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Nanoscale patterning of magnetic islands by imprint lithography using a flexible mold

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A nanomolding process for producing 55-nm-diameter magnetic islands over 3-cm-wide areas is described. A master pattern of SiO_2 pillars is used to form a polymeric mold, which is in turn used to mold a photopolymer resist film. This latter film is used as a resist for etching SiO_2, yielding a pattern of pillars. Finally, an 11-nm-CoPt multilayer is deposited. Magnetic force microscopy reveals that the film on top of each pillar is a magnetically isolated single domain that switches independently. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1501763]

Patterning magnetic media[1–3] is a promising strategy for increasing magnetic recording density toward 100 Gbit/cm^2, well beyond the estimated limit of conventional longitudinal recording media. An isolated magnetic bit of a small enough area forms a single magnetic domain, which can be thermally stable to diameters well below 10 nm. In contrast, recording on a continuous film of unpatterned media at very high density requires decreasing the grain size to the point of thermal instability. Magnetic islands 100 nm in size have been patterned by deposition into substrate holes[4] or onto substrate pillars,[5] by etching[1] or evaporating[6] magnetic films through a resist mask, or by ion-beam modification.[7,8] Writing and reading of patterned magnetic bits has been demonstrated using conventional recording heads.[9,10]

The lithography required for patterning magnetic media for disk drives must be inexpensive, and it must achieve a resolution several times better than current UV optical lithography. However, alignment of successive lithographic steps is unnecessary, and a fairly high defect density (10^{-6}–10^{-3}) can be accommodated by error correction. Contact lithography methods such as nanoimprinting of a melted polymer[11] or nanomolding of a photocuring polymer[12] are ideally suited to these requirements. Patterning resist over large areas has been achieved by both thermal[13–15] and photocured.[12,16] processes. Thermal imprinting has been used to produce patterns of magnetic islands by electroplating into etched holes,[4] by evaporation through a mask followed by liftoff,[6] and by evaporation onto etched pillars.[5]

Here, we describe a complete process for large-area magnetic patterning. Steps in this process are: Fabricating a master by electron-beam lithography, molding a photocured stamp, molding a photocured etch mask from the stamp, and plasma etching to produce SiO_2 pillars (Fig. 1). Finally, evaporation is used to deposit a magnetic film, which is isolated into independent islands defined by the tops of the pillars.[17] We have patterned small selected regions of a CoPt multilayer film over 3 cm with a single stamp and measured their magnetic properties. Compared to previously reported methods for magnetic patterning by imprinting,[4–6] this process is simpler and can accommodate irregularities in the substrate surface. The stamps used can be formed in large numbers from a single master.

Glass substrates for disk drives have a curvature of roughly 5 μm and a peak-to-peak roughness of 10 nm over distances <1 mm,[18] as shown by the line in Fig. 2. To insure that substrate nonplanarity is not converted into resist thickness variations, a compliant stamper is required.[19,20] We use a 50-μm-thick polymer stamp on a 150-μm-thick glass backing plate and a stamping pressure of 2 MPa. The glass provides lateral stability while allowing the stamp to bend to the disk curvature, and local deformation of the stamp conforms to disk roughness. Figure 2 displays approximate model calculations of deformations of the stamp achievable under the applied pressure as a function of wavelength of the deformation, using parameters from our process. Bending is modeled by the curvature of a circular plate supported over a hole of diameter equal to the wavelength. Local deformation of the polymer is defined as the height of sinusoidal topography in a hard indenter which can be accommodated by an elastic semi-infinite solid.[21] For comparison, the roughness of a typical disk substrate[18] is also displayed in Fig. 2. The graphs show that the surface roughness can be accommodated above 200 μm wavelength by bending and between 1 and 200 μm by local deformation. The remaining roughness below 1 μm is about 1 nm, which is insignificant for the etching process. The viscosity of the prepolymer is such that it can flow into the submicron patterns, while not flowing over much larger dimensions, so that peaks and valleys in the substrate are accommodated instead by local deformation and bending.

The SiO_2 master used for producing the stamp consisted of three equally spaced patterned areas, each $(50\ \mu\mathrm{m})^2$, and separated by a distance of 1.6 cm. Each area contains an hexagonal array of 30-nm-high, 55-nm-diameter flat-topped pillars, with a center-to-center spacing of 100 nm. To form the master, a 4-nm-thick Ti adhesion layer was evaporated on SiO_2, and a 160-nm-thick resist of 950 K MW poly(methylmethacrylate) (PMMA) was spun on the surface. A pattern of holes in the PMMA film was produced by exposing with a 30 keV electron beam and developing. Subsequently, 30 nm of

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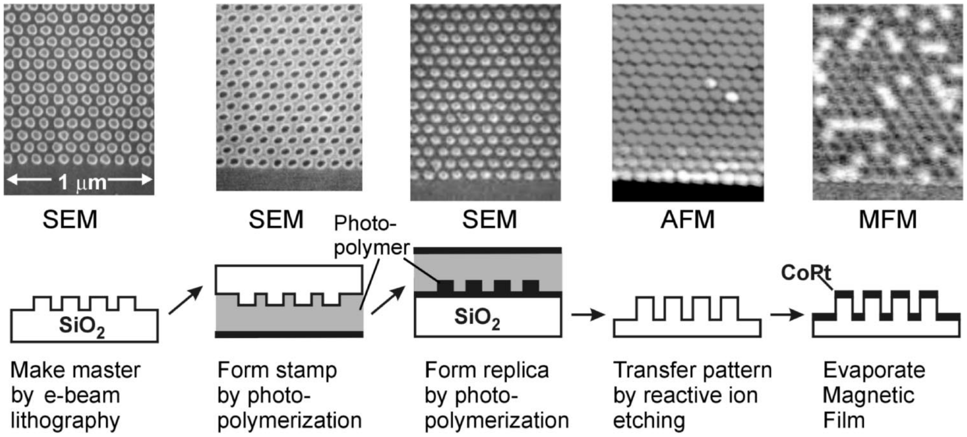

FIG. 1. Steps in the fabrication of patterned magnetic media. The final panel displays a magnetic force microscope image, showing quantized up and down magnetization of isolated domains.

Cr was evaporated and lifted off to form a mask of Cr islands. Reactive ion etching in CF_4 followed by the removal of the residual Cr and Ti left 30-nm-high SiO_2 pillars.

For fabricating the stamp, we formulated a methacrylate photopolymer composition optimized for a number of critical properties: fast cure rate, low UV absorption, low shrinkage, and hardness. Similar types of photopolymers were pioneered by Philips for optical disk manufacturing applications.[22] The photopolymer contains 62% by weight ethoxylated (2) bisphenol A dimethacrylate for hardness and etch resistance, 18% trimethylolpropane triacrylate for enhanced cross linking, 18% 1-vinyl-2-pyrrolidinone to aid chain propagation[22] and 2% 2,2-dimethoxy-2-phenylacetophenone for photoinitiation. The stamp backing plate was first exposed to 3-methacryloxypropyl trichlorosilane vapor in nitrogen to form an adhesion monolayer that links into the polymer. To form the stamp, 0.2 cc of the photopolymer liquid was dispensed on the master, and the glass plate was lowered into contact. After the liquid spread to a 4 cm diameter, it was exposed for 30 s to 365 nm light at 14 mW/cm^2. This stack was then heated for 30 min to 100 °C at 2 mW/cm^2 UV to complete the cure. The stamp and backing plate were peeled off from the master while using a solution of 0.1% detergent (Liquinox) to wet the separating interface. This solution reduces the effective surface energy of the separating surfaces, allowing good release and obviating the need to apply a release coating on the master, which we found could prevent the stamp prepolymer from wetting features in the master. Finally, to form an antistick coating for the replication process, the stamp was sputtercoated with 2.5 nm of AuPd alloy.

To mold a replica of the master to use as an etch mask, a 1% solution of the photopolymer in propylene glycol monomethyl ether acetate is spun at 3000 rpm on the target SiO_2 wafer, forming an 11-nm-thick liquid film. The wafer had been treated with the adhesion agent. The stamp was lowered onto the wafer and pressed by a silicone pad with 2 MPa pressure. (Before molding, the stamp was stored in nitrogen, and the surfaces were brought together in nitrogen to eliminate oxygen diffusion out of the stamp into the resist, which inhibits polymerization.) After 1 min of UV curing through the stamp at 30 mW/cm^2, the patterned film was released from the stamp by the same method used to form the stamp. At this point, a replica of the master has been formed in the cured polymer, with 28-nm-high pillars rising from a 10-nm-thick base.

A few defects appeared in the molded replicas. For example, on the third replica from a single stamp, out of 30 000 pillars formed over the 3 cm region, five isolated pillars were missing, and two larger defect regions contained about 20 missing pillars each. On the sixth replica, there were a few more defects (Fig. 3). Failure seems to occur when the adhesion force between the stamp and replica overcomes the replica adhesion to the substrate, a problem that can be improved by optimizing the interfacial layers.

To form SiO_2 pillars by transferring the pattern in the polymer resist, the sample was plasma etched in CF_4 to re-

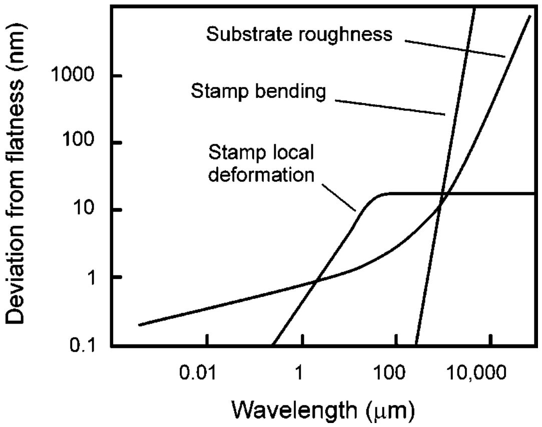

FIG. 2. Accommodation of substrate roughness by bending and local deformation of the stamp, plotted as a function of wavelength of the roughness.

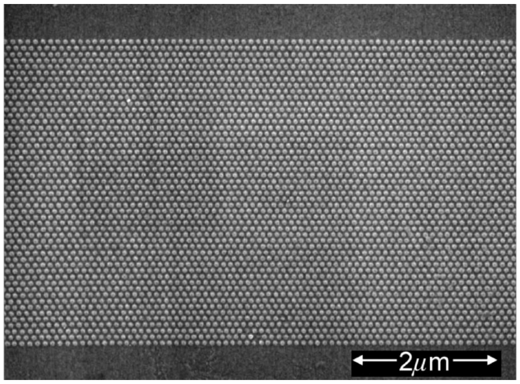

FIG. 3. The sixth molded replica from a single stamper (scanning electron micrograph).

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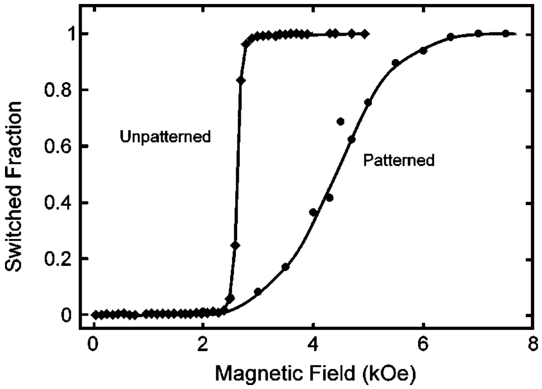

FIG. 4. Switched fraction of the magnetic thin film vs applied magnetic field, measured in remanence. For the patterned film, the switched fraction is measured by counting switched islands, while for the unpatterned film, it is measured by the normalized Kerr effect.

move the 10-nm-base thickness of resist, followed by an etch in a 7/1 CF_4/CH_4 mixture, which is chosen for its improved selectivity over pure CF_4. The remaining resist was removed by oxygen ashing.

CoPt multilayers are suitable for magnetic recording on patterned media because of their perpendicular magnetization, high anisotropy, and high remanent magnetization. The film structure $Si/SiO_2/Pt_{1\,nm}(Co_{0,3\,nm}Pt_{1\,nm})_7Pt_{1\,nm}$ was formed by electron-beam evaporation, holding the substrate at 300–350 K.[23] The chamber pressure was 10^{-5} Pa during deposition, and the evaporation rate was 0.05 nm/s.

To characterize the magnetic film, the magnetization was first saturated, and then the field was reversed in steps, at each step removing the sample from the field for magnetic force microscopy (MFM). The magnetic images show the magnetization of the film on each pillar to change as a single domain, magnetized either in or out of the sample. By counting bright and dark areas in MFM images such as that in Fig. 1, the remanent magnetization curve (Fig. 4) was generated and compared to magneto-optic Kerr effect measurements of the magnetization of the unpatterned region. As the field increases, the magnetization of the pillars and unpatterned film begins increasing at about the same field. The rapid magnetization rise of the unpatterned area results from the propagation of domains from isolated nucleation sites, while the more gradual rise of the pillar magnetization reflects the distribution of coercivity of the individual islands.

In the process we have described, a nearly unlimited number of stamps can be made from a single master, because no hard surface comes in contact with the master during stamp formation, and any residue can be removed nondestructively. In addition to accommodating substrate curvature and roughness, the use of a flexible stamp gives a process less sensitive to localized contamination. If this process can be optimized to form a large number of replicas from each stamp, it may be suitable for large-scale manufacturing.

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