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TECHNIQUES FOR THE MICROFABRICATION OF INTEGRATED OPTICAL WAVEGUIDE COUPLERS

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I INTRODUCTION

During this quarter, we have made considerable progress toward accomplishing the objective of this program, namely, the development of an electron-beam projection exposure system (EPES) capable of producing integrated optical circuits. Our efforts have been concentrated on basic improvements in the electron exposure system to increase the area of exposure for a single pattern and to develop methods of producing multiple-registered exposure patterns. The results obtained thus far are:

(1) The EPES illumination system has been improved to provide an area of illumination 100 percent larger than that of the previous system.

(2) A rotary mask holder has been designed, which will allow the formation of up to eight different registered exposure patterns.

Concentrated research work has also been carried out to develop the transmission mask fabrication technology to allow reproducible electron-beam mask construction. Experiments to date show that further improvements in the etching techniques are required to provide the extremely high resolution transmission patterns needed for IO circuit production.

II PROJECTION SYSTEM ILLUMINATION IMPROVEMENTS

The illumination of the mask plane has been measured and was found to be uniform within 10 percent from the center of the mask out to a diameter of 0.75 in., falling off gradually to a loss of 20 percent in electron flux at 0.9 in. This variation is not enough to account for the effective mask illumination size of only 0.4 in. as measured by the actual area illuminated on the sample when the image of the mask is projected through the aperture lens.

The discrepancy between these two measurements was found to be caused by the spherical aberration of the condensing lens. This lens is an electrostatic lens of the einzel lens type, and it has a relatively large bore (2.00 in. dia.). An aperture for this lens limits the entering rays to a bundle of about 1 in. dia. Half of the lens diameter is filled with an illumination beam and the lens is very weak (focal length 7 in.), creating a strong spherical aberration. The rays near the axis (paraxial) are not deflected as strongly as those rays in the bundle at a diameter of one inch. Consequently, if the condenser lens is set to focus the paraxial rays within the beam-limiting aperture of the aperture lens, the marginal rays from the mask are overfocused and do not enter the beam-limiting aperture. Thus, the outer rays never register in the final exposed image.

The condenser lens was designed to have a minimum spherical aberration coefficient, and substantial improvements cannot be obtained by improving the spherical aberration of the lens. Since the aberration diameter at the beam-limiting aperture plane is proportional to $C_s d^3$, where C_s is the spherical aberration coefficient and d is the beam diameter at the mask, a decrease in C_s of almost 16 times must be effected to compensate for the increase of d from 0.4 in. to 1.0 in.

We examined this problem theoretically, and found no way to obtain such a large spherical aberration reduction.

As an alternative to increasing the illumination area, an ac voltage can be applied to the center electrode of the condensing lens. This alternating potential causes the focus of the lens to fluctuate so that some of the marginal rays can be brought to focus through the aperture lens. The system is not perfect because the marginal rays only pass through the beam-limiting aperture periodically, whereas the paraxial rays are continuously focused, resulting in a pattern with a bright central region. We have built a focus control system for the focus of the condenser lens, which allows various ac waveforms to be superimposed on the dc focus potential. Sine, triangle, square, and ramp waveforms have been tested for the best illumination characteristics. Sine waves have proved to be the most useful and we have been able to extend the illumination area from a diameter of 0.4 in. to a diameter of 0.55 in. by applying a sine wave with an amplitude of 15 volts to the center electrode of the condenser lens (dc potential of 450V).

As another method of improving the illumination, we tried increasing the diameter of the beam-limiting aperture, allowing more of the marginal rays to form the final image. This aperture was originally 0.005 in. in diameter. Two new aperture lenses were fabricated, one with a 0.010 in. diameter and the other with a 0.016 in. diameter. On the basis of spherical aberration data for the aperture lens, the 0.016 in. diameter is the largest possible size aperture that will keep resolution of the aperture lens to better than 1000 Å. However, when tested, the larger aperture was found to produce a lens that suffered from astigmatism rather than from spherical aberration, and whereas the effective mask illumination area increased to a diameter of 0.75 in. the resolution of the lens deteriorated to about 5000 Å. We obtained some improvement

in illumination area with the 0.010 in. dia. aperture; the diameter increased to 0.6 in. and we noted no deterioration of the image.

A third method of illumination improvement is to place a set of deflection plates before the condenser lens to scan the illumination pattern. This technique will not be implemented during this contract, because the above methods currently provide a large enough illumination field for the present integrated optical coupler patterns.

III PATTERN REGISTRATION

The maximum size pattern that can be produced with our projection system has a side-length of about 0.65 mm. This size is not sufficient to produce an entire coupler pattern in a single exposure. Lengths of over 2 mm will be necessary for simple integrated optical circuits. To accomplish this, we are rebuilding our projection system so that we can register a number of patterns on the substrate and thus form an extended pattern on the substrate by sequential exposure.

Our registration system consists of two major components. The first, the mask positioner, can be loaded with up to eight different transmission masks. These masks can be selected individually, and each can be very accurately positioned in the electron beam while the system is under vacuum. The second, is a sample stage that can be moved very accurately in one direction. With this stage, a series of patterns can be juxtapositioned to form one continuous pattern.

The mask positioner was designed and built during the last quarter. It has provisions for eight independently alignable masks. Each mask can be up to 0.75 in. square. The positioner was built to fit the present 6 in. diameter column as a modular unit. However, to accommodate eight masks, the diameter of the unit was increased to 14 inches. A rotary principle is used, whereby all the masks are mounted on a large disc that can be rotated from outside the exposure system through a vacuum seal. The alignment of the mask patterns is assured by the use of a tapered pin as an alignment dowel. This pin has been hand-lapped to give positional accuracies of the rotary stage of better than 2 μm. The entire rotary positioner can be easily removed from the projection system and placed under a toolmaker's microscope. Thus, each mask can be aligned independently to a tolerance of 0.0001 in.

The sample stage has been designed and is being fabricated. Work on the stage is expected to be completed within the next one and a half months. The basic stage is a modified translation stage manufactured by Aerotech, Inc., Allison Park, Pennsylvania. A crossed roller principle is used to give a precise linear motion virtually free of backlash, and the stage is capable of positional resolutions of 1×10^{-6} in. (250 Å). The stage has been reworked to function in a vacuum system, and it will be insulated to withstand the 5000 volts required for the aperture lenses. Translations of up to 2 in. will be possible with this stage.

To measure the position of the stage, we will use a laser-controlled system manufactured by Holograph, Inc. We will use this system, essentially interferometric, outside the vacuum chamber to determine the position of a shaft, connected to the stage, that passes through an O-ring seal in the vacuum wall. Accuracy of the Holograph measuring unit is claimed to be better than 1000 Å.

IV DESIGN AND FABRICATION OF ELECTRON TRANSMISSION MASKS

The transmission masks that are used as the objects in the electron projection exposure system are critical to the production of high resolution patterns. The masks establish both the shape of the pattern and the tolerance to which patterns can be formed. The dimensional tolerance and edge acuity of the transmission mask pattern has to be 1/M times as good as the final image, where M is the system demangification ratio (i.e., a 500 Å final edge roughness requires that the mask pattern be smooth to better than 1 μm at 20 × demagnification). Hence, the production of very accurate masks is required in the projection exposure system. Fortunately, high resolution replication processes have been developed that insure accurate mask production.

A. Fabrication Processing

The basis for the fabrication of transmission masks is the use of standard contact photolithography, and the selective etch properties of certain metal films and silicon. The detailed processing steps are outlined below for the formation of a metal transmission pattern on a silicon support:

(1) A silicon wafer about 11 mils thick is coated on one side with 1 μm gold. (An intermediate layer of chromium or molybdenum about 500 Å thick is deposited first, to prevent diffusion of the gold into the silicon.)

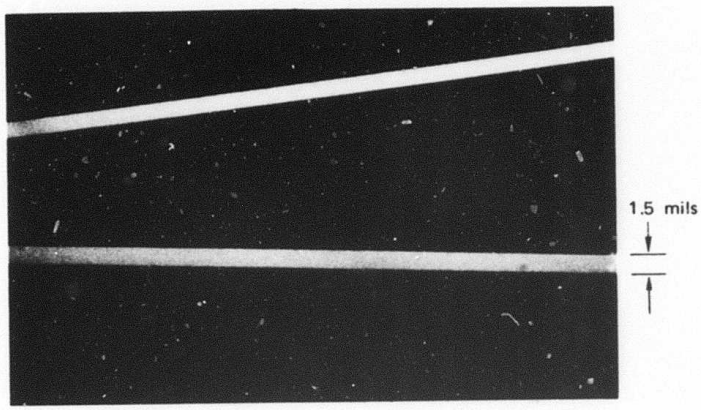
(2) The required object-mask pattern is formed on the gold by conventional photolithographic techniques, and the unprotected gold areas are RF sputter-etched to uncover the underlying areas of the silicon wafer.

(3) The exposed silicon is plasma-etched with sulfur hexafluoride (SF_6) gas to a depth of 1 to 2 mils. (With this technique, the silicon is removed at a ra of about 2.5 μm/min.)

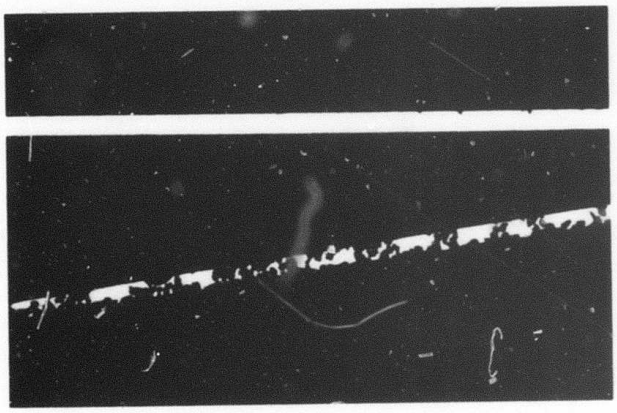
(4) The wafer is then inverted, a metal or ceramic rim mask is placed on the silicon side, and the silicon is etched from that side with either a hot potassium hydroxide (KOH) solution or SF_6 plasma to the point where the base of the pattern etched into the silicon in Step (3) is etched through, while leaving a silicon thickness of about 1 to 2 mils as the walls of the pattern.

(5) The rim mask is removed, leaving the finished object mask.

All the above process steps, with the exception of Step 4, appear to be reproducible and work quite well. Photographs of part of a transmission mask for an integrated optical coupler are shown in Figure 1. Optical transmission micrograph 1(a) shows a "clean" etched-through portion of the pattern with the openings having good edge acuity across the 1.5 mil width. Micrograph 1(b), however, shows an incompletely etched region in the opposite leg of the coupler pattern. The granular formations within the pattern are remnants of silicon that have not been completely etched away. Further back etching of the pattern is not possible, because the thin silicon support over the other areas of the mask would be completely dissolved. Hence, a better technique for the removal of the excess silicon from the back of the transmission mask needs to be developed.



(a) COMPLETELY ETCHED REGION



(b) INCOMPLETELY ETCHED REGION

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FIGURE 1 TRANSMISSION MICROGRAPHS OF OBJECT MASK PATTERN

During the next quarter we plan to test three new methods other than those described in Step (4) for selectively thinning the silicon support wafers:

(1) Orientation-preferential etching on 110 silicon,

(2) Doping-dependent selective etching on boron diffused silicon,

(3) Oxide layers for chemically selective etching.

We believe that one of these approaches will yield satisfactory, reproducible back etching for the formation of transmission masks.

B. IO Coupler Design

During this quarter, we designed and acquired two optical masks for the production of silicon-supported transmission masks of integrated optical coupler patterns The two masks were designed to produce a high coupling region, a separating region, and a low coupling region. We decided on these designs after discussions with Dr. T. Giallorenzi and Dr. A.F. Milton at the Naval Research Laboratory and used approximate theories[1,2] to establish the critical dimensions of the single mode wave guides and coupler region (to be formed by diffusion in $LiNbO_3$).

Figure 2 shows the two mask patterns to be used for initial exposures with the improved electron projection system. These patterns will be demagnified approximately 20 times for final pattern formation on the $LiNbO_3$ substrate. When reduced twenty times the 70 μm wide line should produce a single mode guide in the diffused lithium niobate ($\Delta n \sim 0.01$). The line separation (in the high coupling region), was calculated to give about 3 dB coupling over the close proximity region. The smooth arcs of the separation region were designed to yield low loss[3] (> 1dB) and are tapered at 10 degrees to the axis. In the overlap region, where the two patterns are to be joined, the line width narrows by 20 percent. This was done to compensate for any line-broadening effect of having two electron-beam exposures in this region. The low coupling region was designed to provide:

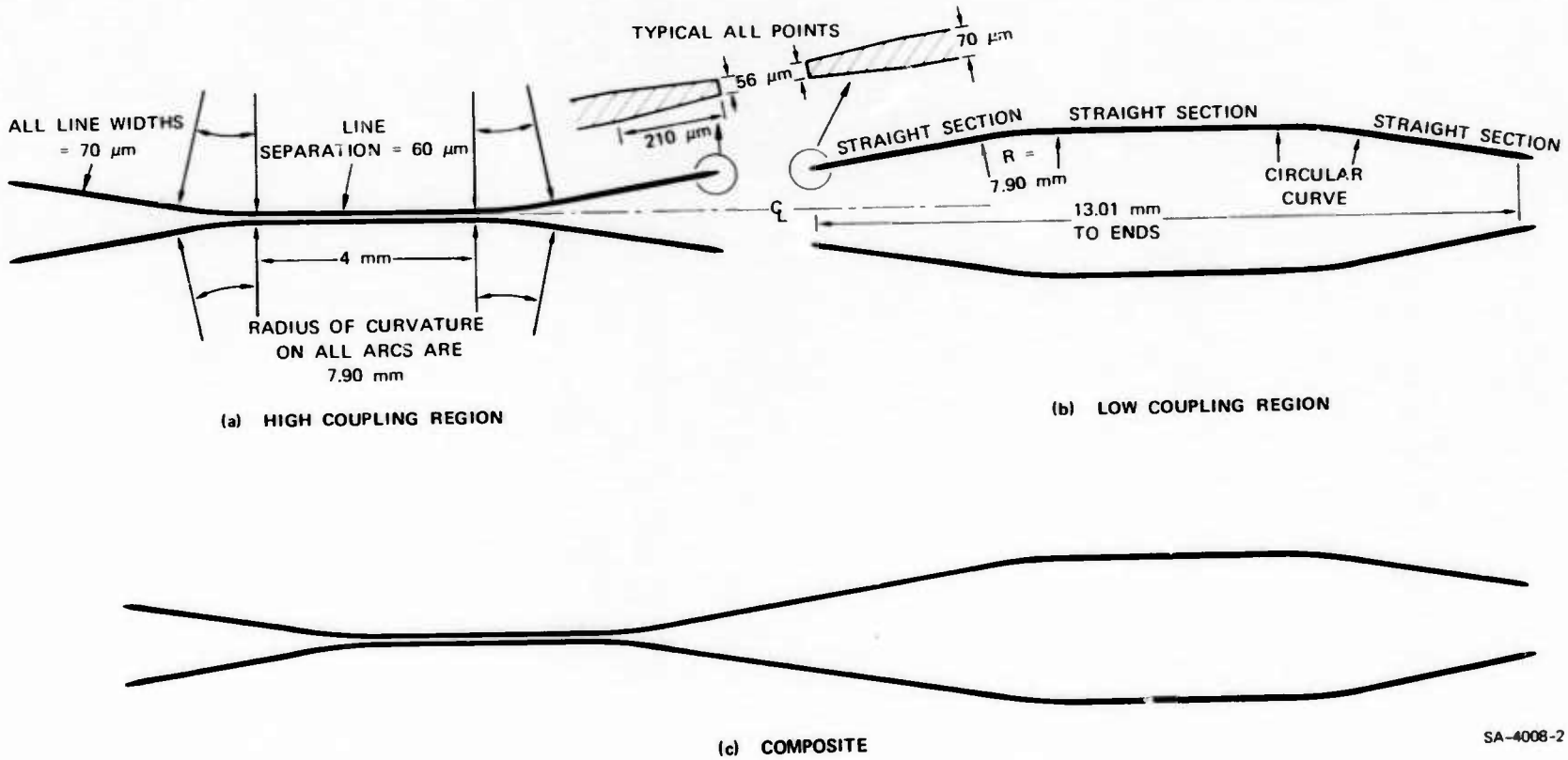

FIGURE 2 OBJECT MASK PATTERNS FOR I.O. COUPLER

(1) Nearly zero power exchange between guides,

(2) A region where phase shift electrodes can be formed if a switch is to be made.

We plan to step and repeat multiple electron-beam exposures (while simultaneously stepping the substrate) using these two masks in the modified projection exposure apparatus. In this way, any combinations of coupler or switch patterns can be built up.

The optical masks that were obtained from Bell Industries* were of reasonably good quality. However, they suffered a set of systematic faults that we attributed to the way in which the computer-generated patterns were composed. Specifically, the discrete X-Y motion of the light source used to generate the patterns gave rise to small steps in what was supposed to be smooth arcs. This was also manifested as jogs that occurred at two points along the pattern. The effect of these errors in the mask will be evaluated. We have concluded that to overcome the above problems, in future designs different composition techniques should be used.

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*Bell Industries, Photomask Division, 1165 Fair Oaks Ave. Sunnyvale, CA.

V SUMMARY

The microfabrication of structures for integrated optics (IO) requires advanced technology in lithographic (pattern production) and thin-film techniques. IO waveguide couplers and optical switches, in which a light signal in one channel of the switch can be coupled to a nearby channel by an electrical signal, in particular require lithographic techniques that produce patterns having very high resolution and good edge acuity. High quality processing for the production of optical waveguides, such as by indiffusion, is also necessary.

In this program, we are developing a system for the production of IO waveguide couplers, based on electron-beam lithography. In particular, we are building an electron projection exposure system (EPES) in which the beam of electrons passing through a pattern mask provides a demagnified (20x) image on an electron-sensitive resist-coated $LiNbO_3$ sample. After development of the resist pattern, indiffusion of titanium is used to cause an index of refraction change in the $LiNbO_3$ to produce channels through which light can be guided. EPES should provide images with resolutions of a few thousand angstroms and edge acuities of about one hundred angstroms. Furthermore, we expect that the system will be fundamentally simple to use, requiring only the production of a new transmission mask to expose a different pattern.

The tasks of this project can be divided into three general categories:

- Development of the technology for making high quality transmission masks.
- Design and construction of a high resolution EPES with the capability of registering patterns successive to one another, providing an effectively large field of exposure.

- Production of IO waveguide couplers by use of the EPES and titanium indiffusion of $LiNbO_3$.

During this quarter, we have concentrated our efforts in the first two categories. Transmission masks of good quality have been produced by photolithographic exposure of a resist-coated layer of gold (1 μm thick) supported by a silicon substrate. After development, the gold is selectively removed from the substrate by RF sputter etching to produce the mask pattern. Hot potassium hydroxide or SF_6 plasma is then used to remove the silicon backing under the pattern, leaving a well supported mask. We have encountered some difficulty with incomplete silicon etching, and in the next quarter we will try several new selective etching techniques.

The first two optical masks that will allow construction of the required electron transmission mask for production of an integrated optical coupler (using the EPES) have been designed and acquired. Fabrication of the two transmission masks are well under way and will be completed during the next quarter.

The EPES is being developed to provide successive exposure capability for up to eight different transmission masks. During this quarter we designed and built a rotary mask positioner to achieve the very accurate positioning of the masks needed to give good registration. Design work was begun on a laser-controlled sample stage so that the sample can be accurately (± 1000 Å) displaced in a linear manner, allowing successive exposures to be joined together.

The size of illumination area at the plane of the mask determines the size of the pattern that can be usefully reduced, and consequently determines the number of masks that are needed to give a complete pattern. By adding a time-varying lens defocusing action to the

condenser lens and by increasing the size of the beam-limiting projection lens aperture, we were able to improve the system by increasing the area of illumination by over 100 percent.

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