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Layer-to-Layer Grating Coupler Based on Hydrogenated Amorphous Silicon for Three-Dimensional Optical Circuits

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A high-index-contrast grating coupler based on hydrogenated amorphous silicon (a-Si:H) was demonstrated as a layer-to-layer coupler. a-Si:H was deposited by plasma-enhanced chemical vapor deposition and vertically stacked with SiO_2 for multilayer integration. The distance between the multilayer waveguides was fixed to 1 µm for optical isolation. The grating coupler pair was fabricated on the basis of simulation results. From the measurements of a fabricated grating coupler in the C-band, the maximum coupling efficiency was estimated to be 22%.

Silicon (Si) large-scale integrations (LSIs) are facing performance limitations caused by increasing signal delays and power dissipation in global wires.[1)] The introduction of optical wires has been proposed as an alternative to that of electrical global wires.[2–4)] As a platform material for such optical interconnections, Si is a cost-efficient candidate because it shares the platform and process technologies of current Si-LSIs (i.e., Si photonics).[5–7)] Optical components, integrated by backend process of LSIs, should avoid damages to the electronic layer. To be backend-process compatible, all the fabrication process should be regulated below 400 °C. Hydrogenated amorphous silicon (a-Si:H) can be deposited at low temperature and multilayer stacking of those waveguides has been studied for the purpose of improving the integration density as well as the total bandwidth.[8–10)]

In order to realize three-dimensional (3D) optical circuits along with multi-stacked layers, a vertical coupling between layers is necessary. Two approaches for the layer-to-layer coupling system can be considered. One involves a directional coupler-type structure that can achieve vertical coupling with a simple structure.[11)] However, the distance between the two layers must be ~200 nm, which is unsuitable in terms of optical isolation outside of the couplers. The other approach, which we propose, involves using a pair of grating couplers. Two grating couplers placed face to face between layers can transmit light even with a spacing of a few micrometers. Therefore, this structure enables multilayer vertical coupling transmission. Recently, several reports have demonstrated a similar concept for chip-to-chip optical transmission by using two grating couplers in two separate silicon-on-insulator (SOI) substrates, but not layer-to-layer transmission.[12,13)]

In this paper, we propose and demonstrate the first layer-to-layer grating coupler based on a-Si:H for vertical coupling.

A schematic image of the layer-to-layer grating coupler is illustrated in Fig. 1. a-Si:H wire waveguides (500 nm in width) were used as the input and output of the grating couplers and expanded to 5-µm-wide waveguides at the grating region in order to improve the tolerance in alignment mismatch. A linearly tapered 200-µm-long structure was employed between the wire waveguides and the 5-µm-wide waveguides to avoid reflection and excite only the fundamental mode in the wide waveguides. The grating depth was fixed to 220 nm (the same thickness as the a-Si:H layer) to simplify the fabrication process by forming the waveguides and gratings in a single step.

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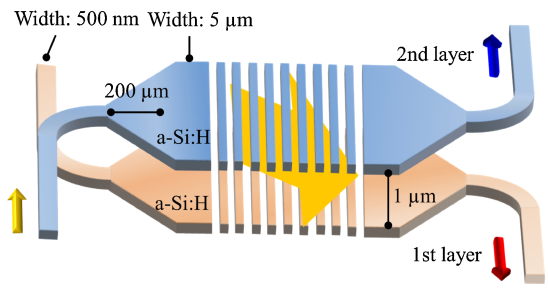

Fig. 1. (Color online) Device structure of layer-to-layer grating coupler.

By using the grating structure, light coupling with the distance of a few-µm can be realized.[14)] In order to couple light without concern for optical isolation, we adopted grating couplers with a layer-to-layer distance of 1 µm — a distance that a directional-coupler-type layer-to-layer coupler will need a coupling length of a few millimeters.

The grating period and number of periods were designed according to a 3D finite-difference time-domain (FDTD) simulation by monitoring the coupling efficiency of the grating coupler pair. The grating period is related to the diffraction wavelength, and the number of grating periods is related to the coupling efficiency of the grating coupler. Transverse-electric (TE) polarized light was used as an input, and the refractive indices of a-Si:H and SiO_2 were set to be 3.48 and 1.45, respectively. The double-layered a-Si:H waveguides and gratings were embedded in SiO_2. The Si substrate and air cladding were not included in the simulated area to reduce the calculation time.

Figure 2 shows the wavelength dependence of the calculated coupling efficiency for 10 gratings with various periods. A red shift of the peak wavelength was observed with longer grating periods. The coupling efficiency also varied with the grating period, reaching a maximum coupling efficiency of 19% with a grating period of 640 nm. In each spectrum, there are several peak positions that can be explained by resonance between the full-etched gratings. These can be suppressed by changing the etching depth.

The coupling efficiency is plotted against the number of grating periods at a wavelength of 1.55 µm in Fig. 3. The

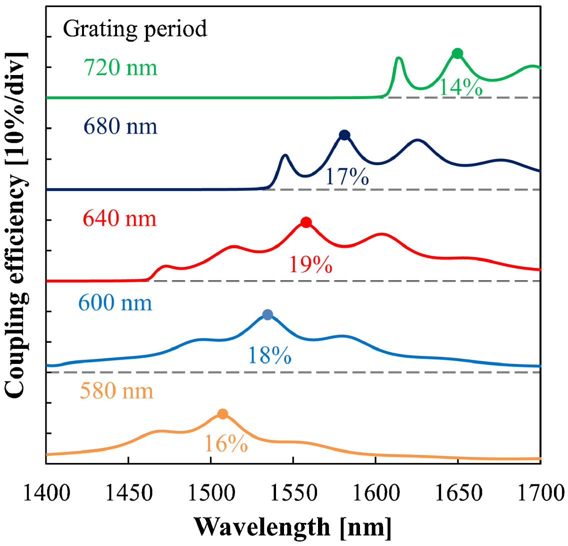

Fig. 2. (Color online) Wavelength dependence of calculated coupling efficiency for various grating periods.

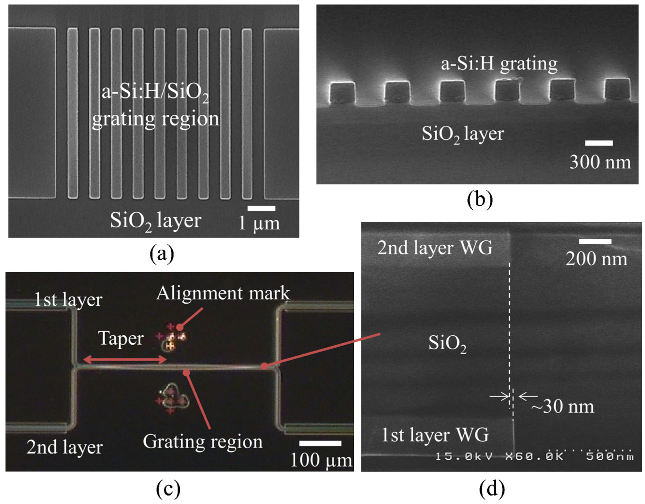

Fig. 4. (Color online) SEM images of (a) top and (b) cross-sectional views of the gratings (period: 640 nm, number of periods: 10) (c) SEM image of overlapped a-Si:H waveguides. (d) An optical microscope image of the fabricated device.

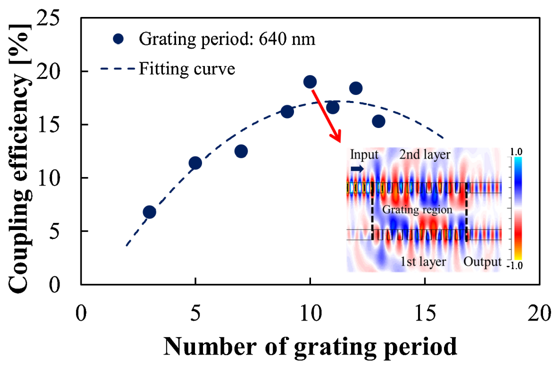

Fig. 3. (Color online) Number of grating period dependence of calculated coupling efficiency. The inset shows the transfer image of electric field with 10 gratings.

transfer image of electric field with 10 gratings is shown in the inset of Fig. 3. Given that the light input is first coupled to another layer and then re-radiated by the gratings, the coupling efficiency depends on the number of grating periods with a peak. The highest coupling efficiency was obtained at around 10 gratings.

From the simulated results, we fabricated the layer-to-layer grating coupler with 10 gratings with a period of 640 nm. Details of the process are as follows.

Films of 100-nm-thick SiO_2 and 220-nm-thick a-Si:H were deposited on a Si substrate covered with 3-μm-thick thermal SiO_2. Alignment marks for electron beam (EB) lithography were formed by evaporating the Ti/Au film on the first a-Si:H layer. The waveguides and grating patterns were formed by using EB lithography with a double-layered ZEP resist and inductively-coupled-plasma reactive-ion-etching.[15] Scanning electron microscope (SEM) images of the cross-sectional and top views of the gratings are shown in Figs. 4(a) and 4(b), respectively. As an over-cladding layer, SiO_2 was deposited and flattened by a chemical and mechanical polishing (CMP) process to obtain a thickness of 1 μm. For the second layer, a 220-nm-thick a-Si:H layer was deposited and patterned in a similar manner. After covering the second a-Si:H layer with SiO_2, the surface was flattened again by the CMP process.

An optical microscope image of the fabricated device is shown in Fig. 4(c). After the first and second layer a-Si wire waveguides are overlapped, each waveguide is widened through tapering and light coupling by the gratings occurs at the center of the figure. The cross marks in the figure were used as alignment marks during the EB lithography process. From Fig. 4(d), we confirmed that the first and second layer waveguides are vertically stacked with an alignment accuracy of around 30 nm, which did not affect the coupling efficiency.

The coupling efficiency of the layer-to-layer grating coupler was measured by coupling the TE-like polarized light to the waveguides through lens-tipped single-mode fibers. To improve the coupling efficiency at the facets, we introduced an inverted-taper spot-size converter composed of narrow waveguides (240 nm) with a tapered structure.[16] The transmission spectra of the grating couplers are shown in Fig. 5. The power transmitted between the first and second layers is plotted as open circles (red) and that which passes through the gratings of the second layer is plotted as open diamonds (blue). The transmitted spectra indicated resonance-like ripples with a period of approximately 9.5 nm, which corresponds to a resonant cavity length of around 40–50 μm. Given that the above resonance matches the distance between both ends of the tapered waveguides, the ripples can be reduced by introducing a more efficient tapered structure. The backward reflection to the input fiber was also measured, however, the reflected power was weaker than the measurement limit of our system (<-30 dB). The losses, including the propagation loss and coupling loss from single-mode fibers to the waveguides, was approximately 6 dB. The efficiency of layer-to-layer coupling was estimated from least-squares fitting curve in order to minimize the effects of the ripples. The maximum coupling efficiency was calculated to be around 22% by subtracting 6 dB from the measured data.

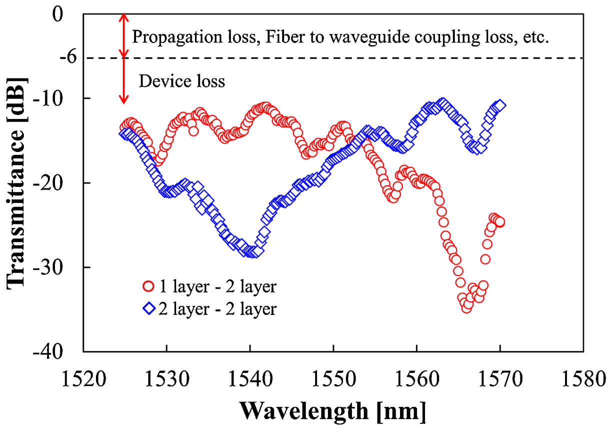

Fig. 5. (Color online) Measured transmitted spectra of fabricated layer-to-layer grating coupler.

The estimated coupling efficiency is 3% higher than that obtained from the simulation results (Fig. 2). This discrepancy can be attributed to the light reflected from the bottom boundary between the Si substrate and SiO_2 and from the top boundary between SiO_2 and the air, which was not considered in the simulation.

In the current symmetric structure with fully-etched gratings, the ratio of the light radiated upward to that radiated downward should be 1. This means that more than half of the light was wasted for each grating coupler. Therefore, 25% is the maximum coupling efficiency that can be achieved by the paired grating coupler. Further improvement in the coupling efficiency can be expected by introducing reflector sandwiched gratings. The efficiency was more than 90% in the simulation with metal mirrors.[17]

In summary, we proposed and demonstrated a grating coupler pair as a vertical coupler between two layers for 3D optical circuits. The layer-to-layer distance was set to 1 µm to suppress crosstalk between layers. All processing temperatures were maintained at less than 300 °C by using high-index-contrast multilayer waveguides with grating couplers based on a-Si:H. The calculated coupling efficiency of the paired grating coupler was 19% for 10 gratings with a period of 640 nm in the 3D-FDTD simulation. From measurements of the fabricated device, we obtained a coupling efficiency of 22%. Combining a-Si:H waveguides with the layer-to-layer grating coupler can provide valuable tools for 3D optical interconnects.

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