Carpet of magnetic colours

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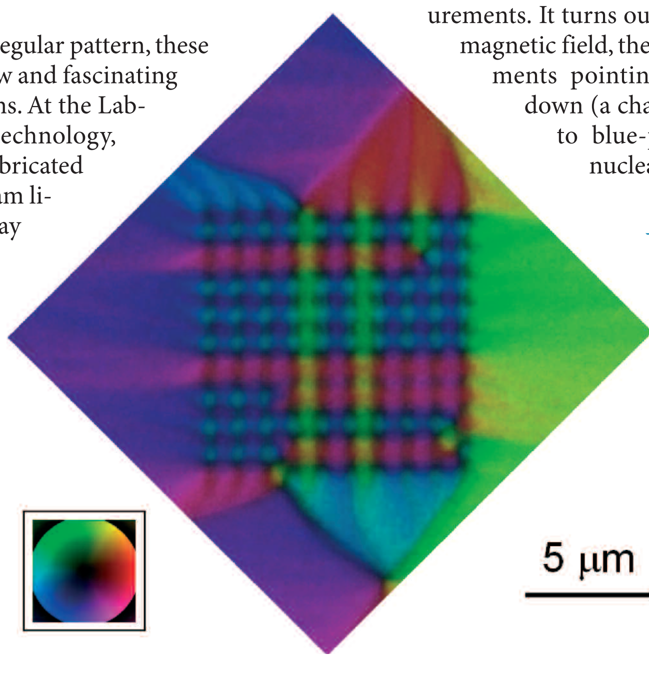
COULD Néel have anticipated in 1944 that his prediction of how magnetic domains form around a cavity [1] would provide inspiration in the nanoworld to use sub-micrometer holes to engineer the properties of magnetic thin films? When Williams experimentally observed magnetic domains under an optical microscope in 1947 [1], could he have imagined the tiny length scales at which we image and identify complex magnetic structures today? The pace of development in lithography methods and imaging techniques in recent years is breathtaking, yielding new scientific discoveries and miniature devices. The opportunity to significantly reduce the lateral dimensions of thin films has led to a revolution in the area of magnetic materials, with nanoscale magnetic elements and their interaction with electric current providing novel sensor and data storage applications. In order to be able to make useful devices, we need to understand how the individual magnetic components function and, while one can perform macroscopic electrical or magnetic measurements, it is important to directly observe at the nanoscale how the magnetic moments behave.

Domains in ferromagnetic materials are regions where the magnetic moments are aligned parallel to each other. They are separated by domain walls; a region where the moments rotate from one domain orientation to the other, reminiscent of the grain boundaries separating grains with different crystal orientations in a polycrystalline material. In the mid-20th century, Néel and Williams predicted and showed that in the presence of a cavity, the magnetic moments align parallel to the cavity edges. This reduces the magnetic field emanating from the walls of the cavity, so minimising the energy of the magnetic system and resulting in a modification of the magnetic domain patterns. Using modern lithography techniques we can now produce Néel's cavities with nanoscale dimensions in ferromagnetic thin films.

Arranged very precisely in a regular pattern, these so-called antidot arrays have new and fascinating properties at reduced dimensions. At the Laboratory for Micro- and Nanotechnology, Paul Scherrer Institut we have fabricated antidot arrays using electron beam lithography to create a square array of holes in a cobalt thin film with periods down to 100 nm. We directly observed the magnetic configurations [2] employing photoemission electron microscopy (PEEM) using synchrotron radiation at the Swiss Light Source which provides magnetic information at high spatial resolution. With these observations we were able to determine how these antidot arrays influence the magnetic moments in the layer. Specifically, the cavities dictate the orientation and position of the domain walls, resulting in periodic patterns commensurate with the hole array. The Figure shows a two dimensional map of the magnetic moments in one of the antidot arrays, here with a period of 1 µm. At first sight, the image looks like a carpet with an intricate, unfathomable design. Taking a closer look, it is possible to identify orthogonal chains of magnetic domains, given by lines of colour running vertically (magnetic moments pointing upwards or downwards) or horizontally (magnetic moments pointing to the left or to the right).

It has been known for some time that the introduction of nanoscale antidot arrays into a magnetic thin film will significantly modify the magnetic properties, resulting in novel magnetic domain configurations and additional magnetic anisotropies [3-6]. These properties can be tuned by modifying the hole shape, size and symmetry. In particular, this changes the way in which the system switches from one magnetic state to another, in other words, how the orientation of the magnetic moments change in an applied magnetic field. An understanding of how this switching occurs, which is important for the control of new magnetic devices, can be achieved by imaging the magnetic configurations. A few images of antidot arrays have already been published [3-6], but very little has been reported about the way in which these configurations develop in a magnetic field. Our first observations with the PEEM [7] gave a hint of cooperative behaviour; we observed that the domains formed in chains, seen as lines of colour in the Figure. In a more comprehensive investigation we were able to uncover the details of switching processes [2] behind the hysteresis loops (field versus magnetisation curves) obtained from magneto-optical Kerr effect measurements. It turns out that on application of a vertical magnetic field, the switching from all magnetic moments pointing up to all moments pointing down (a change in colour from green-yellow to blue-pink in the Figure) occurs by nucleation and propagation of vertical



◀ **Fig. 1:** Magnetic Carpet; A two dimensional colour map of the magnetic configuration in a 10 nm – thick cobalt film with an array of 10 by 10 square holes (size = separation = 500 nm). Lines of colour corresponding to chains of magnetic domains can be seen: running vertically (magnetic moments pointing upwards - green/yellow, or downwards - blue/pink); or horizontally (magnetic moments pointing to the left – dark blue/light blue/green, or to the right - pink/red/yellow).

chains of domains. The vertical domain chain configuration (length and position of chains running from bottom to top in the Figure) is highly dependent on the presence of the horizontal domain chains (those running from left to right). Comparing our PEEM observations with micromagnetic simulations, we were then able to identify the key mechanisms responsible for the observed behaviour: **1)** the ends of orthogonal chains prefer to coincide because they form a stable domain wall configuration and **2)** as the linear chains grow, the moving chain end is blocked by a horizontal chain due to the formation of high angle domain walls.

The antidot arrays have allowed us to observe the details of nucleation, propagation and pinning of magnetic domains in a regular array of nanoscale defects. We found that the final colour design of this magnetic carpet is not only determined by the arrangement of the cavities, but also strongly depends on the pre-existing magnetic configuration, which is in turn dependent on the applied magnetic field history in terms of strength and orientation. The ability to trap the domain walls present at the ends of the domain chains via the existing magnetic structure is potentially interesting for engineering of new magnetic nanoscale devices which exploit domain walls to store information or perform logic operations [8].

The uncovering of the nature of nanoscale antidot arrays has only been possible due to the fruitful collaboration with D. Backes, S. Czekaj, L. Lopez-Diaz, M. Kläui, U. Rüdiger, C.A.F. Vaz, J. A. C. Bland, R. J. Matelon, U. G. Volkmann, P. Fischer and M. Horisberger. ■

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