Study of Cerium Doped Terbium Iron Garnet Thin Films for Magneto-Optical Applications

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Abstract:

Thin films of magneto-optical materials are useful in optical isolators, which are devices used in photonic circuits as "optical diodes" to prevent reflected light from damaging the laser source. This is achieved by an effect called Faraday rotation, which is a rotation of the polarization of light when passing through a magneto-optic material. The material studied in this project was cerium doped terbium iron garnet (Ce:TIG/$Ce_xTb_{3-x}Fe_5O_{12}$). The thin films were deposited on silicon and fused quartz substrates using reactive sputtering in an oxygen environment. The iron and terbium targets were sputtered at a constant power while the cerium power was varied to change the cerium concentration. The samples were annealed at 700°C, 800°C, and 900°C using rapid thermal annealing (RTA). The characterization of the samples included measuring the Faraday rotation using an optics bench setup with a 1545 nm laser. A correlation between increasing cerium content and the Faraday rotation was observed. Future work will include developing optical isolators with Ce:TIG as the magneto-optical material on a silicon platform for use in photonic circuits.

Introduction:

Optical isolators are important for use in waveguides for integrated photonic circuits; these devices prevent reflected light from damaging the laser source. Magneto-optical materials are useful for the development of optical isolators due to their ability to rotate the polarization of light through the Faraday Effect [1]. This effect, $\beta = vBd$, relates the angle of rotation of the polarization (β) to the Verdet constant (v) of the material, applied magnetic field (B), and thickness of the material (d) [2]. In this project, thin films of the magneto-optical material cerium-doped terbium iron garnet (Ce:TIG) were developed and the amount of cerium deposited in the thin films was varied in order to measure the magneto-optical properties and optimize the Faraday rotation.

OPTS

Experimental Procedure:

The samples were deposited using an oxygen reactive sputtering process on silicon and fused quartz substrates. We used three targets in the sputtering chamber: iron, terbium, and cerium. The sputtering power for iron was fixed at 220 W, terbium at 110 W, and the cerium power was varied from 0-100 W in 10 W intervals. We then annealed three samples from each batch, one each at 700°, 800° and 900°C.

We were able to achieve the garnet phase from 0-50 W cerium when these samples were annealed at either 800° or 900°C. Annealing at 900°C for two minutes formed the best garnet out of all our samples. We were also able to achieve the garnet phase from 30-50 W cerium on GGG substrates.

After checking for crystallization using x-ray diffraction (XRD), we further characterized the samples using a scanning electron microscope (SEM), vibrating sample magnetometer (VSM), energy-dispersive x-ray spectroscopy (EDS), and an optics bench setup with a 1545 nm laser to measure the Faraday rotation coefficient of the samples.

Results and Conclusions:

In observing the samples with the SEM, cracking of various sizes was noted on most samples due to a mismatch in the thermal expansion coefficients between the substrate and thin films (see Figure 1); however, this can be eradicated in actual waveguide development by patterning the samples before deposition [1].

Some challenges were encountered when measuring the atomic percentage of cerium contained in the samples with EDS, due to non-uniform composition of the samples from the sputtering process and initial technical difficulties with the EDS. The results were somewhat surprising, as increased cerium sputtering power did not always directly relate to increased atomic percent of cerium, as is shown in Figure 2. This was most likely due to variability in the bias voltage

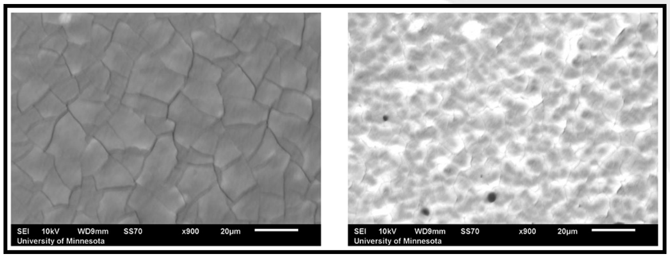

Figure 1: SEM images showing various irregularities in samples. The left image is from a sample with 30 W cerium; the right image is from a sample with 60 W cerium, which did not form garnet. Both samples are on silicon substrates.

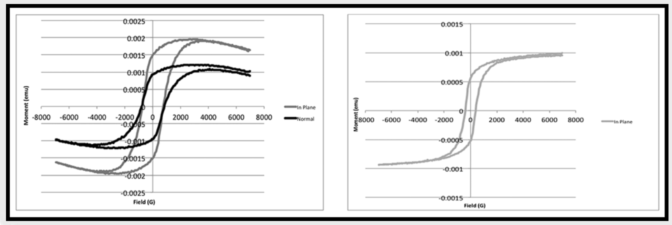

Figure 3: VSM measurements. [Left] Initial VSM measurements for the sample with 20 W cerium. [Right] VSM measurements after subtracting silicon contributions (used in-plane loop only).

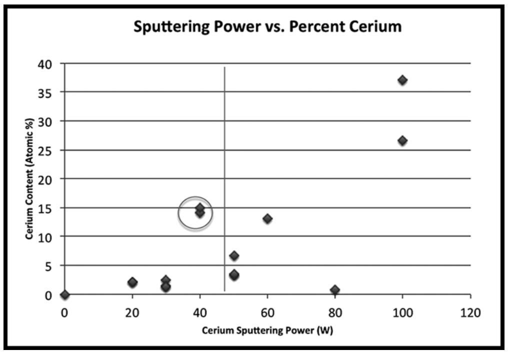

Figure 2: EDS results were slightly inconsistent — the dark grey vertical line represents the cutoff of samples that were able to form garnet. Circled data points represent the garnet sample with the highest atomic percent of cerium.

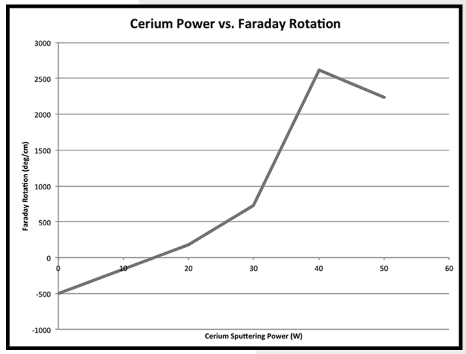

Figure 4: Faraday rotation measurement results.

during the sputtering process, and further sample creation to gather additional data will be necessary in the future.

Measurements with the VSM were also initially challenging, as many of the hysteresis loops were slanted or did not close at one end, which did not agree with previous results from similar samples. We hypothesized that this could be explained by contributions from the silicon substrates, and were able to correct for this by subtracting readings from blank silicon for some of the measurements (see Figure 3).

The Faraday rotation measurements were promising for the samples; large negative Faraday rotations of -2240° cm^{-1} and -2620° cm^{-1} were observed for the two garnet samples with the largest atomic percentage of cerium. In general, a positive correlation between cerium content and Faraday rotation was observed, shown in Figure 4. However, due to irregularities in the sputtering process future characterization will be required to confirm this.

Future Work:

More sample fabrication and characterization will be necessary to determine the optimal recipe for Ce:TIG that produces the greatest Faraday rotation. After this has been determined, waveguides can be fabricated and tested for eventual use in photonic circuits.

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[2] Dulal, P. "Development of Novel Iron Garnet Thin Films for Magneto-optical Applications." A proposal submitted to the ChemE and MSE faculty and the Graduate School of the University of Minnesota by P. Dulal in partial fulfillment of the requirement of the candidacy for the degree of Doctor of Philosophy.