Paper

Fabrication of grating couplers using submicron silicon mold

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This paper describes a novel simple process suitable for fabrication of grating coupler on the optical waveguide using silicon mold. The mold was fabricated using electron beam lithography and fast atom beam etching. Submicron grating patterns were transferred from silicon mold to polymer waveguide layer. In the transfer, grating coupler and waveguide was fabricated simultaneously by the mold at room temperature in the air. In the proposed method, the good replication in submicron region is realized by the casting method without pressing. Maximum coupling efficiency 25% was obtained. This technique can also be used to fabricate other nanometer-scale structures.

Keywords: Grating Coupler, silicon mold, waveguide

1. Introduction

Recently, intense research activity in pattern duplication technology has opened up the technological capability of reliably producing very fine patterns using nanoimprint lithography.[1-5] D.Y. Khang and H. H. Lee have demonstrated room-temperature nanoimprint lithography by solvent vapor treatment of the polymer film[1]. They show that the mold or mask patterns down to 60nm can be transferred well onto the polymer film without the polymer adhering to the mold. T. Muhl et.al. have exploited the potential of local carbon oxidation to give a parallel lithography approach that was prepatterned for electron-induced parallel structuring of the carbon film[2]. M. Li et.al. have fabricated Fresnel zone plates with 75nm minimum line width in polymethyl methacrylate (PMMA) using nanoimprint lithography, and in metals by means of a lift-off technique[3]. The depth of the trenches duplicated in PMMA is uniform across the entire sample surface although about 5% shallower than the protrusion height on mold. S. Bae and S. J.Fonash have shown that patterned Ni layers are printed on amorphous-silicon films[4]. Application of such very fine lithographic technologies to the development of novel optical devices is attractive due to freedom for choosing structural parameter, high reproducibility, high productivity and thus good economic effect.

In many integrated optical devices, it is necessary to couple light from bulk optics to a channel waveguide. Either a prism coupler or a grating coupler can be used to couple a laser beam into a waveguide. Even though a prism coupler can give efficient coupling, surface corrugation grating structures are more compact and simpler for integration. It has been shown that the surface gratings in optical waveguides are useful for several kinds of grating coupler[6,7,8] and optical filters[9]. The grating is formed from photoresist by exposure to a laser interferometer fringe pattern or fabricated using a phase mask. Recently, it has been shown that the replication technologies like embossing, casting or injection molding are very powerful tools to realize polymer waveguide.[10, 11] The LIGA technique is used to form a metal mold and the Si etching technique is also applied to form a Si mold. To realize a waveguide by mold, all of them used the conventional hydraulic press to stamp the pattern. As described above, however, a few experiments have been reported on 100nm scale molding. As far as we know, there is one report on grating coupler replicated by LIGA process, in which hot pressing has been used for the fabrication of polymer interferometer[12].

In this paper, we exploit a novel simple process suitable for fabrication of grating coupler combined with optical waveguide. In the proposed method, optical waveguide has been fabricated on silicon mold. On the silicon mold, submicron grating coupler pattern has been etched. Therefore, the optical waveguide with the grating coupler has been fabricated simultaneously by removing the replica. Moreover, it can be fabricated in room temperature and in the air. We used the normal optical lithography to pattern the core of waveguide and the silicon mold to replicate submicron pitch-grating patterns on the core surface of the waveguide.

2. Structure of grating coupler

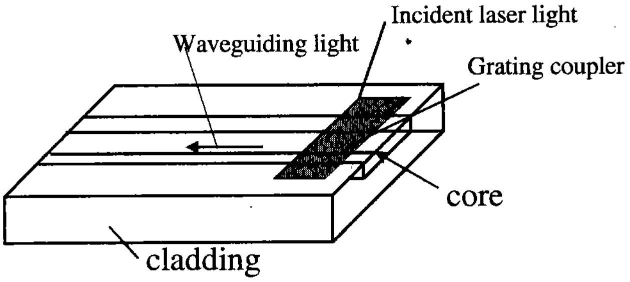


Fig.1.Schematic drawing of the fabricated grating coupler

The grating coupler, like the prism coupler, functions to produce a phase matching between a particular waveguide mode and an unguided optical beam which is incident at an oblique angle to the surface of the waveguide. Schematic drawing of the grating coupler fabricated in our experiment is shown in Fig.1. The coupler is made of polymer material by spin coating. The waveguiding-clad material is PMMA while the core is polyimide. The polyimide (UR-3100) is photosensitive so it can be patterned directly by a conventional photography technique. The grating coupler that is formed on the polyimide film with a pitch of the order of 100nm is fabricated by Si mold. A laser beam is coupled into a polyimide waveguide using diffraction by the grating coupler.

3. Fabrication of the silicon mold

Silicon molds for grating coupler with the period of 200nm and 500nm were fabricated using electron beam (EB) lithography and fast atom beam etching. The EB resist (ZEP-520, Nippon Zeon Co. ZEP) consists of a copolymer of α-chloromethacylate and α-methylstyrene. The resolution of the resist is less than 10nm.

The process is as follows. First, a Si wafer is spin coated with resist at 6000 r.p.m for thickness about 300nm. Then, it is prebaked at 150℃ for 5min. and the wafer is exposed with e-beam at acceleration voltage of 30kV, the doze time is 60μs and the beam current is 10pA. The resist is developed for 5min. in the developer (MIBK) and rinsed in IPA for 60sec. The wafer is postbaked at 150℃ for 10min. and etched with fast atom beam (FAB) etching equipment[13]. Since FAB has good directionality and deposits no charge upon the wafer surface, the Si surface is etched anisotropically and it is possible to obtain the high aspect ratio. FAB etching condition is as follows. The flow rate of the process gas SF$_6$ is 12sccm, the discharge voltage is 2.5kV and the discharge current is 40mA. The etching time is 15minutes. Finally, the residual resist is removed by the oxygen ashing.

Masks of 1:1 line and space patterns for FAB etching are prepared by using an EB pattern generator. The grating period is 500nm and the area of the patterns is 500 μmx500μm. Fig. 2 shows a typical view of the grating fabricated on silicon wafer, taken with a scanning electron microscope. The good periodicity is obtained as shown in Fig.2. The duty ratio of the grating is somewhat small due to the doze time. A line and space of 1:1 will be obtained for the optimized EB dose conditions. The grooves of the gratings are approximately 200nm in depth measured by the AFM equipment. The obtained high aspect ratio of the grating is useful for a high efficient grating coupling.

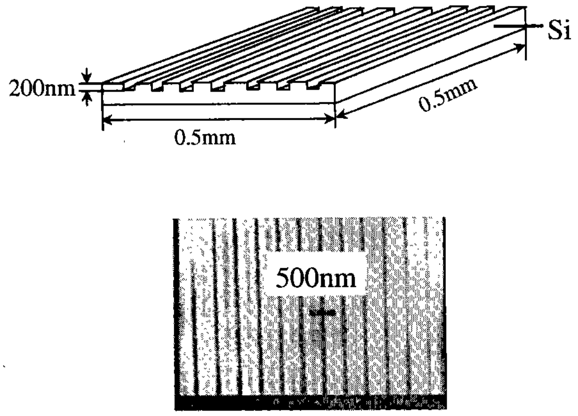
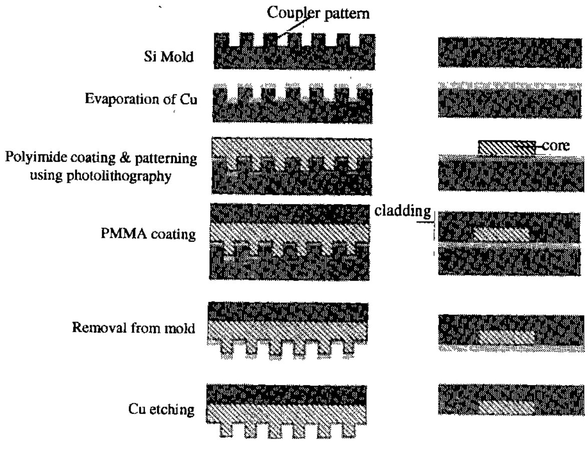


Fig.2. Fabricated molds on silicon surface

4. Fabrication of the Grating Coupler

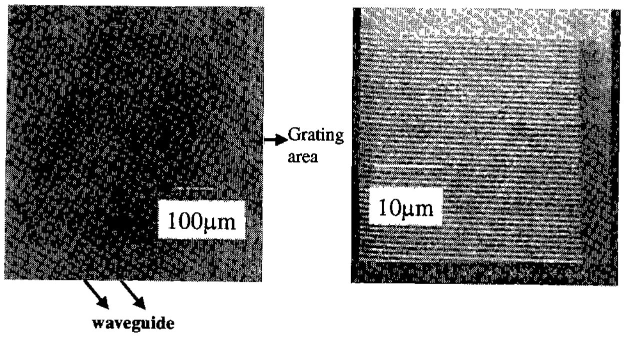
In the proposed mold casting method, the waveguide material is spin-coated on the silicon mold, on which the grating pattern for the coupler has been pre-formed. Therefore, in stripping the sample from the mold easily by taking use of the bad adhesiveness between copper thin film and silicon wafer, we can fabricate the optical waveguide with grating coupler in room temperature and in the air. Polyimide (n=1.53) and PMMA (n=1.49) are chosen as the core and cladding materials respectively. Fig.3 shows the fabrication steps for the realization of buried waveguide with nanometer-scale gratings. The left part of the figure is the front view while the right part is the side view. The substrate was a silicon wafer with eight 0.5mmx0.5mm molds on the surface.

Firstly, a very thin (about 10nm) layer of copper (Cu) film is evaporated to function as easy removal layer due to the poor adhesion force between silicon and copper thin film. Then, the polyimide film is spin coated and patterned to fabricate core layer with a refractive index of about 1.53 in 3 to 5μm thickness. In order to get well-resolved patterns, good contact between the mold plate and the lithography mask is necessary. Spinner coating is employed with 2000 r.p.m. and 20sec. duration. The polyimide film is pre-baked at 80℃ for 1hour. Using a conventional photomask with the 10μm wide waveguide patterns, the polyimide film is patterned due to its photosensitivity. The development process for the polyimide waveguide involves 4min. developing (at 20℃) with DV505 developer, 1min rinsing with IPA and without post-baking. It is important to keep strictly the development conditions in order to get reproducible results. Next, the cladding layer is coated. About 30%-wt. PMMA solution diluted with chlorobenzene is prepared to form the cladding layer. The sample is then baked at 80℃ for 4 hours in air to harden the polymer materials. The mold is mechanically apart from the polymer sampler that now contains the desired gratings by cutter at room temperature. Finally, the copper film is removed by wet etching to finish the process. When the film is stripped from the mold, neither adhered polymer nor the copper film was found in the silicon mold. In this method, it is required no press which is needed for imprint lithography. The fabricated sample is shown in figure 4(a) for the waveguide width 10μm. In figure 4(b), a part of the gratings is shown for the grating coupler with a pitch of 500nm.



Front View Side View

Fig.3. Fabrication process for grating coupler using Si mold



(a) (b)

Fig.4 (a) The grating coupler (0.5x0.5mm^{2}area). (b) Grating part with a pitch of 500nm.

Fig. 5 (a) shows a typical view of the grating mold fabricated on silicon wafer, measured by AFM. The good periodicity is obtained as shown in Fig.5 (a). The duty ratio of the grating is somewhat small due to the doze time. A line and space of 1:1 will be obtained for the optimized EB dose conditions. The grooves of the gratings are approximately 200nm in depth measured by the AFM equipment. The obtained high aspect ratio of the grating is useful for a high efficient grating coupling. The replication pattern fabricated by this method is shown in Fig.5 (b). It can be seen the replication pattern is thinner than the mold due to the removed thickness of copper thin film. And the depth and width of the grating change a little due to the removed thickness of copper thin film. The limit of the fabrication process is about 100nm pattern due to the copper thin film as a limiting factor. The pattern accuracy can be corrected because the thickness of the copper film is known. Although the edge roundness and warpage is also changed a little, it is confirmed that this novel method is effective to transfer the nanoscale pattern on microstucture. By stripping the sample from the mold, the sample may bend slightly. However, since the material of the waveguide is almost PMMA, the bimorph-like bending is not generated inherently.

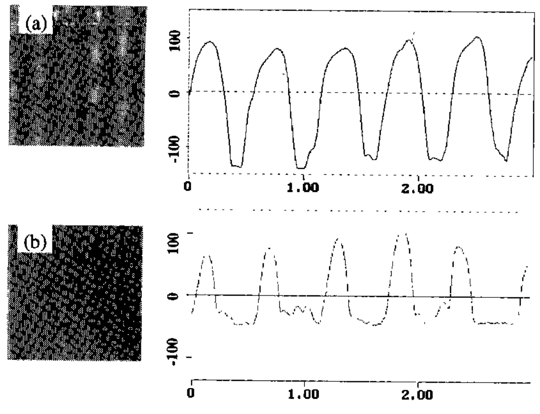


Fig.5. A pair of the fabricated mold and replica profiles measured by AFM. (a) The Si mold profile; (b) The replica profile.

5. Measurement of coupler characteristics

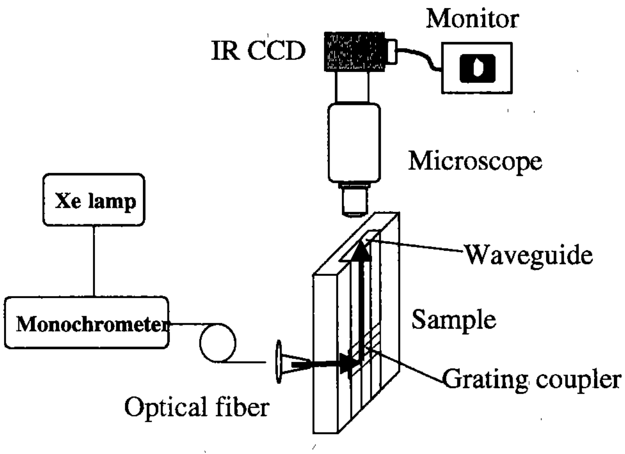


Fig.6. Experiment setup for measuring the wavelength dependence

The efficiency was measured directly by cleaving the waveguide close to the grating and collecting and measuring the light flux emerging from the cleaved end of the waveguide. Since the core of the grating coupler is only a few micrometers thick, observation of the end of waveguide is accomplished by at least 1000X magnification microscope. The diffraction efficiency of the first-order beam under the perpendicular incidence condition for a series of samples with varying grating pitch is measured by using a laser diode as a light source. The coupling efficiency for the best result was 25%. Such high efficiency is very attractive for many possible applications.

Additionally, the angular dependence of diffraction efficiency is also investigated with the experiment setup shown in figure 6. The light source is Xe lamp from which a collimated light beam passes through grating monochromater to generate monochromatic light output through the multimode optical fiber. The wavelength ranges from 200nm to 1200nm. The sample, with its waveguide at the top surface, is fixed on an x-y-z micropositioner. Microscope used for output image magnification is also mounted on an x-y-z micropositioner to facilitate the alignment that is required.

Figure 7 shows the coupling characteristics obtained by monitoring the output spot intensity from the end of the sample for a variable incidence wavelength λ. The figure shows the intensity of the output beams as a function of the wavelength for the angle of incidence θ=0, 5, 10^0. The peak value of output light intensity is shifted to short wavelength with the change of incident angle. The theoretical change ratio $\Delta\lambda/\Delta\theta$ of grating coupler is calculated to be 1.04nm/deg, which agrees with the experiment value about 1.0nm/deg in some linear range. The wavelength region of the light coupled to the waveguide is approximately 40nm wide as shown in Fig.7. The relatively narrow coupling region confirms that the periodicity of the Si mold is transferred well to the polymer although it also depends on the mode of waveguide.

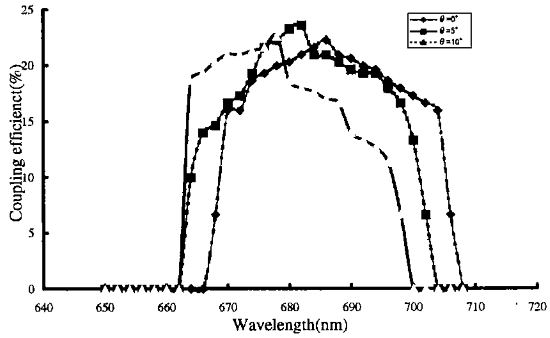
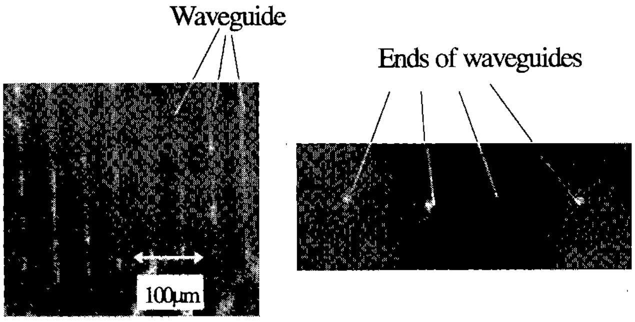


Fig.7. Output light intensity measured as a function of wavelength



(a) (b)

Fig.8. (a) Light transmission observed in the waveguide coupled by the grating coupler. (b) Output spot from the end of the waveguide observed by IR-CCD camera when the beam from the fiber is coupled into the waveguide through the grating area.

Figure 8(a) shows the guided wave (λ=0.633μm) propagated in the waveguide when the beam is incident on the grating coupler area. The output spot observed at the end-face by IR CCD and microscope (see Fig.6) camera when the beam from the fiber is coupled into the waveguide through the grating area is shown in Fig. 8(b).

6. Conclusions

Nanoscale patterns were transferred from silicon mold to polymer layer at room temperature and normal pressure. We fabricated a grating coupler to demonstrate the usability of silicon mold as tools for the fabrication of polymer submicron optical components. Silicon molds were fabricated with electron beam lithography and fast atom beam etching process. All tools yielded good replication results. No detectable wear was found by using the copper film to decrease friction. Grating coupler was fabricated by casting method without pressing. Maximum coupling efficiency 25% was obtained. In addition, because of the simple fabrication process of the silicon mold, the proposed technique to realize nanopattern on microstructure is not only valuable in the fabrication of optical components but also useful for other field where low-cost microfabrication structures are needed.

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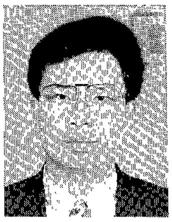

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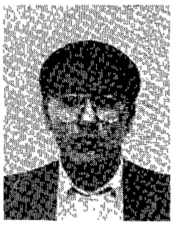

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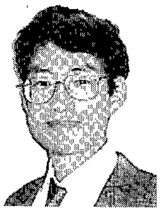

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