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High-Efficiency Micromirrors and Branched Optical Waveguides on Si Chips

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Compact mirrors and branched waveguides which can be integrated on LSI chips have been developed. The bent optical waveguides covered with an Al layer act as efficient micromirrors which change the light direction at a right angle. The Al capping also reduces the light propagation loss of the optical waveguide. Various shapes at the corner of the bent waveguide have been investigated and a reflectivity of 81 % has been obtained for the double-reflection type micromirror whose corner radius is 34 μm. This reflectivity is two orders of magnitude higher than that of the conventional curved waveguide with the same radius. Using the micromirrors, compact four branch waveguides have also been designed and fabricated.

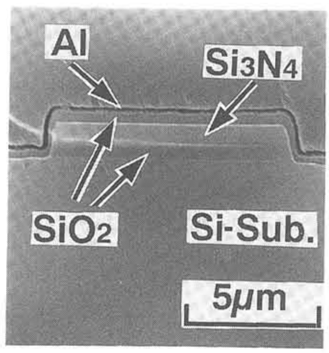
1. Introduction

As LSI chips become larger, global metal interconnection is becoming longer, resulting in an increase of parasitic capacitance and resistance. Therefore, the signal delay by the capacitance and resistance becomes an important issue. Furthermore, the increase in the clock rate also enhances the power dissipation to drive the metal interconnection. Optical interconnection is one of the promising methods to solve these problems. For example, in the case of optical clock distribution for 0.2 μm CMOS processor with 910 K gates (Vdd: 1.5 V, clock frequency: 250 MHz) with the total interconnection length of 80 mm, both the power dissipation and clock delay time are estimated to be reduced by less than one-half compared with the metal interconnection case [1], where the signal delay and the power dissipation of the laser diodes, thier drivers, photodetectors and amplifiers are considered. In order to realize the optical interconnection on LSI chips, conventional curved waveguides with large curvature radius of several mm and Y-shaped branch waveguides with a divergence angle of several degrees are not suitable.

In this paper the design and fabrication of micromirrors and branched waveguides which can be integrated on Si LSI chips are reported.

2. Characteristics of optical waveguides with Al capping

Micromirrors have been fabricated by capping the bent optical waveguides with an Al layer. Before explaining the micromirrors, the fabrication procedure and the characteristics of the Al capped waveguides are described in this section. The waveguides have been fabricated by using conventional Si LSI technologies [2-4]. The cross sectional SEM photograph of the fabricated waveguide is shown in Fig. 1. First, the bottom SiO_2 cladding layer (refractive index: 1.45, thickness: 0.8 μm) was grown on the Si substrate by thermal oxidation. Then, the 0.5 μm Si_3N_4 core layer with a refractive index of 2.0 was deposited by low pressure CVD at 750 °C. After electron beam lithography, the core and bottom cladding layers were etched by RIE to the Si surface. Next, the upper SiO_2 cladding layer with a thickness of 0.6 μm was deposited by atmospheric pressure CVD at 450 °C. Finally, the waveguides were covered with a 0.3 μm thick Al film. The sidewall at the corner of the bent waveguide covered with the Al layer acts as a micromirror.



Film Thickness	
Al	0.3 μm
Upper Clad SiO_2	0.6 μm
Core Si_3N_4	0.5 μm
Bottom Clad SiO_2	0.8 μm

Fig. 1. Cross sectional SEM photograph of the fabricated waveguide.

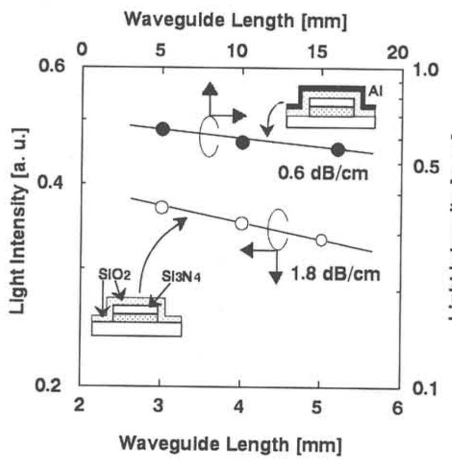


Fig. 2. Light propagation characteristics for uncapped and Al capped optical waveguides.

Figure 2 compares the light propagation losses for the Al

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capped and uncapped optical waveguides. It is found that the propagation loss is improved from 1.8 to 0.6 dB/cm by the Al capping. The optical propagation loss could be induced by the light scattering at the sidewall of the core layer with a roughness due to the patterning process [3]. By the Al capping a part of the scattered light can return to the core layer and propagate, resulting in a reduced loss.

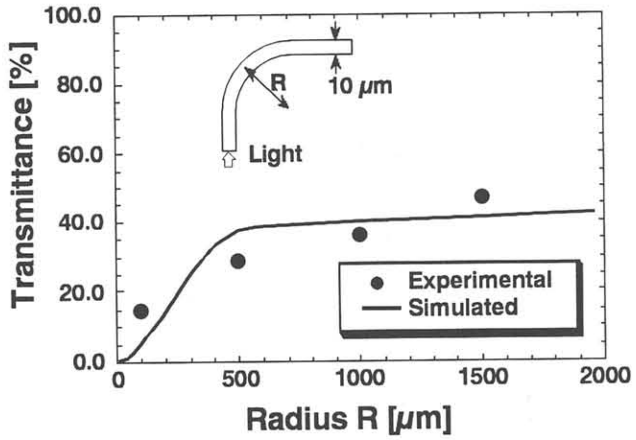
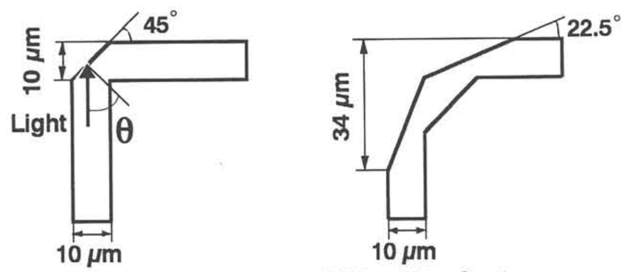


Fig. 3. The characteristics for curved waveguides without Al capping layer.



(a) Single-reflection (b) Double-reflection

Fig. 4. Two shapes of the fabricated micromirrors.

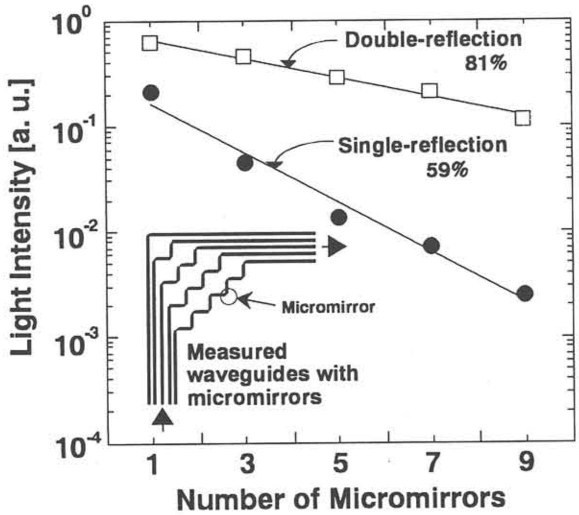


Fig. 5. Reflectivity of two kinds of the micromirrors shown in Fig. 3.

3. Micromirror

For the conventional curved waveguides, the light intensity drastically decreases with reducing the curvature radius less than 500 μm (Fig. 3). On the other hand, the micromirrors can effectively change the light direction in a small region as explained below. Two kinds of micromirrors have been fabricated as shown in Fig. 4. One is the single-reflection type micromirror with a size of 10x10 μm^2 shown in (a) and the other is the double-reflection type micromirror with a size of 34x34 μm^2 shown in (b). Reflectivities of these micromirrors have been evaluated from Fig. 5. In this figure the horizontal axis represents the number of micromirrors which are connected in series as indicated in the inset of Fig. 5. The vertical axis indicates the light intensity through these micromirrors. Since the total length of all waveguides is the same, the reflectivity of the micromirror can be derived from the slope of the line in Fig. 5. The reflectivity of the single-reflection type micromirror is 59 % while the double-reflection type micromirror has a higher reflectivity of 81 %. The difference in the reflectivity between these two micromirrors could be explained by the relation between incident and total reflection angles. The total reflection angle at the Si_3N_4 core / SiO_2 cladding layer interface is calculated to be 46.5°. Since the light incident angle θ at the corner of the single-reflection type micromirror is 45° and smaller than the total reflection angle, the light is mainly reflected at the Al sidewall. On the other hand, the incident angle of 67.5° for the double-reflection type micromirror is larger than the total reflection angle of 46.5°. Therefore, the total reflection condition at the core/clad interface is satisfied and the light is mainly reflected at this interface. Furthermore, a part of the light randomly scattered by the interface roughness can be again reflected into the waveguide by the Al sidewall. From these effects, the high reflectivity could be obtained for the double-reflection type micromirror.

4. Branched waveguide

The four branch waveguides have been designed and fabricated using the micromirrors described above. First, the comb shape branched waveguides shown in the inset of Fig. 6 were fabricated. Micromirrors are formed at one side of the branching point of the waveguides and thus the reflected

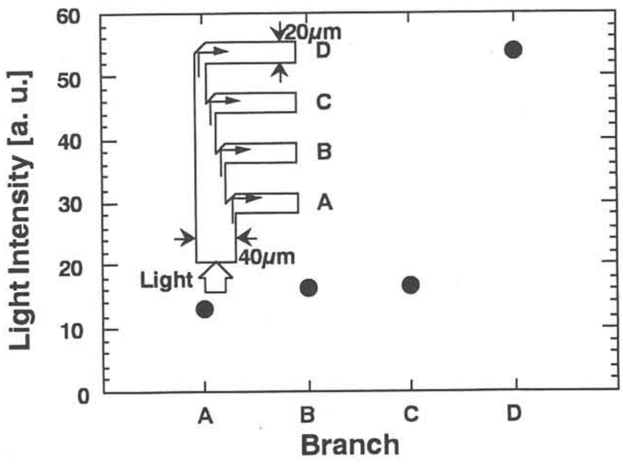


Fig. 6. Light intensity from one side four branch waveguides.

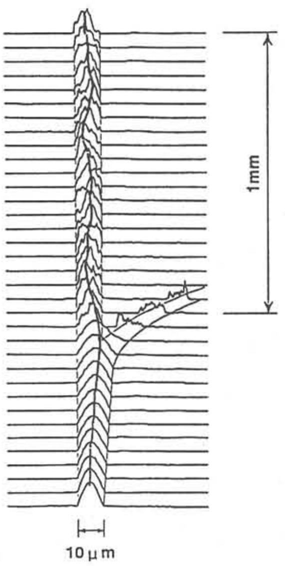


Fig. 7. Light intensity in the branched waveguide simulated by beam propagation method.

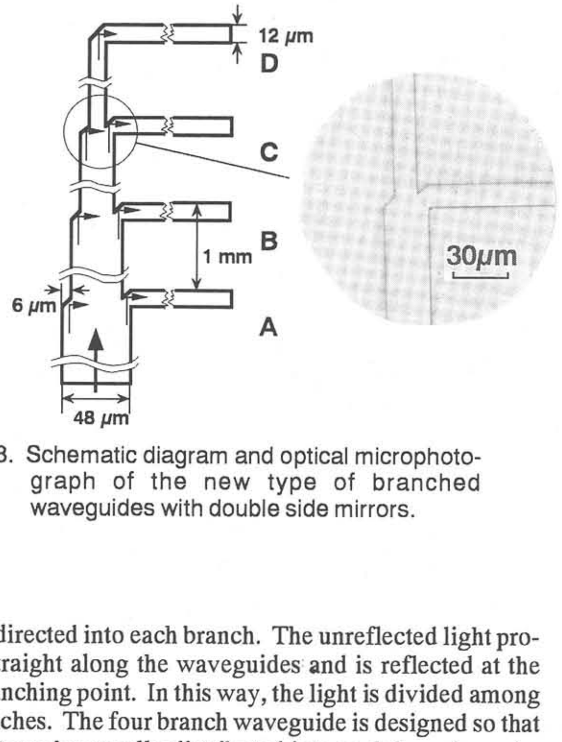


Fig. 8. Schematic diagram and optical microphotograph of the new type of branched waveguides with double side mirrors.

light is directed into each branch. The unreflected light proceeds straight along the waveguides and is reflected at the next branching point. In this way, the light is divided among the branches. The four branch waveguide is designed so that the light can be equally distributed into each branch, under the assumption that the light is divided into each branch in proportion to the mirror size. The measured output light intensity at each branch is plotted in Fig. 6. The difference in output light intensity for branches A, B and C is sufficiently low. However, the light intensity for the branch D is 4 times larger than that for the branch A. To explain this result, the light intensity distribution around the branching point has been simulated by beam propagation method (Fig. 7) [4]. It is found that after the branching from one side of the waveguide, the light intensity undulates along the waveguide. The large intensity change in the branch D in Fig. 6 might be attributed to this undulation. In order to reduce this large intensity change, a new type of branched waveguides has been designed and fabricated as shown in

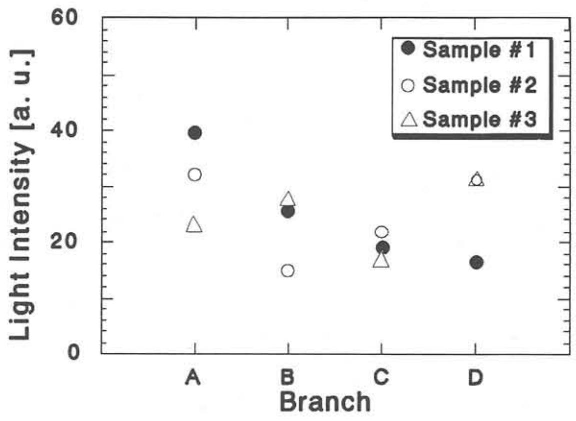


Fig. 9. Output light intensity from a new type of branched waveguides shown in Fig. 8.

Fig. 8. The incident light is reflected by the double mirrors located at both sides of the branching point and, as a result, the undulation is expected to be suppressed. The measured light intensity shown in Fig. 9 indicates that the difference in the light intensity at each of branches is reduced within a factor of two.

5. Conclusions

Micromirrors have been fabricated by capping the bent optical waveguides with an Al layer. A reflectivity of 81% has been obtained for the micromirrors with a size of 34x34 μm^2. This reflectivity is significantly high for such a small size micromirror. The propagation loss of the optical waveguides has been also decreased from 1.8 to 0.6 dB/cm by capping the waveguide with an Al layer. Moreover, four branch waveguides have been designed and fabricated with the Al sidewall micromirrors. A light intensity variation for the four branch waveguides with double side mirrors is limited within a factor of two.

6. Acknowledgment

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7. References

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