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Writing magnetic patterns with surface acoustic waves

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A novel patterning technique that creates magnetization patterns in a continuous magnetostrictive film with surface acoustic waves is demonstrated. Patterns of 10 μm wide stripes of alternating magnetization and a 3 μm dot of reversed magnetization are written using standing and focusing acoustic waves, respectively. The magnetization pattern is size-tunable, erasable, and rewritable by changing the magnetic field and acoustic power. This versatility, along with its solid-state implementation (no moving parts) and electronic control, renders it as a promising technique for application in magnetic recording, magnonic signal processing, magnetic particle manipulation, and spatial magneto-optical modulation. *© 2014 AIP Publishing LLC.*
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INTRODUCTION

Magnetizing a thin film with a pre-determined magnetization pattern is conventionally accomplished using a magnetic recording head, as in a hard disk or tape; using localized heating, as in magneto-optic recording,[1] or by contact printing with another magnetized film.[2] Here, we demonstrate an alternative, solid-state technique, using surface acoustic waves to manipulate the coercivity in regions of a magnetostrictive film so that the magnetization may then be selectively reversed. The key advantages of this technique are twofold: the generation of surface acoustic waves can be realized in a robust, solid-state device (i.e., no moving parts) and electronic control of the wave sources can be used to create varying patterns.

The surface acoustic wave is an ultrasonic wave mode that is confined to the surface of a medium. As it propagates in a magnetostrictive film, tensile and compressive strains are generated at the wave crests and troughs, respectively. Through the Villari effect,[3,4] this spatially varying strain selectively lowers the coercivity of the magnetostrictive film. When a magnetic field is applied, magnetization in the film can be reversed in regions where the strain has temporarily lowered the coercivity below the level of the applied field. In this way, a magnetization pattern replicating the acoustic wave can be created.

We demonstrate this process using standing acoustic waves to generate stripes of alternating magnetization in a magnetic film. Similarly, we show that by focusing the acoustic waves to a focal point, an isolated magnetic dot can be written. In each case, the feature size of the magnetization pattern can be manipulated by the applied magnetic field and acoustic power. In principle, it should be possible to write arbitrary magnetization patterns by scanning the focal point throughout the film area or generating more complex interference patterns from multiple sources.

Potential applications for this technique include acoustically addressed solid-state magnetic memory, where a magnetization dot serves as a data bit;[5] magnonic signal processing, where spin wave transmission is modulated by a spatially periodic magnetic field;[6] and spatial light modulation,[7] where light transmission is dependent on magnetization. In biological studies, magnetic manipulation of cell and molecules through lithographically patterned conducting wires[8] and micron-sized magnetic elements[9] has been reported. Here, the magnetic field gradient generated at the boundary of opposing magnetization can be used for manipulation. Shi *et al.* demonstrated an "acoustic tweezers" technique which utilizes the standing surface acoustic wave to arrange the cells.[10] Our technique opens the possibility of a hybrid "magneto-acoustic tweezes" that is capable of using both acoustic wave pressure and magnetic field gradient for magnetic particle manipulation.

EXPERIMENTS AND DISCUSSION

The surface acoustic waves for creating the magnetization pattern are excited using interdigitated transducers (IDTs)[5,11] fabricated on a piezoelectric substrate (ST-X cut quartz in this case), as shown in Fig. 1. The transducer is designed for an impedance of 50 Ω at an operating frequency of 158 MHz. It consists of 574 interdigitated electrodes spaced regularly with a center-to-center separation of 10 μm. Each electrode is 5 μm wide. The acoustic aperture, as indicated in Fig. 1, is 3 mm.

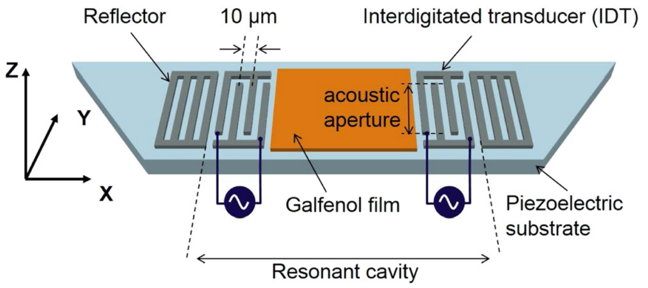

FIG. 1. Schematic of the experimental device.

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When driven by an *ac* signal, the transducer launches a propagating strain wave of 20 μm wavelength (i.e., twice the electrode pitch). Most of the wave energy is confined within the depth of one wavelength from the surface, making it energy efficient to strain the film on the surface.

Two reflectors are fabricated 12.5 μm away from the transducers on each side in order to form a resonant cavity and amplify the strain. Each reflector has 476 shorted electrodes, which are also 5 μm wide with a 10 μm pitch. Both the transducers and reflectors are patterned from 110 nm aluminum thin film using standard lithography techniques.

A galfenol thin film is deposited in the resonant cavity on the quartz substrate, serving as the medium for magnetization patterning. It is *dc* sputtered at 200 W from a $Fe_{81.6}Ga_{18.4}$ target and the measured film thickness is 57 nm. Galfenol is selected here due to its ease of sputtering[12] and its high magnetostrictive effect, up to 400 ppm.[13] The as-deposited galfenol film has a coercivity of 6.8 kA/m, measured by a vibrating sample magnetometer.

Prior to patterning the magnetization in stripes, the galfenol film is saturated with a 28 kA/m field along the y-direction (see Fig. 1). Then the two acoustic transducers are driven synchronously, generating acoustic waves traveling towards each other in the +x and −x directions, respectively. This results in a standing acoustic wave being set up in the galfenol film. The acoustic power is 1.33 W/mm (i.e., power applied to the transducer divided by the acoustic aperture). The standing wave has a 10 μm period. At the antinodes, the film undergoes the maximum strain. At the nodes, the film experiences no strain. This spatially periodic strain modulates the coercivity of the galfenol film via the Villari effect, creating a spatially periodic variation in coercivity, as illustrated in Fig. 2(a).

Then a reversing field of −5.8 kA/m, lower than the coercivity of the unstrained film, is applied. Consequently, the magnetization around the antinodes, whose local coercivity is lower than the field, is reversed. The magnetization remains unaffected at the nodes. This creates an alternating magnetization stripe pattern, which is imaged using Kerr microscopy (Fig. 2(b)). It should be noted that, first, the period of the pattern is 10 μm, determined by the standing wave created. A pattern with a different periodicity can be achieved if acoustic waves with a different wavelength are used. Second, the width of the stripe is tunable. With constant acoustic power, if the field strength is increased, magnetization in a larger area around the antinodes is switched (Fig. 2(c)) and the stripes (the reversed magnetization) become wider eventually merging with each other (Fig. 2(d)). Similarly, if the field is held constant and the acoustic power increased, the stripes are seen to widen and finally merge resulting in a film completely magnetized in the opposite direction. After the stripes are merged, the pattern is "erased" and may be rewritten if needed. Thus, by selecting the wavelength and power of the acoustic wave as well as the amplitude and direction of the magnetic field, a width-tunable, erasable, and rewritable stripe magnetization pattern of the desired period can be obtained.

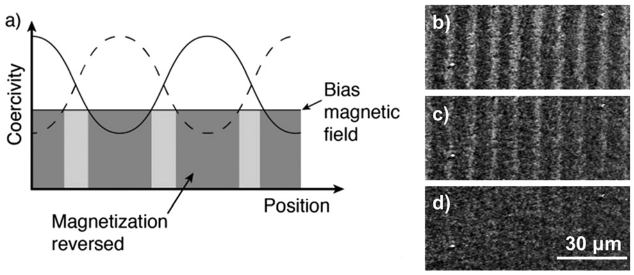

FIG. 2. (a) Schematic of the standing-wave-modulated coercivity and expected striped pattern in a reversing field. Kerr images of the 10 μm period stripes written with an acoustic power of 1.33 W/mm and a reverse field of (b) 5.8 kA/m, (c) 6.2 kA/m, and (d) 6.4 kA/m (stripes are merged together).

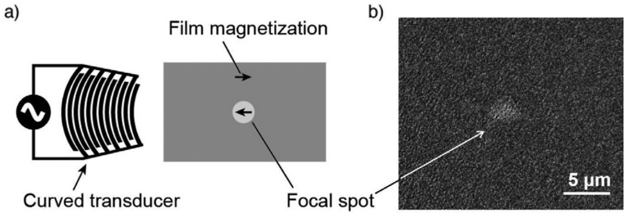

FIG. 3. (a) Schematic of a curved transducer. Magnetization at the focal point is switched in a reversing field. (b) Kerr image of the reversed magnetization at the focal spot.

A dot can be patterned by focusing the waves using a transducer with curved electrodes (Fig. 3(a)). Both the transducer and the galfenol film are fabricated as described above. The transducer has 440 concentric electrodes, which are also 5 μm wide. The curvature of the electrode is particularly designed to match the acoustic velocity and power flow anisotropy in the quartz substrate[14] generating acoustic waves that converge to a tight focal point.

To write the dot, the galfenol film is first saturated with a field of 28 kA/m. Then, the transducer is driven with 1 W and generates a focusing wave. The wave amplitude reaches the maximum at the focal point. Around the focal point, the strain lowers the coercivity sufficiently so that its magnetization is switched when a −4.2 kA/m reversing field is applied. The reversed region stands out as a 3 μm dot in the previously saturated galfenol film when observing under a Kerr microscope (Fig. 3(b)). The dot size can be varied with the applied magnetic field and the acoustic power and wavelength (shorter wavelengths than used here would result in a smaller dot).

Limited by the accessible photolithography capability, the patterns here are written with a 20 μm wavelength wave. However, acoustic wave with a wavelength of ~230 nm has been reported[15] and a feature size ~100 nm should be achievable. This makes it possible to miniaturize the magnetization pattern for achieving higher magnetic recording density or manipulating smaller particles.

CONCLUSION

In these experiments, we have demonstrated an electronically controlled, solid-state technique for magnetic patterning. It utilizes the surface acoustic wave to locally lower the coercivity in a magnetostrictive film, allowing the local magnetization to be reversed in a field smaller than the unmodulated coercivity. Magnetization patterns of 10 μm stripes and a 3 μm dot were obtained using standing and focusing acoustic waves, respectively. The demonstrated patterns are tunable and scalable. Together with its advantages in simplicity and non-invasiveness, this technique holds potential for magnetic particle manipulation, magnetic recording, and magnonic and magneto-optical signal processing.

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