Simulation and experimental validation of a selective magnetization process for batch-patterning magnetic layers

C Velez, W C Patterson and D P Arnold
Interdisciplinary Microsystems Group, Department of Electrical and Computer Engineering, University of Florida, FL, 32611, United States

Email: camilovelez@ufl.edu

Abstract. This work reports experimental validation of a simulation tool that models a selective magnetization process for batch-patterning magnetic poles into magnetic layers. The magnetic patterning process is simulated via the finite-element method to solve the magneto-quasi-static Maxwell equations using the measured nonlinear magnetic properties of the materials (magnetization curves). The simulation results are compared to experimental measurements of the stray fields of selectively magnetized substrates prepared under different processing conditions. The fields are measured by a magneto-optical imaging technique approximately 50 μm above the surface. The simulations are shown to predict the general trends observed in the experimental results.

1. Introduction
Permanent magnetic materials are widely used in MEMS sensors, actuators, etc., but typically such materials are restricted to a single magnetization direction, i.e. the entire magnet is “poled” in only one direction. In contrast, at the macroscale, much more complex, three-dimensional magnetic field arrangements are typically used to create desirable magnetic field patterns, such as Halbach arrays. These arrangements generally enable stronger magnetic fields and/or field gradients, which enhance device end effect performance. The ability to create complex magnetic field patterns with sub-millimeter or even micrometer feature sizes in MEMS could significantly enhance the utility of magnetic materials, and also enable new microscale device architectures.

Previous attempts for creating complex magnetic structures (patterning) with sub-millimeter feature size began with machining permanent magnets, individually magnetizing, and assembly them [1–3]. Due to the high attractive forces between magnetic poles the assembly is troublesome, together with the lack of batch processing make this approach not very scalable to large manufacturing scales. A newer solution is the inkjet-print of micro-magnets [4], but this approach still requires additional permanent magnets to guaranty a certain field orientation. The solution presented here is to magnetically pattern permanent magnet layers by “writing” magnetic poles of desired shape and orientation. Three mechanisms for magnetic micro-patterning have been mainly used. First, poles can be created by generating spatially varying magnetic fields using current-carrying conductors [5–7], but scalability below 1 mm is an issue. Second, thermomagnetic patterning [8,9], where magnetization is altered using heat from laser irradiation enabling magnetic features in the range of 50-100 μm, but limited to the surface of the material. Lastly, magnetic fields can be shaped using soft-magnetic magnetizing heads to selectively magnetize poles into magnetic layers [10–14].
The selective magnetization process using shaped magnetizing heads has been shown to be widely adaptable to different pole sizes (microns to millimeters), materials (ultra-thin magnetic layers, electroplated thick films, bulk rare earth materials), and geometries (simple stripes to complex shapes). We have also introduced a simulation approach for modeling the process and the resultant magnetic structures [15]. In this paper, systematic and quantifiable comparisons are made between the simulation predictions and experimental results of the process, specifically the stray fields of selectively magnetized substrates fabricated under different process conditions (varying reversal magnetic field amplitudes). The magnetic stray fields of the patterned layer are measured by a magneto optical imaging technique [16].

2. Selective magnetization process description

To imprint magnetic pole patterns in the substrate, the selective magnetization method reported in [11] is used. First, the substrate is uniformly pre-magnetized out-of-plane (upward) using a 6 T pulsed magnetic field. Then a soft magnetic “magnetization mask” is placed in contact with the substrate, and a reversal (downward) magnetic field pulse is applied. The high permeability of the magnetization mask concentrates the magnetic flux in the poles of the mask, thereby flipping the magnetization down in those areas. In the other regions (between the poles underneath the air gaps of the mask), where the fields are weaker, the magnetization remains in the original upward orientation.

Figure 1 shows the magnetizing mask used in this work and the resulting pole pattern of a selectively magnetized substrate. The mask has a simple stripe pattern and is conventionally machined from AISI 1018 mild/low carbon steel (relative permeability $\mu_r=102$) with the feature size (line/space) of 1 mm and feature depth of 0.6 mm (Figure 1). The magnetic substrate for selective magnetization is a flexible iron oxide material with 0.57 mm thickness, remanence of $B_r=180$ mT, and coercivity of $H_{ci}=125$ kA/m ($\mu_0H_{ci}=0.16$ T).

![Figure 1](image)

2. Selective magnetization simulation

The selective magnetization process is modeled using COMSOL Multiphysics using a 2D simulation. The finite-element method is used to solve the magneto-quasi-static Maxwell equations, following the methods reported in [15]. The experimentally measured nonlinear magnetic properties of the substrate and mask materials (magnetization curves) are used in the simulations.

Simulations are divided in two consecutive and dependent steps: first, the application of the reversal magnetic field (Figure 2, top row), followed by second, the stray field generated by the remanent magnetization in the substrate after selective magnetization (Figure 2, bottom row). In the first step, the...
substrate is initially considered uniformly magnetized up, and the simulation models the fields during the peak of the downward selective reversal pulse. The result of this first step is then used to calculate the conditions for second step. Following Samwel, et al. [17], the remanent magnetization at every point in the substrate is calculated using the DCM (dc-demagnetization measurement) for the material. The DCM curve relates the peak field from step one to the resultant residual magnetization used in step two. Step two of the simulation computes the stray fields for the selectively magnetized substrate (with the magnetizing mask no longer present).

The sensitivity of the magnetization process with respect to the reversal B field amplitude is evident in simulations shown in Figure 2, comparing reversal fields of 100 mT, 400 mT, and 700 mT. Figure 3 shows the profile of the predicted $B_z$ stray fields at 50 $\mu$m above the surface of the substrate for the same three cases. For the 400 mT case, the simulations indicate that it is possible to selectively reverse the substrate through its entire thickness, as compared to the thermomagnetic patterning [8,9], which was limited to ~1 $\mu$m in depth. This case also yields the strongest magnetic stray field contrast (Figure 3). It is evident that when the reversal field is too weak (100 mT), the substrate is not patterned (direction of the magnetization doesn’t change), and only surface domains will be altered producing very weak remanent fields. In the opposite case, when a very high reversal field (700 mT) is applied, the entire substrate is reversed, not only the sections underneath the mask. These two extreme cases suggest there exists an ideal (optimal) reversal magnetic field at which the substrate sections underneath the mask reverse without affecting the magnetizations of the remaining substrate. Consequently, a parametric series of simulations and experiments are conducted, varying the reversal B field from 50 to 1100 mT in order to determine the optimal field (further discussed below).

Figure 2. Selective magnetization process simulation (during magnetization – top row) and stray B field generated by the magnetic substrate after selective magnetization (after magnetization – bottom row). The M field inside the magnetic substrate and the mask (the shape of the mask is drawn for illustration).

Figure 3. Simulation of the stray magnetic field 50 $\mu$m above the substrate for three reversal magnetic fields.

4. Selective magnetization and magneto-optical imaging measurements

Magnetization fields from 100 mT to 1000 mT are applied using a pulse magnetizer on independent samples. Magneto-optical images of each sample are taken [16] using a 250 mT saturation magneto-optical indicator film at 50 $\mu$m above the surface of the substrate. Figure 4a presents an example 3D representation of the field pattern after magnetization, and Figure 4b presents the average measurement of the $B_z$ field across the feature line (average of 1240 profiles). Figure 4c shows the average $B_z$ field (measured at 50 $\mu$m) generated by samples experimentally magnetized at 88 mT, 411 mT, and 926 mT. The values $B_{\min}$ and $B_{\max}$ defined in this figure correspond to the fields measured in the center of the mask pole and air gap, respectively.

Figure 5 compares $B_z$ field simulation and experimental values. The maximal values of $B_{\max}$ and $B_{\min}$ were 45 mT and -23 mT, measured on sample magnetized with 411 mT. The results show the
simulations accurately predict the general trends of the fields. However, there is some discrepancy in the absolute field magnitudes; the simulations underpredict the measurements. Discrepancies in the magnitude of the B fields between simulation and measurements can be attributed to experimental inaccuracies in the magneto-optical measurements; underestimation of the B fields generated by the mask during simulations; or oversimplifications in the simulation model (e.g. only permits magnetization in the z-direction).

As an overall figure of merit for the magnetization process, the magnetic contrast is defined as \[ C = \frac{B_{\text{max}} - B_{\text{min}}}{B_{\text{max}} + B_{\text{min}}} \]. Figure 6 shows a comparison between the B field contrast from simulations and the experimental measurements. These results confirm the existence of an optimal external magnetic field value at which the contrast is maximized (~500 mT in this case). A contrast difference between simulations and measurements is on the order of 29%.

**Figure 4.** Magneto-optical images of the selectively magnetized sample (at 411 mT) taken at 50 μm above the surface (a) Magneto optical topographical view of the Bz field (b) Magneto optical image of the Bz field and average profile along the x axis. (c) Bz field profiles for samples magnetized with different external magnetic fields.

**Figure 5.** B_{\text{max}} and B_{\text{min}} measured/simulated 50 μm above the substrate for different reversal fields during magnetization.

**Figure 6.** B-field contrast 50 μm above the substrate for different reversal fields during magnetization.

### 5. Conclusions

In summary, this paper demonstrates good capabilities of the simulation tool for predicting the magnetic stray fields for samples magnetized with various reversal fields. The simulations and experiments also prove that an ideal reversal magnetic field exists, and should be applied in order to maximize the magnetic field contrast on the magnetized sample. Ongoing efforts seek to improve and further validate the simulation tool over different process variables (dimensions, materials, etc.), such that it can be used to predict the stray fields from different magnetized layers under different process conditions.
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