Electronic Supplementary Material

High-yield fabrication of perpendicularly magnetised synthetic antiferromagnetic nanodiscs

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Experimental methods

Growth of metallic films

All magnetic stacks were grown at room temperature (RT) in a direct current magnetron sputtering system with a base pressure of ~ 2–8×10^{-8} mbar and an Ar pressure of ~ 7–8×10^{-3} mbar. Single layer stacks were grown in the form Ta(2)/Pt(4)/CoFeB(0.9)/Pt(4)/Ta(2) (thicknesses in nm). Here, CoFeB is our magnetic layer, Pt creates perpendicular anisotropy and Ta is used as a smoothing/capping layer. The synthetic antiferromagnetic (SAF) bilayer series was grown in the form Ta(2)/Pt(4)/CoFeB(0.9)/Pt(t_{Pt})/Ru(0.9)/Pt(t_{Pt})/CoFeB(0.9)/Pt(4)/Ta(2) (thicknesses in nm), where t_{Pt} was varied from 0.41–0.69 nm. Here, Ru gives the Ruderman-Kittel-Kasuya-Yoshida (RKKY) coupling and the thinner Pt interlayers are used to tune this coupling: thicker Pt reduces the coupling [S1,S2]. The nanodiscs of different sizes were fabricated from a thin film of the form Ta(2)/Pt(2)/CoFeB(0.9)/Pt(0.3)/Ru(0.9)/Pt(0.3)/CoFeB(0.9)/Pt(2)/Ta(2) (thicknesses in nm). The double SAF stack discs were made from a thin film of the form Ta(2)[/Pt(2)/ CoFeB(0.9)/Pt(t_{Pt})/Ru(0.9)/Pt(t_{Pt})/CoFeB(0.9)/Pt(2)/Ta(2)]$_2$, where t_{Pt} = 0.45 and 0.3 nm.

Al underlayers and caps were grown in the sputtering system, with a magnetron power of ~ 200 W at an Ar pressure of ~ 8–9×10^{-3}. The Ge underlayers were grown via thermal or electron beam evaporation. All samples were grown on Si prime wafers from University Wafer.

Nanoparticle lithography

Polystyrene (PS) beads with a carboxylate or sulphate coating were obtained from Polybead®, Polysicence Inc. They were diluted in deionised water as necessary: 100 nm beads diluted 2:1, 200 nm beads diluted 1:1 and the others undiluted. The spin coating recipe consisted of two stages: (1) a slow spin at 200 rpm to spread out the beads evenly and (2) a fast acceleration (~ 1000 rpm/s) up to the much higher speed of 8000 rpm to order, adhere and dry the beads.

Plasma ashing of the thin film, for cleaning prior to PS bead application, and of the spin coated beads, to shrink them, was performed with an oxygen plasma etcher at a power of 20 W.

Ar ion milling was used to cut out the nanodiscs from the thin film. This was done with an Ar pressure of ~ 1.6×10^{-3} mbar, a beam current of 28 mA and a beam voltage of 600 V. Under these conditions, a SAF stack took ~ 40 s to mill through and the Al caps milled at a rate of 0.32 nm/s.

Al caps were removed by dissolving in ma-D 533/S photoresist developer (a tetramethylammonium hydroxide based solvent), a TMAH based solvent, from micro resist technology GmbH, which took <1 min. The Ge sacrificial layers were removed by dissolving in a 35 wt. % H_2O_2 solution in water, during the 10 min soaking step.

Magnetic characterisation

Magnetic measurements of the thin films and nanoparticles were made using RT polar magneto-optical Kerr effect (MOKE) with a NanoMOKE3 system from Durham Magneto Optics Ltd. The laser spot size of the system is ~ 5 μm, meaning that a measurement of the nanodiscs prior to lift-off is an average over a number of particles, whilst it is possible to measure single particles after lift-off and redeposition, providing they are separated out across the sample. RT VSM was additionally used to assess the thin films, in both easy (out of plane) and hard axis (in plane) configurations, and the particles in a liquid suspension. Domain imaging was performed by RT polar MOKE laser scanning microscopy.

From the easy axis MOKE loops (see Fig. S1) we obtain the RKKY coupling field, H_J: the field that is halfway between the switching fields for the antiparallel (AP) to parallel (P) transition and the P to AP transition in the minor loop. The coercivity field, H_C, is half the difference between these two transitions, such that $H_J + H_C = H_{EA}$ where H_{EA} is the easy axis saturation field.

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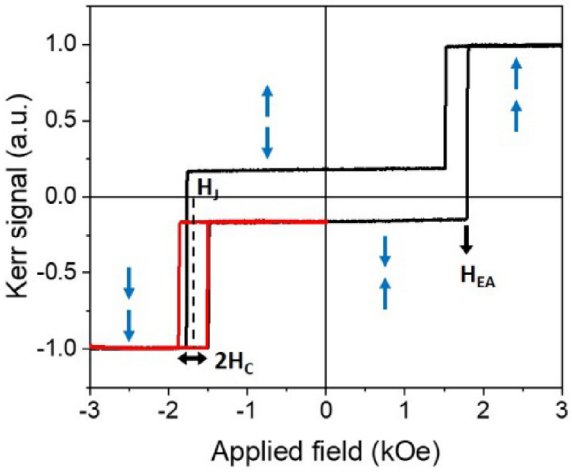

Figure S1 Diagram showing how the magnetic variables are obtained from easy axis major (black) and minor (red) hysteresis loops of a thin film. The blue arrows represent the direction of magnetisation of each of the CoFeB layers.

Morphological characterisation

Scanning electron microscopy images were taken with an FEI FEG XL30 system with a beam voltage of 5 keV. Atomic force microscopy (AFM) measurements were made with a Park Systems XE-100 AFM in non-contact mode. AFM data was processed using the program Gwyddion.

Supplementary figures

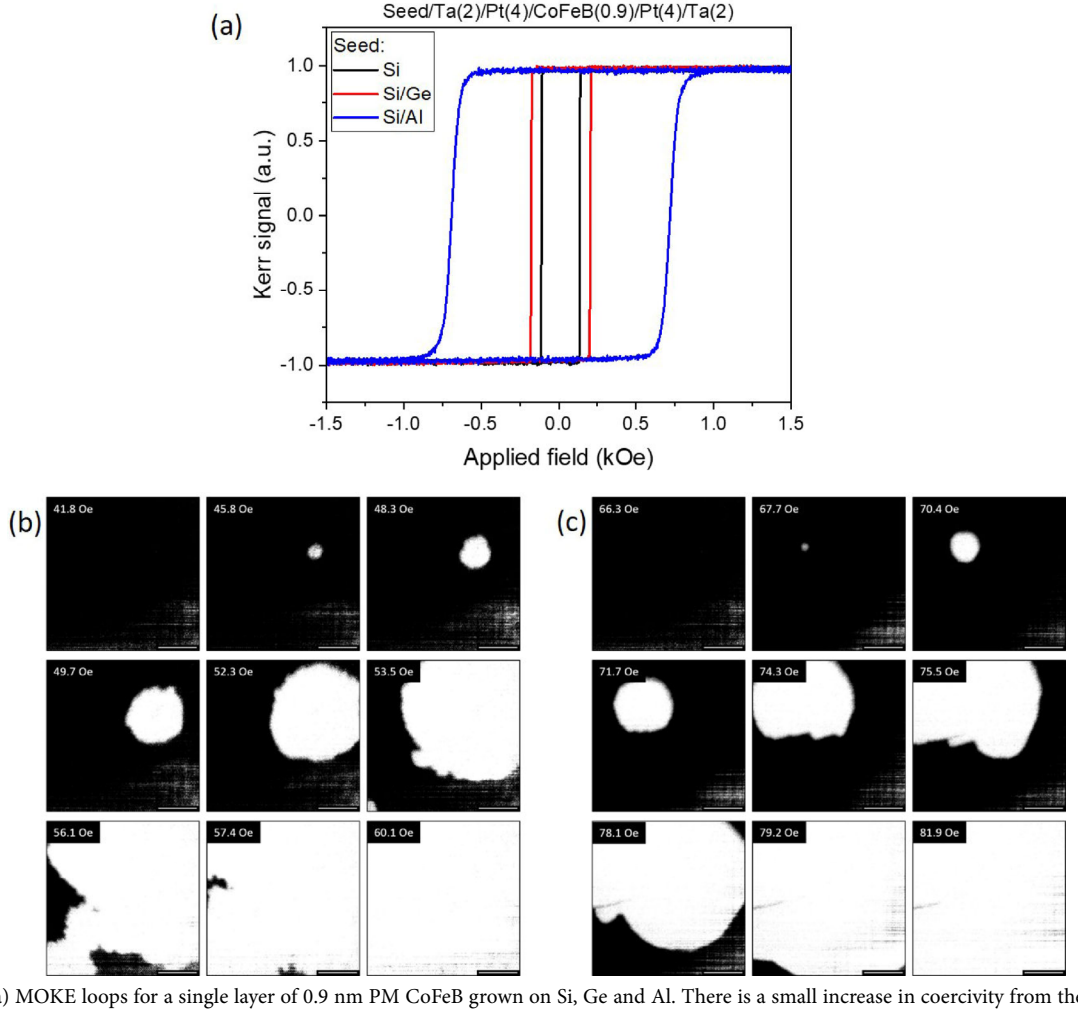

Figure S2 (a) MOKE loops for a single layer of 0.9 nm PM CoFeB grown on Si, Ge and Al. There is a small increase in coercivity from the Si sample to Ge sample (~ 65 Oe), but a much larger one from the Si to Al sample (~ 580 Oe). There is also a loss of sharpness in the transition of the Al sample. The Kerr domain images of the samples grown on Si and Ge are shown in (b) and (c) respectively (scale bar is 100 μm). Both sets of images show single nucleation sites and rapid domain wall propagation; the magnetic transitions have propagation dominated dynamics, corresponding to the sharp switches in the MOKE loops.

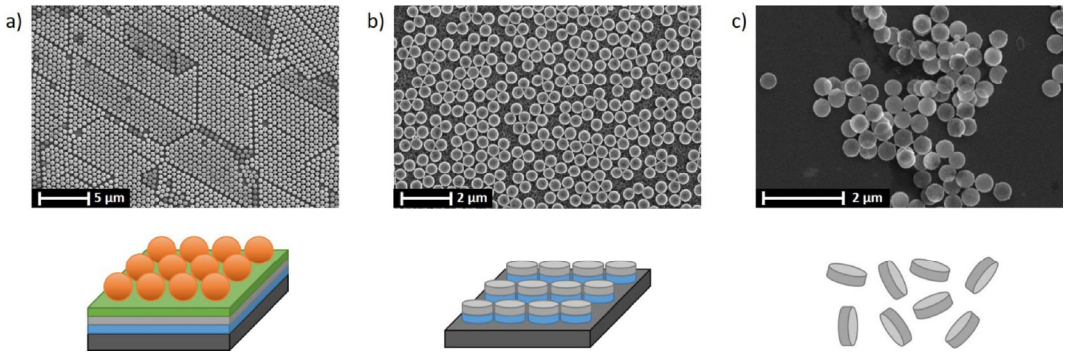

Figure S3 Three key steps of the new nanodisc fabrication method: (a) the plasma ashed PS bead lithography mask; (b) ion milled nanodiscs, on chip, after the removal of the mask; and (c) nanodiscs that have been lifted off and redeposited for imaging. Each step is depicted by a schematic (taken from Fig. 2) and a corresponding SEM image.

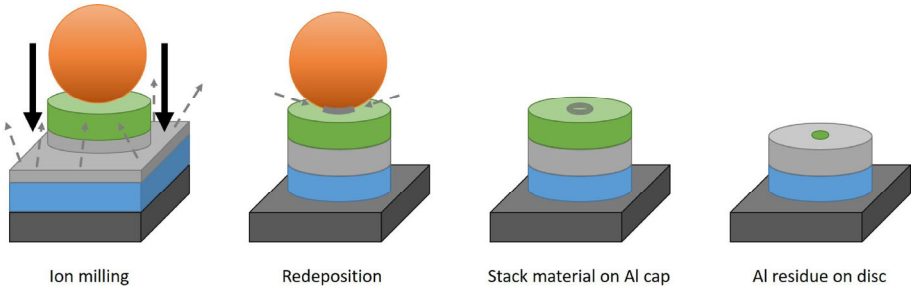

Figure S4 A schematic demonstrating how the redeposition of film material during ion milling can cause a small lump to appear in the centre of our magnetic discs. The bombardment of Ar ions on the sample causes the expulsion of atoms of the thin film stack in all directions. A small amount of these atoms will redeposit themselves in the gap between the PS bead and the Al cap. Some of this redeposition will be removed with the PS beads, however some will remain on top of the Al cap. The etching of the Al cap removes the redeposited material, however, its presence will limit the access of the solvent to the Al at the centre of the disc. This leads to a reduction in rate of the etching at the centre of the cap, causing a small amount of Al to be left behind at the centre of the disc. The implementation of a longer Al etch time should eliminate this feature.

ESM references

[S1] Bandiera S, Sousa RC, Auffret S, Rodmacq B, Dieny B. Enhancement of perpendicular magnetic anisotropy thanks to Pt insertions in synthetic antiferromagnets. Appl Phys Lett 2012;101:72410. https://doi.org/10.1063/1.4745924.

[S2] Lavrijsen R, Fernández-Pacheco A, Petit D, Mansell R, Lee JH, Cowburn RP. Tuning the interlayer exchange coupling between single perpendicularly magnetized CoFeB layers. Appl Phys Lett 2012;100:52411. https://doi.org/10.1063/1.3682103.