Applied Physics Letters

High magnetic field matching effects in NbN films induced by template grown dense ferromagnetic nanowires arrays

X. Hallet, M. Mátéfi-Tempfli, S. Michotte, L. Piraux, J. Vanacken et al.

Citation: Appl. Phys. Lett. **95**, 252503 (2009); doi: 10.1063/1.3276557
View online: http://dx.doi.org/10.1063/1.3276557
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v95/i25
Published by the American Institute of Physics.

High magnetic field matching effects in NbN films induced by template grown dense ferromagnetic nanowires arrays

X. Hallet,[1,a)] M. Mátéfi-Tempfli,[1] S. Michotte,[1] L. Piraux,[1] J. Vanacken,[2] V. V. Moshchalkov,[2] and S. Mátéfi-Tempfli[1]
[1]*Unité de Physico-Chimie et de Physique des Matériaux, Université Catholique de Louvain (UCL), Place Croix du Sud 1, B-1348 Louvain-la-Neuve, Belgium*
[2]*Institute for Nanoscale Physics and Chemistry, Katholieke Universiteit Leuven, Celestijnenlaan 200D, 3001 Leuven, Belgium*

(Received 17 November 2009; accepted 29 November 2009; published online 22 December 2009)

Dense arrays of ordered ferromagnetic nanowires have been used to create periodic magnetic pinning centers in thin superconducting NbN films. The nanowires were electrodeposited in a highly ordered porous alumina membrane and the thin NbN film was deposited on top of the perpendicularly oriented magnetic nanowires. Matching effects have been observed up to 2.5 T (11th matching field) and are maintained at low temperature. An appreciable enhancement of the superconducting properties is observed. At low fields, a hysteretic behavior in the magnetoresistance is found, directly related to the magnetization processes of arrays of interacting single domain ferromagnetic nanowires. © *2009 American Institute of Physics*. [doi:10.1063/1.3276557]

One of the most important issues for applications of type-II superconductors is the achievement of very high critical currents. This involves a strong pinning of the vortices. For this purpose, defects in the superconductor can act as pinning centers. Using lithographic techniques, the effect of periodic lattice of artificial pinning centers (holes,[1] blind holes,[2] etc.) on the superconducting properties of thin films has been studied extensively. These periodic pinning centers lattices induce a global increase in the critical current of the films through the so-called matching effect. Such enhancement of the critical current results from the commensurability of the vortex lattice with the pinning lattice and it leads to enhanced superconductivity at specific values of the magnetic field. More recently, there has been a lot of interest in the use of ferromagnetic materials as pinning centers.[3–5] Indeed, the magnetic field produced by the individual ferromagnets attracts the vortices, thus enhancing the critical current. In addition, the magnetic pinning force can be tuned simply by varying the magnetic moment[4] and may also lead to a magnetic field-induced superconductivity[5] at high magnetization values.

However, up to now the observation of these effects were restricted to relatively low magnetic fields (due to relatively large pinning lattice parameters), to temperatures very close to the superconducting transition and to low T_c superconductors. This is because lithographic techniques are not able to produce, in a time and cost efficient manner, large area pinning lattices with a small period. Alternative methods to the lithographic patterning using templates of self-assembled nanostructures and of nanoporous materials are promising approaches for applications. Nanoporous alumina templates were used to produce an antidots lattice in a thin superconducting film.[6] Very recently, the barrier layer of a highly ordered alumina template was used as a template to create dense arrays of pinning centers in thin superconducting films.[7] In this letter, we report on the fabrication and properties of superconducting thin films nearby large-area of dense arrays of ferromagnetic nanowires aligned perpendicular to the film. A highly ordered nanoporous alumina membrane is used to grow electrochemically an array of long ferromagnetic nanowires (Ni or Co) arranged parallel to each other and with small wire interdistance. Then, a superconducting thin film is sputtered on the top face of the filled template, thus nearby the nanowire array, to induce a strong periodic pinning potential. Numerous matching effects are found as well as a strong enhancement of the critical current at high magnetic fields. In addition a hysteretic behavior in the magnetoresistance is found at low fields, directly related to the magnetization processes of the interacting single domain ferromagnetic nanowires.

The nanoporous alumina templates are made using a conventional two step anodization process. Details about this fabrication process can be found elsewhere.[8] In this study, we used long-range ordered 50 μm thick membranes with a pitch (d) of 100 nm. The diameter (ϕ) of the pores was adjusted to 60 and 75 nm, respectively, by chemical etching. Then, a metallic cathode was evaporated on one side of the porous membrane followed by a conventional pulsed electrodeposition in order to grow the nanowires.[9] Subsequently, a mechanical polishing using 20 nm silica particles was performed to remove the cathode and to get the extremities of

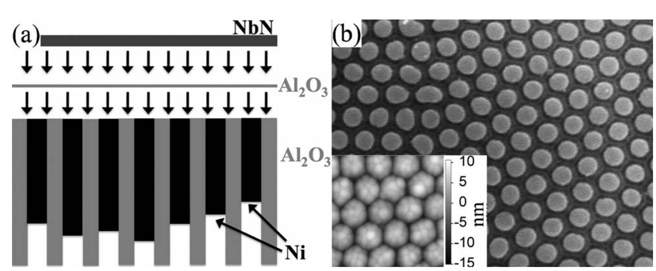

FIG. 1. (a) Schematic representation showing the deposition of a 10 nm thick Al_2O_3 insulating layer and of a 25 nm thick NbN film on the extremities of an array of Ni nanowires embedded in a nanoporous alumina template. (b) SEM image of the surface of the filled template after the polishing step. The inset shows the AFM picture of the surface after the evaporation of the insulating layer.

a)Electronic mail: xavier.hallet@uclouvain.be.

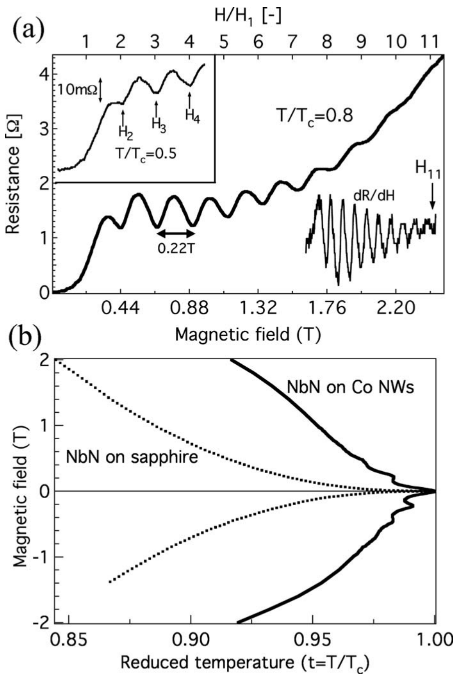

FIG. 2. (a) Magnetoresistance curve at $T/T_c=0.75$ for a 25 nm thick NbN film on top of an array of 75 nm in diameter Ni nanowires ($T_c=9.45$ K). Top inset: same magnetoresistance curve at $T/T_c=0.5$. Bottom inset: derivative of the curve obtained at $T/T_c=0.75$. (b) Superconducting to normal state transition line for a 25 nm thick NbN film deposited on top of an array of 60 nm in diameter Co nanowires (solid line) and on a flat sapphire substrate (dotted line).

all the nanowires at the surface of the template. Finally, a thin insulating layer of Al_2O_3 (5–10 nm thick) was evaporated and a 25 nm thick NbN film was reactively sputtered on the surface [Fig. 1(a)]. Prior to deposition of the superconducting thin films, the surface cleanliness, and the percentage of pore filling were checked by scanning electron microscopy (SEM). Figure 1(b) shows a typical SEM image obtained after the polishing step. The percentage of pore filling is estimated to be 99%. Atomic force microscopy (AFM) characterization of the surface was also made [inset of Fig. 1(b)] revealing that the extremities of the nanowires are approximatively 20 nm above the template surface. This effect can be explained by the difference in the polishing rates between the alumina template and the metallic nanowires embedded into it.

The samples have been investigated using magnetotransport measurements. Figure 2(a) shows a magnetoresistance curve at $T/T_c=0.75$ for a 25 nm thick NbN film on top of an array of Ni nanowires ($\phi=75$ nm; $d=100$ nm). In Fig. 2(a), the magnetoresistance is recorded with the applied magnetic field sweeping from zero up to 2.5 T. At zero field, the nanowires are in a remanent magnetic state, as obtained starting at positive saturation of the magnetization. Numerous oscillations, caused by matching effects are visible, showing the strong influence of the pinning center array on the vortex lattice. The oscillations are observed over the whole magnetic field range, i.e., up to 2.5 T as depicted from the derivate curve in the bottom inset of Fig. 2(a). The matching magnetic fields are in good agreement with what is expected for a triangular lattice ($d=100$ nm), i.e., $B_n=n \times \frac{2\phi_0}{\sqrt{3}d^2} \approx n\times 0.22$ T. The upper magnetic field refers to the 11th matching field. It should be emphasized that matching effects have never been reported at such high magnetic fields. This results from the high degree of ordering and small interdistance of the nanowire array embedded in the alumina membranes used in this work. In addition, at the temperatures considered in Fig. 2(a), the small spacing between the pinning centers is of the order of the coherence length. As a result, the thin film behaves in fact more like a one-dimensional wire network. Such networks are known to show numerous matching effects since no vortices can be placed in the interstitial sites.[10] Another advantage of our system is that the matching features are maintained at low temperature ($T/T_c=0.5$) as shown in the top inset of Fig. 2(a). This is generally desired for practical applications involving low T_c superconductors cooled at liquid helium temperature.

Figure 2(b) compares the superconducting phase diagram for a 25 nm thick NbN film sputtered on an array of Co nanowires ($\phi=60$ nm; $d=100$ nm—solid line) with the one obtained for the same NbN film deposited on a flat sapphire substrate (dotted line). Superconductivity takes place below the corresponding curves. The critical magnetic field is strongly enhanced, which means that the sample can be used at much higher fields before vortices start to move causing dissipation.

Figure 3(a) shows the magnetoresistance curve for a 25 nm thick NbN film deposited on an array of Ni nanowires (60 nm diameter) at $T/T_c=0.8$. The resistance of the sample was measured when the external field was swept from positive saturation down to negative saturation (solid) and then the field is swept back to positive saturation (dotted). A hysteretic behavior is clearly observed at low field, demonstrating the strong influence of the magnetic state of the nanowires array on the superconducting properties of the NbN film.

The magnetization curves of the same sample measured by superconducting quantum interference device magnetometry (above T_c at 15 K) is presented in Fig. 3(b). Low diameter, high aspect ratio magnetic nanowires present a behavior close to that of an ideal infinite cylinder that has a square hysteresis loop and where each nanowire has only two stable states magnetized perpendicularly to the membrane, identical in magnitude but opposite in direction. However, due to the spread in their structural features, the assembly of wires obeys a coercive field distribution, which arises from inhomogeneities in features such as wire length, diameter dispersion, and specific microstructure of each wire. In addition, in dense arrays of magnetic nanowires, dipolar interaction becomes important and may even weaken the perpendicularly magnetized state.[9]

Schematic representation of the magnetic state of the nanowires array is shown in Fig. 3(b). During a cycle with H applied along the wire axis, the magnetization will reverse from the positive to negative saturation during the descending part, and from negative to positive saturation on the ascending part of the cycle. The reversal of the magnetization of the entire array from one saturated state to the other corresponds to the successive reversal of individual nanowires. Sweeping back the field to zero from a positive saturation, it is seen in Fig. 3(b) that a fraction of wires (about 19%) already experience a reversal due to the interwire dipolar interaction.

Considering now the first positive matching field H_1 at 0.22 T, we can observe that a relatively small difference in the overall magnetization state of the nanowire array leads to a large change in the magnetoresistance curve of the superconducting thin film depending on whether the field is swept from positive saturation or from negative saturation. As the field is decreased to H_1 from positive saturation, a pronounced drop in the resistance is observed. In this case, all the nanowires are magnetized up, which results in a strong periodic pinning potential. In contrast, if the field is decreased from negative saturation to zero field and then increased to the positive field value H_1 (dotted curve), only a small decrease in the resistance is observed around 0.22 T. From the hysteresis loop shown in Fig. 3(b), it appears that about 15% of the nanowires are still magnetized down, giving rise to a strong perturbation to the periodic pinning potential and leading to a weakened matching effect, as shown in Fig. 3(a).

The same argument can be invoked to explain the absence of resistance drop in Fig. 2(a) at the first matching field (H_1=0.22 T) for the sample with the 75 nm in diameter Ni nanowires array, in which the dipolar coupling is even stronger. In this case, the field is swept from zero field (in the remanent state obtained from positive saturation) to 2.5 T. Therefore, at the first matching field, about 20% of the nanowires are still magnetized down leading to a strongly disordered pinning potential. As a whole, these results clearly indicates that the strong pinning of the vortices is mostly caused by the magnetic pinning potential induced by the ordered array of ferromagnetic nanowires rather than from the height modulation at the surface of the filled template.

It is important to mention that this template method is quite tunable, thus making possible to design the pinning potential. Electrodeposition into nanoporous templates enables to prepare a variety of ferromagnetic nanowires arrays, with both their diameter and density controlled to a large extent. In addition, the diameter of the pores can be adjusted in a range of 40%–80% the interpore distance. Finally, the thickness of the superconducting film and the distance between the film and the nanowire array can also be changed easily.

In conclusion, we used nanoporous alumina templates to grow dense arrays of ferromagnetic nanowires serving as magnetic pinning centers in nearby NbN thin films. Matching effects have been observed up to 2.5 T which corresponds to the 11th matching field. Such large matching fields are typically one order of magnitude higher than what has been previously reported using lithographically defined magnetic pinning patterns. Matching effects are maintained down to relatively low temperature (T/T_c=0.5). An appreciable enhancement of vortex pinning has been observed at high fields. The magnetic interaction between the nanowires array and the thin superconducting film was undoubtedly recognized as the major pinning mechanism. A hysteretic behavior of the magnetoresistance was found at low field due to the magnetization reversal process of the array of interacting single domain nanomagnets.

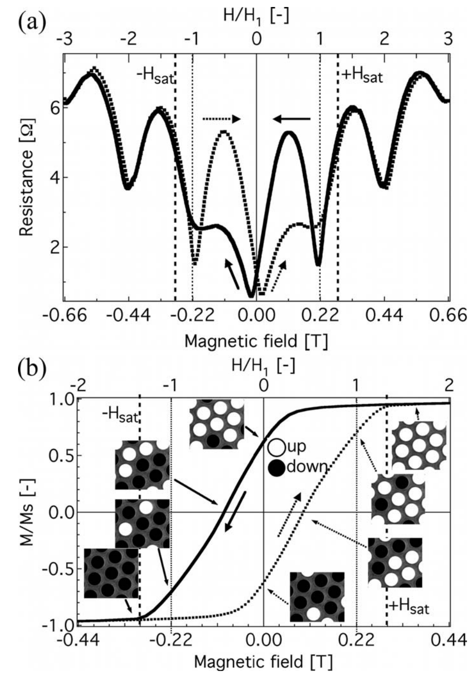

FIG. 3. (a) Magnetoresistance curves for a 25 nm thick NbN film on 60 nm diameter Ni nanowires array at T/T_c=0.8. The field was swept from positive to negative saturation (solid curve) and from negative to positive saturation (dotted curve). (b) Corresponding magnetization curve of the same sample above T_c.

X.H. is a Research Fellow of the National Fund for Training in Research in Industry and Agriculture (FRIA), Belgium. This work was partly supported by the Interuniversity Attraction Pole Program (P6/42)—Belgian State—Belgian Science Policy and Methusalem Funding (METH/08/05). We thank B. Nysten (UCL) for the AFM measurements.

[1]A. T. Fiory, A. F. Hebard, and S. Somekh, Appl. Phys. Lett. **32**, 73 (1978).
[2]A. Bezryadin, Yu. N. Ovchinnikov, and B. Pannetier, Phys. Rev. B **53**, 8553 (1996).
[3]D. J. Morgan and J. B. Ketterson, Phys. Rev. Lett. **80**, 3614 (1998); A. Yu Aladyshkin, A. V. Silhanek, W. Gillijns, and V. V. Moshchalkov, Supercond. Sci. Technol. **22**, 053001 (2009); I. F. Lyuksyutov and V. L. Pokrovsky, Adv. Phys. **54**, 67 (2005).
[4]W. Gillijns, A. V. Silhanek, and V. V. Moshchalkov, Phys. Rev. B **74**, 220509 (2006).
[5]M. Lange, M. J. Van Bael, Y. Bruynseraede, and V. V. Moshchalkov, Phys. Rev. Lett. **90**, 197006 (2003).
[6]U. Welp, Z. L. Xiao, J. S. Jiang, V. K. Vlasko-Vlasov, S. D. Bader, G. W. Crabtree, J. Liang, H. Chik, and J. M. Xu, Phys. Rev. B **66**, 212507 (2002).
[7]X. Hallet, M. Mátéfi-Tempfli, S. Michotte, L. Piraux, J. Vanacken, V. V. Moshchalkov, and S. Mátéfi-Tempfli, Small **5**, 2413 (2009).
[8]H. Masuda and K. Fukuda, Science **268**, 1466 (1995).
[9]K. Nielsch, R. B. Wehrspohn, J. Barthel, J. Kirschner, U. Gösele, S. F. Fischer, and H. Kronmüller, Appl. Phys. Lett. **79**, 1360 (2001).
[10]B. Pannetier, J. Chaussy, R. Rammal, and J. C. Villegier, Phys. Rev. Lett. **53**, 1845 (1984).