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One-dimensional magnetic grating structure made easy

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A simple and easy method of the fabrication of one-dimensional magnetic grating structure is developed. By using the interference pattern of two femtosecond laser beams, a selective-area annealing of as-deposited Co_2MnSi film was achieved and one-dimensional magnetic grating structures were fabricated. The as-deposited films exhibit no magnetic response at room temperature. Several microscopies were applied to confirm the periodic crystalline and magnetic structures. The Faraday-like rotation of the polarization of the zeroth- and first-order diffracted beams were measured, and that of the first-order diffracted beam is nearly six times larger than that of the zeroth-order beam. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2355455]

The ever-growing demand of information technology requires the solutions for heavy traffic of communications, high-density storage, and high-speed computing. In the last few decades, photonics, the technology of photons, analogous to the case of electronics as the technology of electrons, has been proven to be a promising solution for high-speed communication and computing. The pioneering works by Yablonovich[1] and John[2] ignited the intensive researches in the field of photonic crystals (PCs), and opened an era of photonics because of their promising applications in micro- and optoelectronics.[3] PCs are materials or artificial structures with a spatially periodic variation of dielectric constants. If PCs are made of magnetic materials, which are called magnetic PCs (MPCs), one more degree of freedom can be added to the ordinary PCs.[4] Under an external applied magnetic field, for instance, the optical properties of MPCs can be tuned. In addition, temperature is another important variable for tuning, since the magnetic transition at their Curie or Néel temperature might change the magnetic permeability. As a consequence, the complex dielectric constant is altered. Metallic magnetic materials have a complex dielectric tensor with off-diagonal components, which induce the magneto-optical (MO) responses.

The MO diffraction technique is very useful to investigate the micromagnetic properties of periodic structures based on magnetic/nonmagnetic media. There are several reports on the one-dimensional (1D) array structures prepared by selective-area reactive ion etching[5] or electron-beam lithography followed by ion milling.[6,7] Inoue *et al.*[8] also investigated theoretically the MO Faraday effect of discontinuous magnetic media with a 1D array structure to understand the experimentally observed enhancement of Faraday rotation from porous magnetic media.[9] However, the fabrication of 1D MPCs by selective-area reactive ion etching or electron-beam lithography followed by ion milling usually consumes great effort and time, and more simplified fabrication methods are required in practice.

We have fabricated 1D magnetic gratings and investigated their various properties. In this letter, the experimental results of a 1D magnetic grating made by a rather simple method will be presented. The fabricated 1D magnetic gratings consist of alternating arrays of magnetic and nonmagnetic regions. The rotation of polarization of first-order diffracted beam is greatly enhanced, compared to the zeroth-order (undiffracted) beam.

An amorphous thin film was deposited on glass substrates using rf magnetron sputtering at room temperature in a base pressure lower than 3×10^{-7} Torr. The sputtering target was prepared from a Co_2MnSi ingot produced by arc-melting the mixture of stoichiometric Co, Mn, and Si powders. The Ar pressure was kept at 1 mTorr during deposition and the deposition rate was 7 nm/min. In order to record the gratings, we used the two-beam interference of femtosecond laser pulses. The femtosecond laser system used in this experiment was a regeneratively amplified Ti:sapphire laser with 800 nm output wavelength, 130 fs pulse duration, 1.0 mJ maximum pulse energy, and 1 kHz repetition rate. The pulse energies of two interfering beams were equal to each other, and the intersection angle between them was 24°. A detailed description of femtosecond laser interference crystallization is described elsewhere.[10]

A commercial scanning probe microscope (PSIA XE-100) was used to study surface morphology together with magnetic domain structure. The magnetic domain structures were obtained by operating in the noncontact lift mode. Hysteresis loops were measured by using a Kerr microscope

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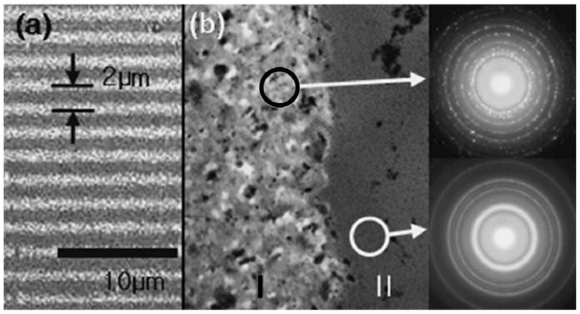

FIG. 1. (a) SEM image of a Co_2MnSi film irradiated with 20 000 shots of two 120 μJ laser pulses and (b) TEM image of the same sample. "I" denotes the area which corresponds to the bright-band in the SEM image, whereas "II" indicates the dark-band region. The TEM selective-area diffraction pattern from each region is also included in (b).

magnetometer on the sample area of 80×64 μm^2 with a field sweeping rate of 30 Oe/s. The rotation of the polarization was measured in the normal incidence by using a polarimetric method.[11] A He–Ne laser was used as a light source and a detection system equipped with a photomultiplier tube (Hamamatsu R374) is used. For the polarizing optics, two MgF_2 Rochon polarizers (Karl Lambrecht Corporation MFRV5) were used. The external magnetic field was applied perpendicular to the undiffracted and first-order diffracted beams using an electromagnet capable of a maximum field of 5 kOe. Since the direction of magnetic field is different from the traditional measurements of Faraday rotation, we will call it a Faraday-like rotation.

Initially, Co_2MnSi film was deposited onto a Si wafer at room temperature. The transmission-electron microscopy (TEM) study reveals that the as-deposited film has an almost amorphous structure [see Fig. 1(b)] and exhibits no magnetic responses. It is well known that some of the Heusler alloys lose their ferromagnetism upon structural order-disorder transition.[12–15] By annealing the film at 500 °C for 2 h the $L2_1$ crystalline structure and the ferromagnetic behavior were recovered. Annealing at higher temperature, say, 600 °C for 5 h, results in the decomposition of the film into Co, Mn, and Co_2Si.

Based on the above observations, we applied the selective-area laser annealing to the as-deposited Co_2MnSi film to fabricate 1D MPC. The thickness of the as-deposited film is 100 nm. As shown in Fig. 1, both the scanning-electron microscopy (SEM) and TEM studies reveal that a 1D magnetic grating was fabricated by using the selective-area annealing with the two-beam interference technique of femtosecond laser pulses.

Figure 2 shows the atomic-force microscopy (AFM) and magnetic-force microscopy (MFM) images from the samples irradiated by 10 000 (we refer to this as sample $\mathfrak{A}$) and 3000 (we refer to this as sample $\mathfrak{B}$) laser shots at 61 μJ. For sample $\mathfrak{A}$, the AFM image in Fig. 2(a) clearly shows a pronounced surface roughness in the bright-band region, while the dark-band region is smooth, as expected. The corresponding MFM image also revealed two different magnetic states in the sample. The dark-band region may have received sufficient energy to trigger crystallization, however, the grain size was extremely small below the superparamagnetic limit [~5 nm for Co (Ref. 16)]. Therefore, the dark-band region is expected to be paramagnetic or weakly ferromagnetic at room temperature whereas the increased grain size of the bright-band region should overcome the superparamagnetic effect. The MFM results indeed indicate that the bright-band region has substantially higher magnetization than the dark-band region. A trace of precipitated Co was observed in selected-area electron diffraction patterns from the bright-band regions. It implies that the irradiance at the bright-band regions is still too high to form the ordered $L2_1$ structure. In sample $\mathfrak{B}$, the microstructural difference could not be detected using TEM, although the AFM image in Fig. 2(b) evidently suggests that there is a topological difference between the dark- and bright-band regions. In addition, the MFM image clearly resolved two different magnetic structures with the same periodicity of 2 μm, directly matching the topological difference.

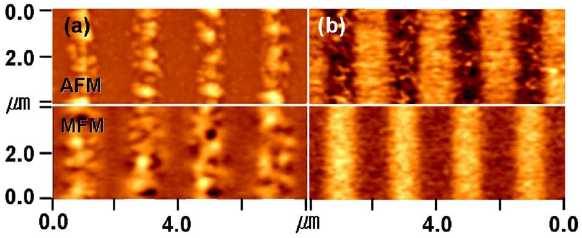

FIG. 2. (Color online) AFM (upper row) and MFM (lower row) images of the Co_2MnSi films irradiated (a) with sample $\mathfrak{A}$ and (b) with sample $\mathfrak{B}$.

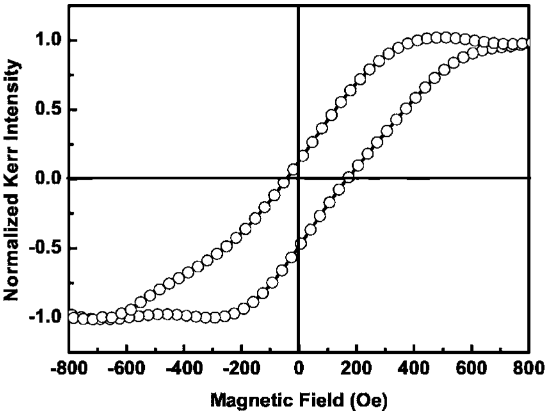

FIG. 3. Hysteresis loop measured in longitudinal Kerr rotation for sample $\mathfrak{B}$. Lines are guide to the eyes only.

Although sample $\mathfrak{A}$ has a magnetic contrast, the sample surface is too rough and the boundaries between the dark- and bright-band regions are not sharp. Consequently, two magnetically different regions are not clearly differentiated. Furthermore, the magnetically more ordered regions are very inhomogeneous. Meanwhile, sample $\mathfrak{B}$ has clearer boundaries than sample $\mathfrak{A}$ and shows clear distinction between two magnetically different regions. Therefore, we believe that sample $\mathfrak{B}$ is more appropriate for our purpose and we will discuss the properties measured for sample $\mathfrak{B}$.

The hysteresis loop has been recorded by measuring the longitudinal Kerr rotation and is displayed in Fig. 3. A magnetic field was applied along the groove direction. The measured hysteresis loop suggests to us that sample $\mathfrak{B}$ is composed of a few magnetically inhomogeneous phases, which is indicated by a rather steep slope. It is another indication of the formation of the 1D magnetic grating fabricated by the selective-area annealing using the two-beam interference of femtosecond laser. In the case of external magnetic field directed normal to the sample plane or normal to the groove direction, the film could not be saturated within the range of

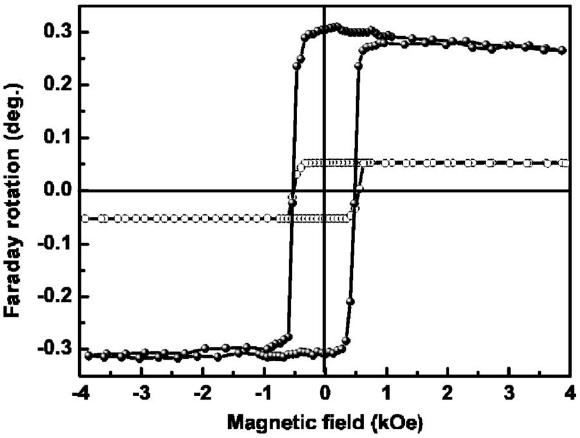

FIG. 4. MO Faraday-like effect for the zeroth- and first-order diffracted beams from sample 𝔅. Lines are guide to the eyes only.

external magnetic fields (1 kOe in plane, 3 kOe normal to the plane).

Figure 4 shows MO Faraday-like effect for the zeroth- and first-order diffracted beams for sample 𝔅. The Faraday-like rotations of both beams clearly exhibit hysteretic behavior. As seen in Fig. 4, a nearly six times enhanced Faraday-like rotation has been observed for the first-order diffracted beam. For now, we do not know the exact reason for the enhanced MO rotation of the first-order beam diffracted from the periodical magnetic array; however, we speculate that, since some kind of phase-matching condition leads to the constructive interference for the first-order diffracted beam, the same phase-matching condition might also lead to the enhanced Faraday-like rotation. Further studies are in progress both theoretically and experimentally to understand the enhanced MO effect for higher-order diffracted beams.

In conclusion, we have fabricated gratinglike one-dimensional magnetic photonic crystals by using a very simple method: selective-area annealing of two-beam interference of femtosecond laser. The AFM and the MFM studies reveal that the obtained 1D magnetic grating has an array-type structure with a significant magnetic contrast. We observed a considerably enhanced MO Faraday-like rotation for the first-order diffracted beam, compared to the zeroth-order beam. Further studies are needed for more thorough understanding of the enhancement, which are in progress.

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