# Artificial spin lattices on insulating substrates via variable-pressure electron-beam lithography

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Artificial spin lattices (ASLs) are arrays of nanoscale magnets whose properties can be tuned by geometry and composition[1]. In terms of geometry, periodic ASLs are known as artificial spin ices (ASIs), whereas aperiodic ASLs are called artificial magnetic quasicrystals (AMQs). Composition-wise, the majority of ASLs are realized in permalloy ($Ni_{0.8}Fe_{0.2}$). ASLs have significant implications in reservoir and neuromorphic computing[2] and can also be utilized in X-ray optics to create and alter X-ray orbital angular momentum[3]. ASLs are commonly patterned using electron beam lithography (EBL), but surface charging in EBL can limit ASL investigations that require electrically insulating substrates.

Here, ASLs were successfully patterned on sapphire using variable pressure EBL[4,5] under water vapor. An 80-nm thick bilayer PMMA resist stack (450K and 950K molecular weight) was spin coated on sapphire. ASL patterns were exposed in the resist using a modified environmental scanning electron microscope operated under 1 mbar water at 30 keV accelerating voltage. The exposed film was developed in 4:1 ethanol: water for 45 s at 3°C followed by 10 s IPA rinse. Cold development of PMMA reduces line edge roughness[6]. 20 nm permalloy and 2.5 nm aluminum were evaporated on the developed film followed by lift-off in NMP for 10 minutes at 40°C. SEM images in Fig. 1 show a square ASI, and an einstein, from "one stone"[7], AMQ.

Hysteresis loops from ASLs were obtained using longitudinal MOKE. Fig. 2 shows the magnetization normalized to its saturation value vs. applied magnetic field (mT) at room temperature for the square ASIs pattern from Fig. 1 (a). The magnetic field was swept in the range of $-80 \text{ mT} \leq \mu_0 H \leq 80 \text{ mT}$. As expected, the ASI exhibited a much higher coercive field than a uniform permalloy thin film. Magnetic characterization of einstein AMQs is currently in progress. Thus, ASLs were successfully patterned on insulating substrate using VP-EBL and the magnetic behavior of the patterns were characterized using MOKE.

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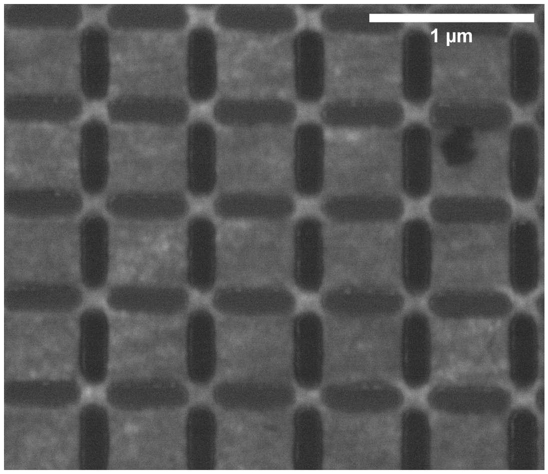
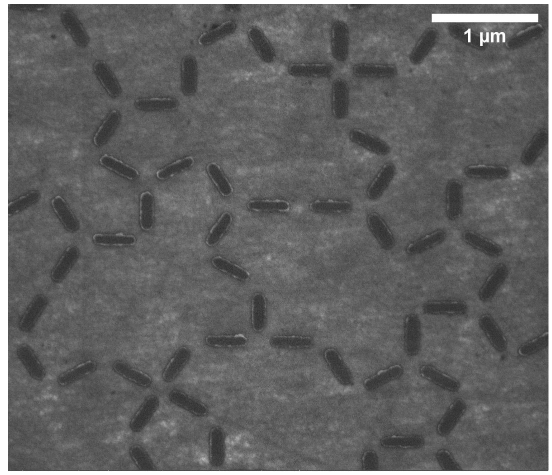




(a) Square artificial spin ices (ASIs)





(b) Monotile ("einstein") artificial magnetic quasicrystal (AMQ)

Figure 1: SEM images of (a) square artificial spin ice (ASI) and (b) monotile ("einstein") artificial magnetic quasicrystal (AMQ); fabricated on sapphire substrates using VP-EBL.

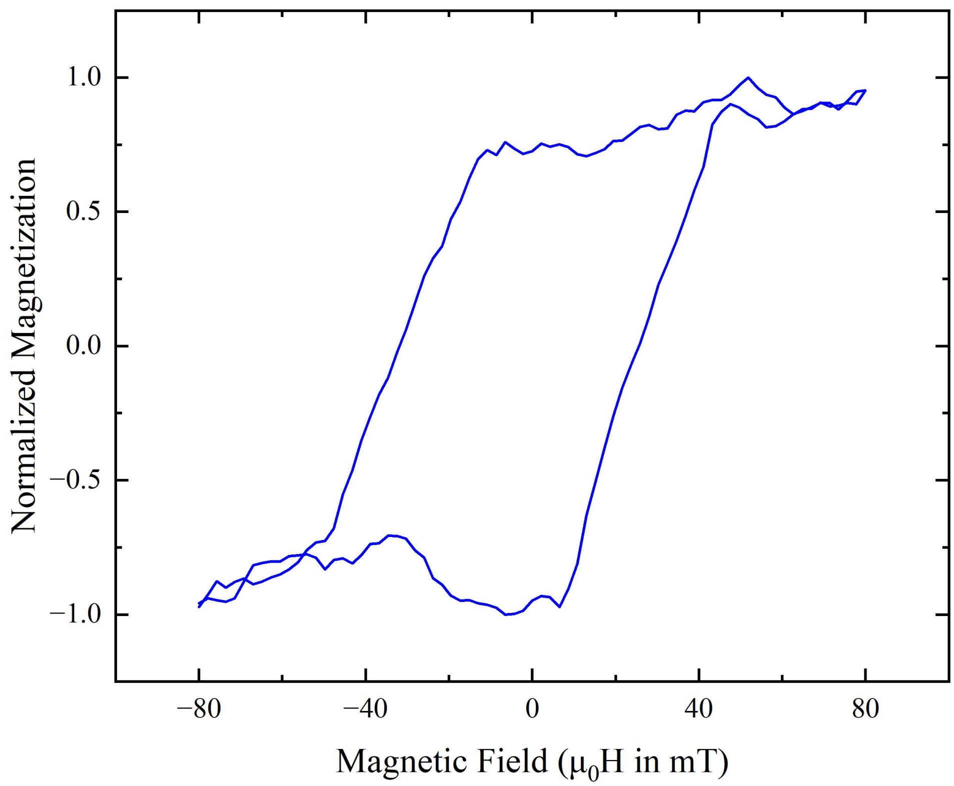




Figure 2: Magnetization normalized to saturation value vs applied magnetic field ($\mu_0 H$ in mT) at room temperature for square artificial spin ice (ASIs) patterns (shown in Fig. 1(a)) obtained from magneto-optical Kerr effect (MOKE) measurements.