects. We have shown that vortices are pinned by the antidots of the cluster and that there exists a strong interaction between them. Several stable vortex configurations have been indentified which are related to vortices of n flux quanta per antidot but also to half filling configurations where the antidots of one diagonal have larger flux quantum number ($n+1$) than the ones on the other diagonal (n). It is clearly demonstrated that the Pb/Cu samples are better than the $W_{1-x}Ge_x$ samples for this kind of study and thus a large superconducting coherence length, $\xi(0)$, is crucial for the realisation of a sufficiently large amplitude of the observed quantum effects.

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