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Physica B 284–288 (2000) 893–894

PHYSICA B

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Flux pinning by magnetic dots with in-plane magnetization

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Abstract

Flux pinning is studied in superconducting Pb films with a lattice of sub-micron Co dots. Matching anomalies are observed in the magnetization curves, corresponding to stable vortex configurations in the periodic pinning potential created by the lattice. By comparing magnetic dots (Co) with different stray field strengths and non-magnetic dots (Ge, Au), a pronounced enhancement of the pinning efficiency by the local stray field of the Co dots is demonstrated. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Artificial pinning arrays; Flux pinning; Magnetic dots

The study of the magnetic flux line lattice (FLL) in a type-II superconductor with an artificial pinning array has gained a lot of attention in the past few years [1–5]. A periodic pinning potential gives rise to a huge enhancement of the critical current (up to its theoretical limit, the depairing current), interesting matching effects appear due to the stabilization of commensurate FLLs, and new FLLs are created which could not be formed in a homogeneous superconductor. Whereas usually thickness modulations or sub-micron holes have been used as artificial pinning centres [1–5], it was shown recently that also ferromagnetic dots act as efficient pinning centres [6–9]. We focus in this paper on the effect of the *local magnetic stray field of magnetic dots* on the pinning efficiency.

The system studied is a 50 nm Pb film on top of a square array (period $a = 1.5$ μm) of Au(7 nm)/Co(20 nm)/Au(7 nm) dots with lateral dimensions of 360 nm × 540 nm (easy axis). These hybrid superconducting-ferromagnetic structures are fabricated by combining e-beam lithography and MBE techniques [9]. Characterization of the dot array by magnetic force microscopy (MFM) indicates that all dots are initially multi-domain, whereas after saturation along the easy axis they retain a single-domain remanent state [9]. Since single-domain dots create much stronger local stray fields compared to multi-domain dots, the influence of the stray field can be studied by comparing the pinning effects in the same sample before and after magnetizing the dots.

SQUID magnetization measurements ($M(H)$) were performed in a perpendicular field. Fig. 1 shows the $M(H)$ loops of the hybrid system for T very close to the critical temperature ($T_c = 7.2$ K) before and after the dots are magnetized. $H_1 = \phi_0/(1.5\ \mu m)^2 = 9.2$ G represents the first matching field for which the density of flux lines equals the density of dots. In both curves, clear matching anomalies are visible: a huge drop at $H/H_1 = 1$, and peaks at $H/H_1 = 2$ and 3, which are due to the formation of stable FLLs that are commensurate with the underlying pinning array [4,5]. A clear influence of the stray field can be noticed when comparing the $M(H)$ curves for the magnetized and the non-magnetized dots. The difference of $M(H)$ for the magnetized and non-magnetized dots is shown in the inset of Fig. 1. After magnetizing the dots (i) $M(H)$ is further increased, indicating stronger pinning; (ii) the matching anomalies are much more pronounced; and (iii) additional matching anomalies appear (e.g. at $H_1 = \frac{3}{2}$). For comparison, we also studied the pinning phenomena in similar Pb films on identical square lattices of non-magnetic insulating (Ge) and metallic (Au) dots. In all hybrid systems we observed (i) a strong

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PII: S0921-4526(99)02209-7

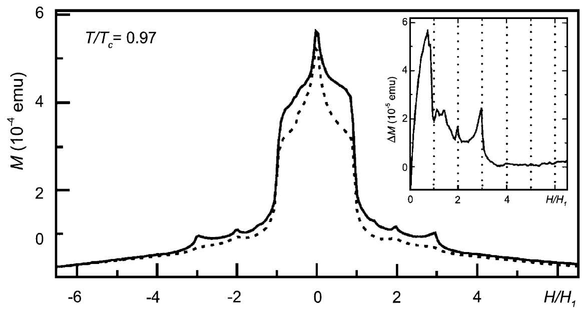

Fig. 1. $M(H/H_1)$ curve at $T/T_c = 0.97$ of a Pb film on top of a square array of Au/Co/Au dots before (dashed line) and after (full line) the dots are magnetized.

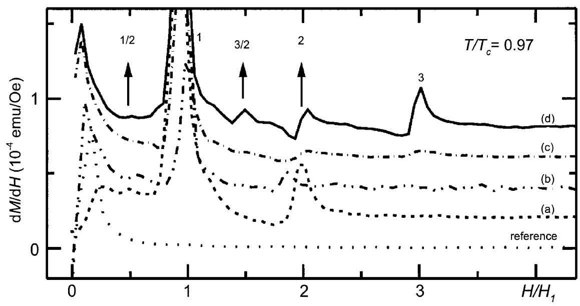

Fig. 2. $-\,dM/dH(H/H_1)$ curves for a Pb film on a square lattice of (a) Ge-, (b) Au-, (c) non-magnetized, and (d) magnetized Au/Co/Au dots and for a reference 50 nm Pb film. The curves are vertically shifted for clarity.

enhancement of $M(H)$ compared to a reference Pb film without dots and (ii) matching anomalies at specific multiples of H_1. This indicates that an important pinning contribution also arises from the structural and geometric defects in the Pb film near the dot edges due to the dots underneath the Pb film. Fig. 2 shows the derivative dM/dH for the different hybrid systems. Comparing the magnetic (Au/Co/Au) with the non-magnetic (Ge and Au) dots, we observe that the magnetic dots result in more matching anomalies in a broader field range.

Our experiments hence indicate that the dots with the strongest stray field provide the most effective pinning. A stronger stray field locally suppresses superconductivity around the dot, creating a more effective pinning centre. After the dots are magnetized, all dots exhibit exactly the same stray field pattern, which enhances the order of the pinning potential, thus providing an additional contribution for the enhanced matching effects after magnetization of the dots [10].

Acknowledgements

Supported by the Fund for Scientific Research-Flanders (FWO), the Flemish Concerted Action (GOA), the Interuniversity Poles of Attraction (IUAP), and the ESF VORTEX Programs. MJVB and KT are Postdoctoral Research Fellows of the FWO.

References

[1] M. Baert et al., Phys. Rev. Lett. 74 (1995) 3269.
[2] V.V. Moshchalkov et al., Phys. Rev. B 54 (1996) 7385.
[3] V.V. Moshchalkov et al., Phys. Rev. B 57 (1998) 3615.
[4] K. Harada et al., Science 274 (1996) 1167.
[5] C. Reichhardt et al., Phys. Rev. B 57 (1998) 7937.
[6] J. Martín et al., Phys. Rev. Lett. 79 (1997) 1929.
[7] D.J. Morgan et al., Phys. Rev. Lett. 80 (1998) 3614.
[8] Y. Nozaki et al., J. Appl. Phys. 79 (1999) 8571.
[9] M.J. Van Bael et al., Phys. Rev. B 59 (1999) 14 674.
[10] C. Reichhardt et al., Phys. Rev. B 54 (1996) 16 108.