Implementation of a Grating-type Spatial Optical Switch based on Phase Change Material and its Static Measurement

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Keywords: Spatial Optical Switch, Diffraction Grating, Phase Change Material.

Abstract: We have implemented a new grating-type spatial optical reflection switch based on phase change material (PCM) for usage at optical communication wavelength. This grating device switches on/off the light or steers the light propagation direction by switching the PCM grating between its amorphous and crystalline states. Thus, the switching status is non-volatile and the device is promising for power saving optical network. Based on the design by numerical computations, the prototype grating device was fabricated by electron beam lithography and laser interference lithography techniques. The static switching characteristics were measured by optical diffraction experiments for the two states of the grating.

1 INTRODUCTION

Since the proposal of chalcogenide-type phase change material (PCM) memory and switching devices by Dr. S. R. Ovshinsky in 1960s (Ovshinsky, 1968), PCM has achieved tremendous success in rewritable optical disks such as CDs, DVDs and Blue-ray Discs. Recently, this material has attracted dramatically increasing interests in modern semiconductor industry as a non-volatile phase change random access memory (PRAM) (Burr et al., 2010); (Raoux et al., 2010). Thanks to its fast-speed, long cyclability and superior scalability, PRAM is expected to replace the close-to-limit Flash Memory and is even considered as a potential candidate for the universal memory in new computer architecture. Following exactly the same strategy, PCM has also been proposed to be used in optical switches (Strand et al., 2006); (Ikuma et al., 2008). Though the expected speed of a PCM optical switch is on the order of tens of nano-second, much slower than that of a modern pico-second or femto-second optical switch, the non-volatile characteristic makes it attractive in fields such as optical path routers which operate at moderate speed but require low power consumption. In this genera, it is orders of magnitude faster than the millisecond speed achievable by micro electro mechanical system (MEMS) switches, thermo-optic switches or liquid crystal switches. Recently, a prototype waveguide-type PCM optical switch has been demonstrated by our group (Ikuma et al., 2010). We have also proposed a spatial type PCM optical switch based on diffraction grating (Wang et al., 2009).

In this paper, we review some aspects of the proposed grating-type switch and describe its fabrication process. Finally, its basic static diffraction performance is measured and discussed.

2 PRINCIPLE OF A GRATING-TYPE OPTICAL SWITCH

Figure 1 shows schematically the proposed grating-based optical switch. It uses a Kretschmann configuration with a semi-cylindrical prism on top of the index-matched substrate to couple the light in and out, and a PCM grating fabricated on the opposite surface of the substrate to diffract the light. This configuration has been carefully engineered so that the number of diffracted orders by grating is reduced to a minimum. First, the total-reflection scheme suppresses all the transmitted diffraction orders. Secondly, the period of grating is such chosen that only the first order reflected diffraction and the specular reflection are allowed to exist. More details are provided in the reference (Wang et al., 2009). As a result of the numerical simulations,

Wang X., Kuwahara M., Kawashima H. and Tsuda H..
Implementation of a Grating-type Spatial Optical Switch based on Phase Change Material and its Static Measurement.
DOI: 10.5220/0004338801010105
In *Proceedings of the International Conference on Photonics, Optics and Laser Technology* (PHOTOPTICS-2013), pages 101-105
ISBN: 978-989-8565-44-0

the optimal grating structure is assumed to be of a period of 600 nm and a duty-ratio of 50%.

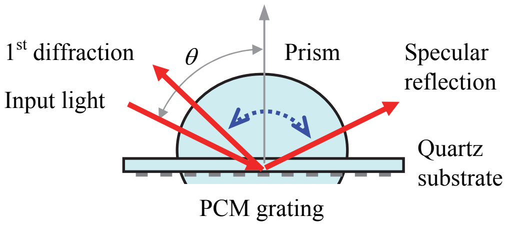
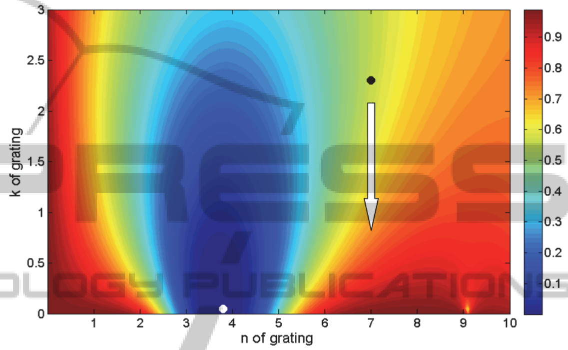


Figure 1: Schematic of the proposed optical switch by PCM grating. Light is coupled in and out by the top semi-cylindrical prism. The incidence angle of input light is indicated by θ.

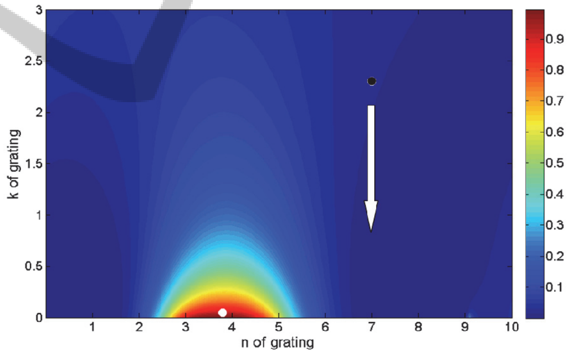
To show how the diffraction efficiency of the grating depends on the refractive index, Figure 2 shows the simulated efficiencies of specular reflection and first diffraction order as the contour maps with regard to the grating's refractive index n + *i* k. The simulation was carried out by the rigorous coupled wave analysis (RCWA) method (Moharam and Gaylord, 1982); (Li, 1997) for the optimal grating with an incidence angle of 62° and an *s*-polarization input. In the maps, the refractive indices of a popular phase change material, $Ge_2Sb_2Te_5$ (GST), are represented by the white and black dots for its two phase states. GST material was invented by Yamada et al. (1987) and is an important PCM because of its superior crystallization speed and large refractive index contrast during phase change. For the optical switch applications, this material is also a good candidate because its amorphous state is virtually transparent at 1.55 µm wavelength (n + *i* k = 3.8 + *i*0.05, as measured by our spectroscopic ellipsometer), and its crystalline state has a moderate absorption (n + *i* k = 7.0 + *i* 2.3).

According to Fig. 2, we can see that, when the grating is in amorphous state (white dots), the specular reflection efficiency is almost zero, while the first diffraction has a very high efficiency of 92%. On the other hand, when the grating turns into crystalline state (black dots), the efficiency of specular reflection is about 60% but that of first diffraction becomes negligible. All other orders of diffraction are computed to be zero. Therefore, by properly controlling the phase state of a grating made of GST, we can turn on/off the specular reflection light, or steer the inputted light to either the specular reflection direction or the first diffraction direction. Thus it can be used as an optical path router. The first diffracted beam can even be designed to couple back to the input direction and diverted to other route by a circulator, thus simplifying the optical coupling at input port.

The relatively poor reflection efficiency for the crystalline state grating (black dot in Fig. 2(a)) is due to the relatively larger absorption of crystalline GST. As indicated by the arrows, if a PCM with lower k becomes possible, a higher reflection efficiency and lower first diffraction are achievable for the crystalline state. In fact, Strand et al. (2006) has tried and succeeded in tuning the absorption of GST to a much lower value by adding some alloy composition.



(a) Specular reflection



(b) First diffraction order

Figure 2: Contour maps showing the diffraction efficiencies of specular reflection and first diffraction order as functions of the refractive indices of PCM grating. The white dots indicate the n + *i* k of the amorphous GST material, and the black dots indicate that of the crystalline GST. A lower absorption k for the crystalline GST is desirable for better crystalline performance. The incidence angle θ is assumed to be 62°.

It should be noted that the above behaviour does not apply to a *p*-polarization light because of the inherent anisotropy in the grating structure. The *p*-polarized light always comes out as specular reflection. From another point of view, the PCM grating may also be used as a switchable polarization splitter where the *s*-polarization can be selectively separated from the specular reflection port.

3 FABRICATION OF THE PHASE CHANGE MATERIAL GRATING

According to numerical simulations, the optimized grating structure is a GST grating of 50 nm thickness and a 300 nm line-and-space. We had used electron-beam (EB) lithography to fabricate this sub-micrometer PCM grating on a silica substrate. For easy optical alignment, a large grating area of 2×2 mm^2 is preferable. It turned out that this large area of electron beam writing is quite challenging because of the charging-up effect on a silica substrate. We had to choose a lower electron acceleration voltage and carefully coat the resist film with a conducting polymer layer (Epacer 300). After hours' EB writing a rather uniform grating structure was obtained.

To make the fabrication process simpler and cheaper, later we shifted our process to the laser interference lithography where a Lloyd's mirror interferometer (Fucetola et al., 2009) was built up. A He-Cd laser of 441.6 nm wavelength was used as the optical source. The sample holder was located at about 70 cm far away from the spatial filter, and the holder angle α is set as 68.4° in order for the grating period to be 600 nm (as period = λ/2cosα). The diluted photo-resist OFPR800 was found to be sufficiently sensitive at the wavelength of 441.6 nm and have adequate resolution to produce the 300 nm line and space pattern. By carefully tuning the exposure time and develop time to the optimal condition, a large area (1×3 cm^2 elliptic shape) of uniform grating could be developed in very short time. An example of such made grating pattern is shown in Fig. 3. Because of the existence of small residual fluctuation in wavefront of our interference system, the grating lines also show some fluctuations when observed under a scanning electron microscope (SEM), and are less uniform than those fabricated by EB lithography. Nevertheless, it is expected that the fluctuation will not affect much when conducting the optical experiment.

Then, a GST PCM layer was deposited on the resist pattern with a reactive RF-magnetron sputtering system (CFS-4ES by Shibaura Co.) in an Ar gas atmosphere. The pressure of the Ar gas was set to 0.5 Pa and the RF power was set to 100 W to keep the sample cool enough. After lifting-off in acetone, a GST grating of designed period was obtained.

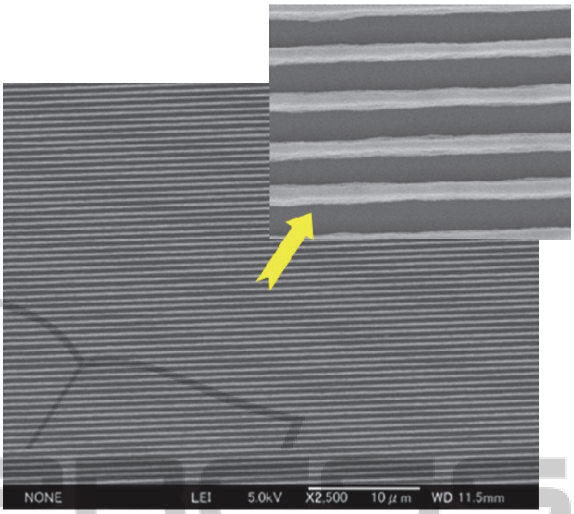


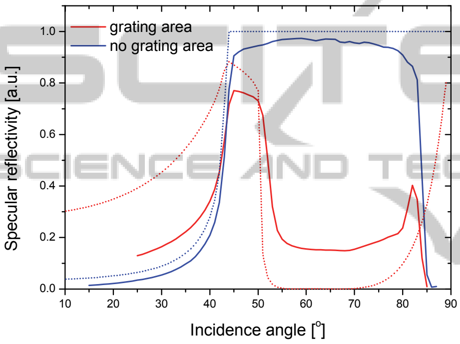
Figure 3: SEM image of the grating pattern fabricated by laser interference lithography.

4 STATIC DIFFRACTION MEASUREMENTS

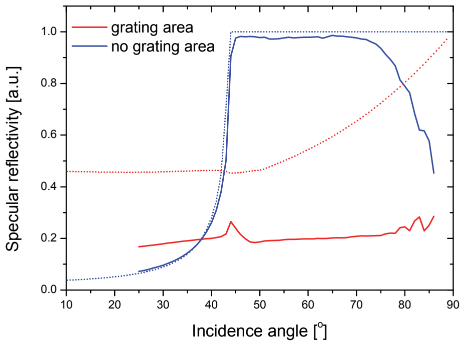
To validate the switching behaviour given by Section 2, we measured the static optical diffraction of the GST grating when it is in the amorphous or crystalline state. All the measurements were performed on a modified spectroscopic ellipsometer (VASE by J. A. Woollam Co., Inc). We used the ellipsometer simply as an optical platform, to take advantages of its convenient optical coupling system as well as the precise goniometric mechanism. The equipment's standard sample holder and stage were replaced by a handmade stage together with other optical gadgets in order to implement the Kretschmann configuration. In addition, the hardware control setting has been customized to allow the angles of input and output arms to be set independently. In this way, for a fixed incident beam, we can measure its diffraction at any direction.

In Figure 4(a), the specular reflection efficiency of *s*-polarized light for an amorphous GST grating was measured for different incident angle θ. The reflection of the no-grating area was also measured and plotted in the same figure as a reference. Indeed as the incidence angle θ goes beyond the total reflection angle, the specular reflection drops quickly because of the diffraction by the grating. This behaviour agrees well with the light scattering predicted by simulation which is also plotted in the same figure with dotted line. However, the residual specular reflection at incidence angles larger than 55° does not go to zero. The reason is considered to be due to imperfection of the PCM grating.

Next, to conduct the measurement for a crystalline GST grating, the as-deposited amorphous GST grating sample was annealed at 200°C for 5 minutes to convert into the crystalline state. The measured results are shown in Fig. 4(b). As expected, the specular reflection does not show a fast drop. However, the overall amplitude is quite lower than simulation which might also be due to fabrication error and large absorption in crystalline GST. Especially the thickness of GST was suspected to be thicker than designed.



(a) Amorphous GST grating



(b) Crystalline GST grating

Figure 4: Measured specular reflection efficiency of *s*-polarized light for a GST grating. The optical wavelength is set as 1.55 μm. The specular reflection of no-grating area is also measured as a reference. In addition, the simulation results are plotted in dotted lines.

5 CONCLUSIONS

To verify the concept of a spatial grating-type PCM optical switch, we have fabricated the designed grating structure using electron-beam lithography and laser interference lithography techniques. The laser interference lithography is especially useful to generate large area periodical pattern. The static switching characteristic of the grating was verified by optical diffraction measurements for both the amorphous and crystalline states, and they agree roughly with the theoretical expectations. We believe that further precise control in fabrication will improve the experimental results. In the future, dynamic phase change by laser pulse will be necessary to testify the switching actions. The optical switch can be driven by a more absorptive visible wavelength to switch between its two phase states, just as what have been done in an optical disk system. In addition, PCM with a lower absorption at 1.55 μm is greatly desirable in order to improve the switching efficiency of the crystalline state switch.

ACKNOWLEDGEMENTS

This study was supported by a grant from the Industrial Technology Research Program, 2011, of the New Energy and Industrial Technology Development Organization (NEDO), Japan. A part of the fabrication work was conducted at AIST Nano-Processing Facility, supported by "Nanotechnology Network Japan" of the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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