Fabrication of a Macroscopically Degenerate 3D Artificial Spin Ice

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Frustration describes a competition among interactions, where not all can be satisfied. An example of geometrical frustration is water ice, where a degeneracy of positions of Hydrogen atoms relative to Oxygen atoms leads to residual entropy in the ground state. Artificial spin ices were introduced as a way to study this geometrical frustration in 2 dimensions [1]. Artificial spin ices are patterned nano-magnetic islands that form dipoles in a square lattice (Figure 1a). Four intersecting dipoles form a vertex which the ice rule dictates should have two dipoles pointing towards and two away from vertex in six typical configurations with different relative energies and at proportions relative to the number of possible configurations (Figure 1b). This multiplicity of configurations leads to a macroscopically degenerate ground state and residual entropy analogous to water ice.

Previous work on 2D spin ices have displayed macroscopically ordered ground states where the degeneracy of the ice rule is lifted, owing to an asymmetrical interaction between parallel and perpendicular dipole magnets in the vertex [2]. Proposed solutions have included introducing height offsets in the lattice, creating a three dimensional square ice [3] where the interaction of perpendicular magnets is reduced and at a critical height offset, the macroscopic degeneracy will be restored. Our work here describes the fabrication (Figure 2) of such a 3D spin ice system fabricated using a two exposure electron beam lithography process where plateaus are defined in etched silicon, raising one of two perpendicular lattices to defined offsets. A second electron beam exposure defines the islands on both lattices, which after lift-off of Permalloy ($Ni_{80}Fe_{20}$), become the offset magnetic dipoles. We successfully fabricated a 3D artificial spin ice with various height offsets between perpendicular lattices (Figure 3). We will present x-ray magnetic circular dichroism (XMCD) photoemission electron microscopy (PEEM) measurements demonstrating that the critical height offset does restore the macroscopic degeneracy of the ground state.

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2. A. Farhan, P.M. Derlet, A. Kleibert, A. Balan, RV Chopdekar, M. Wyss, H. Perron, A. Scholl, F. Nolting, HJ Heyderman, Phys. Rev. Lett. **111**, 057204 (2013)
3. D. Thonig, S. ReiBaus, I. Mertig, and J. Henk, Journal of Physics: Condensed Matter 26 (2014) 2660066

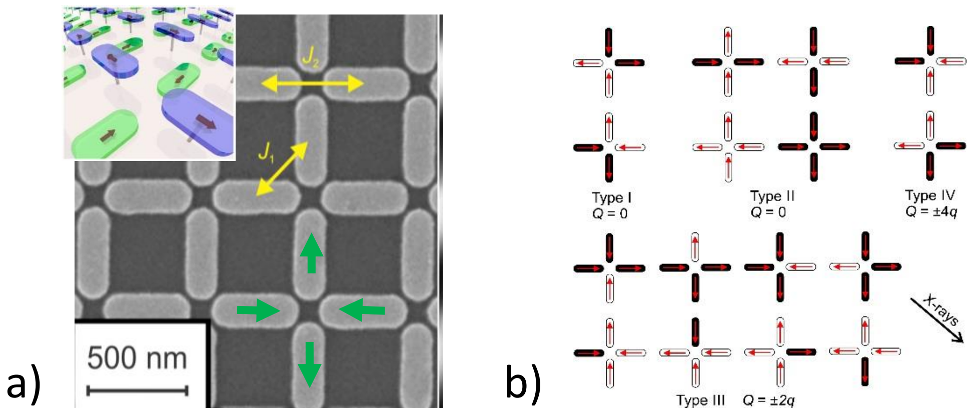

Figure 1: Schematic of 2D artificial spin ice. a) SEM image of 2D square ice with green arrows noting the dipole moments and their interaction at a vertex [2]. Yellow arrows represent the relative distance of the magnets influencing coupling strength $J_{1,2}$. Inset represents the idea to offset lattices of magnets to change relative coupling strength of parallel and perpendicular magnets [3]. b) Classification of possible magnet configurations. Type I is lowest energy, Type III represents monopole defects.

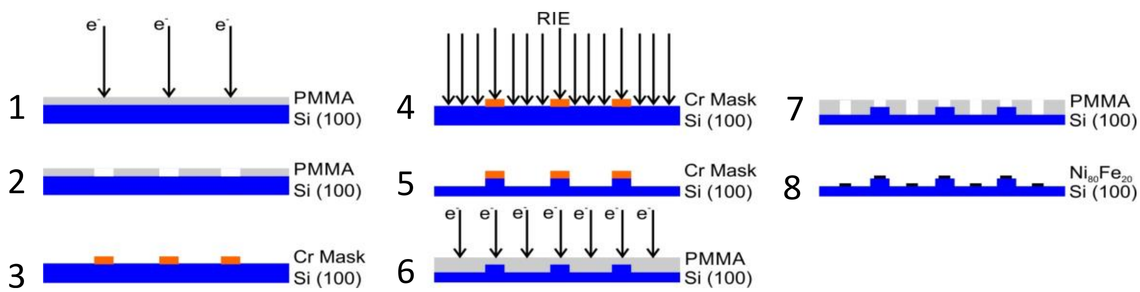

Figure 2: Fabrication process for 3D artificial spin ice. Steps 1-3 are the first electron beam exposure and liftoff of Cr for an etch mask. Steps 4-5 show etching of the Silicon to form plateaus. Steps 6-8 show the second aligned electron beam exposure and liftoff of Permalloy ($Ni_{80}Fe_{20}$) for magnetic island formation.

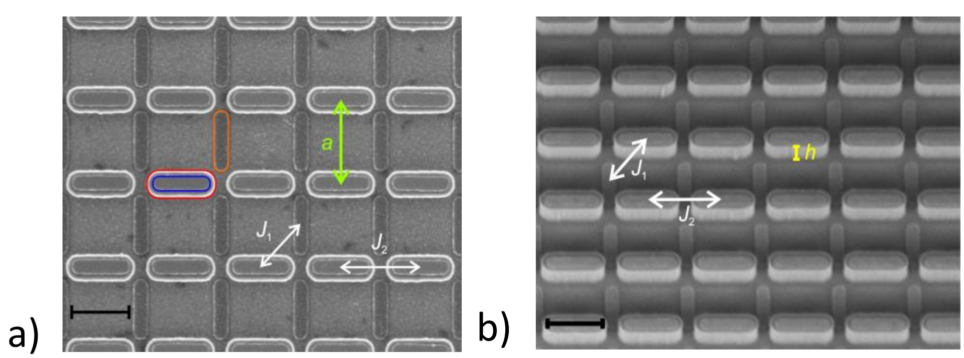

Figure 3: Fabricated 3D artificial spin ice. a) Top down SEM image where the Silicon plateau is outlined in red and the nano-magnets are outlined in blue and orange. b) Tilted view SEM showing height offset created by the silicon plateau.