Laser direct writing of channel waveguides using spin-on polymers

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A focused argon-ion laser beam (λ = 350 nm) is used to fabricate optical channel waveguides on oxidized silicon wafers using a commercially available spin-on polymer. The polymerization process is photon induced, thus allowing the reaction to occur in a room-temperature ambient. This allows the fabrication of waveguides on a variety of substrates including those with low melting points. The losses in these waveguides are typically less than 1 dB/cm, making them applicable to a variety of optical interconnect problems. In particular, we demonstrate their use in the fabrication of an optical power tap.

INTRODUCTION

The speed of integrated circuits (ICs) has been steadily increasing over the past two decades. This increase in IC switching speed has been accompanied by a growing burden on the task of interconnecting these ICs. In fact, many high-speed systems are limited in their performance, not by the electronic materials, but by the methods of interconnection employed. Implemented judiciously, optics can offer a viable alternative to conventional electronic means of signal interconnection. At the board or wafer level, simple techniques for fabricating the optical channel with the electronic system are needed. Although optical fibers offer uncontested performance for these applications, the physical design problems associated with applying them to the board and optically coupling in and out of them are formidable. Also, special functions, such as power splits or busses, cannot be integrated onto the boards without consuming a large fraction of the valuable circuit board space. A more practical means would be to fabricate optical waveguide structures by embedding them in or depositing them on the circuit board material that is used for mounting the discrete ICs. Although much work has been done in fabricating waveguides in materials such as lithium niobate, this material is impractical as a substrate for board level electronics because of its high dielectric constant and cost. In addition, several problems such as subsequent processing and compatibility with discrete and/or packaged ICs would have to be solved. Optical waveguides on a high-frequency circuit board material such as RT Duroid or on silicon for silicon printed circuit boards would be a practical alternative. By using commercially available spin-on polymers, we have demonstrated that high-quality waveguides can be deposited on these substrates.¹ The techniques lend themselves to mass production by using conventional projection photolithography techniques as well as customizing/prototyping using laser direct writing techniques. In this paper, we concentrate on using the laser as a prototyping tool for fabricating optical waveguide structures on polished, oxidized silicon wafers.

EXPERIMENT

The starting material is a commercially available spin-on polymer (Norland 61).² This polymer, originally designed as a single part adhesive for optical elements, is a clear, colorless, liquid photopolymer that is cured when exposed to ultraviolet (UV) light within the range of 354–378 nm. Adhesion to glass is reported to be excellent with the polymer exhibiting flexibility and low shrinkage. Although Norland 61 has an index of refraction of 1.563 at λ = 546.1 nm, variations of this compound exist with indices ranging from 1.524 to 1.563.

Silicon wafers (3 in.) were used as the substrate material to emphasize the applicability to silicon printed circuit board systems. Because the index of refraction in silicon is 3.4, a 2-μm layer of SiO₂ was grown to act as a buffer layer. The SiO₂ layer has an index of refraction of 1.46, which prevents the evanescent wave from coupling into the underlying substrate. In some substrate systems, a suitable buffer layer is not readily available. Under these conditions, a spin-on polymer with the correct index of refraction can be applied to the entire substrate, producing the same effect as the SiO₂ layer on the silicon wafer.³ An example of this is the use of Electrolite 4481 (n = 1.48) as the buffer layer for copper-clad printer circuit boards. By patterning this buffer layer to be slightly wider than the waveguides, one has access to the substrate materials itself, in this case, the copper cladding. The use of these various compounds and the fact that the photolytic process is a low-temperature process means one has tremendous freedom in substrate selection.

The UV curable polymer is spun onto an oxidized silicon wafer. The only cleaning necessary has been a simple solvent rinse. Typically, the polymer is applied to the wafer and then spun at 2000 rpm for 120 s. This produces a uniform film approximately 10 μm thick. A 10-μm-thick waveguide is too large to be used as a single-mode waveguide so the waveguides produced in this work are multimode.

After spinning, the polymer is patterned by exposing it with the laser writing system. The laser writing system consisted of an argon-ion laser tuned to the 350–360-nm lines and fuscused via a modified microscope onto a set of computer-controlled XY translation stages. The laser spot size had a diameter of 5 μm after being focused by a 10× objective (NA = 0.22). The lateral writing rates varied from 10 to 400 μm/s and a typical incident laser power was less than 10 μW. After exposing, the pattern is developed by rinsing the film in acetone. The unexposed regions rinse away, leaving a patterned channel waveguide on the oxidized silicon.
wafer. Figure 1 is a scanning electron microscopy (SEM) micrograph of the channel waveguides on a cleaved silicon substrate. Note that the guides are very smooth except at the waveguide/substrate interface where rough spots are visible. Note also that the waveguide cross section is not a perfect circle because its shape is influenced by the Gaussian intensity distribution of the focused laser beam. The physical dimensions of this guide, approximately $4 \mu m \times 8 \mu m$, are large enough to propagate several modes.

The typical length of the waveguides produced was 7.5 cm. This allowed ample length to determine the physical dimensions and optical losses. Optical losses in the waveguides were measured by detecting the light scattered from a portion of the surface of the guide and plotting as a function of position along the waveguide. This was accomplished by utilizing the same laser writing system but using the focusing optics as the collection optics. Subsequent to measuring the loss in each waveguide, measurements of thickness and width were done by cleaving a portion of the guide and examining them in an electron microscope. The use of stylus profilometry to determine the thickness was ruled out because the stylus deformed the polymer waveguides.

**DISCUSSION**

The typical incident laser power density needed to polymerize the spun-on material is approximately 25 W/cm². From thermal calculations, we can assume a laser-induced temperature rise of less than 1°C. This low-temperature rise makes this technique suitable for a variety of substrates including those with low melting points. The physical dimensions of thickness and width as a function of the laser spot dwell time are shown in Fig. 2. The dwell time is based upon the laser spot diameter of 5 μm. For ease of comparison, the substrate scan speeds are also shown. In Fig. 2(a), where we have plotted the waveguide thickness, several interesting points should be noted. In the range of 10–50 ms dwell time, both curves show a linear behavior indicating a direct correlation between the total incident energy and the waveguide thickness. This relationship is further confirmed by noting that the higher incident laser power curve produces waveguides with similar thicknesses as the lower power curve but for shorter dwell times. As the dwell time increases, we expect to see a further increase in thickness but instead see a saturation of the thickness due to reaching the initial spin-on thickness of the polymer film. The total energy dose for waveguides produced at the slow scan speed (50 ms dwell time; 6.4 μW laser power) is approximately 1.6 J/cm². This is near the Norland recommended energy dose of 6 J/cm² for completely curing the polymer. However, it must be pointed out that although the energy dose is similar, the incident power density in the laser-cured waveguides is approximately three orders of magnitude higher (30 W/cm²) than in a conventional mercury lamp curing (0.02 W/cm²).
id, high-intensity cure may manifest itself in a shorter kinetic chain length and thus smaller sized polymer molecules. Under these conditions, the physical and/or optical properties of these films could differ significantly from those of the slower cured films. It would be expected that further increases in dwell time would have no further effect but in fact it does. Increased dwell time, and hence increased incident energy, produces a fully formed polymer waveguide that is detached from the surface. An obvious reason for this could be surface tension resulting from shrinkage during curing. However, the linear shrinkage rate is stated at only 1.5% and with an aspect ratio of approximately 1:1, we would not expect surface tension to be the dominant factor. At the present time, we do not understand the detachment at higher incident energy levels; however, the process window is large enough that patterning can occur without approaching this region of overexposure. Furthermore, if the patterned film is not fully cured, low-level UV light or low-level thermal curing can be applied to complete the curing without overexposing.

The shape of the data in Fig. 2(b) is not as obvious. The width of the laser-written line is determined by a combination of polymerization in the spun-on film and the reaction that forms the adhesion at the polymer/SiO₂ interface. This latter reaction is propagated by the same radicals that form the bulk polymer. Therefore, we can assume that a minimum extent of polymerization (EP<sub>min</sub>) must occur at the interface to guarantee adhesion. For simplicity, we define the extent of polymerization as the polymerization rate (i.e., the growth of the polymer) times the duration of the reaction. In our case, we use the dwell time and assume the polymerization rate is constant during this time (EP ≈ f<sub>dwell</sub> × R<sub>p</sub>). Although assuming the polymerization rate is constant during the dwell time is not exactly correct, it is sufficient for the argument we are presenting here. In many photoinitiated polymers, the polymerization rate (R<sub>p</sub>) is proportional to the square root of the light intensity. Qualitatively, we can see this as follows. The polymerization rate is proportional to the concentration of chain radicals. However, the chain radical concentration is difficult to measure directly so we assume we are in steady state, i.e., we are neither creating an excess of chain radicals (initiation reaction) nor decreasing the concentration of chain radicals (termination reaction). Under these conditions, the initiation rate is equal to the termination rate. The initiation rate is directly proportional to the light intensity while the termination rate is proportional to the square of the chain radical concentration by the law of mass action. Therefore, at steady state, the chain radical concentration, and hence the polymerization rate, is proportional to the square root of the light intensity. Because of this intensity dependence and the Gaussian beam shape, the polymerization rate will be a function of the radial distance away from the center of the beam. Therefore, the extent of polymerization will also show this dependence as given by

\[ \text{EP} \sim f_{\text{dwell}} \sqrt{I_0} \exp \left( -r^2 / r_0^2 \right), \]

where \( I_0 \), \( r \), and \( r_0 \) are the intensity, radial position, and spot radius, respectively. If we assume a minimum polymerization extent (EP<sub>min</sub>) is necessary for adhesion and solve for the radial position, we can show the dependence of the waveguide width on dwell time as

\[ \text{width} / 2 = r_{\text{max}} \sim r_0 \sqrt{-\ln \left( \frac{\text{EP}_{\text{min}}^2}{I_0 f_{\text{dwell}}^2} \right)}. \]

Equation (2) was used to generate the solid curves in Fig. 2(b) with \( r_0 = 3.3 \mu m \), \( I_0 = 9.9 \) and \( 18.7 \) W/cm² corresponding to the incident power levels of 3.4 and 6.4 μW, respectively, and a single value of EP<sub>min</sub> used as the fitting parameter. Although the model is simple, the trend clearly follows the experimental data. This indicates that the width of the waveguide is determined by the dwell time and the intensity-dependent polymerization rate. From a practical point of view, the dwell time (scan speed) and incident power become a means of modulating both the width and the thickness of the waveguide structure. Although not exploited at the present time, the ability to vary the thickness of the waveguide as a function of the position along the guide can be achieved easily using laser patterning, but is impossible to achieve with conventional photolithography techniques.

The lower limit on resolution appears to be the diffraction limit of the optics. Simple-mode waveguides with dimensions of the order of 1–5 μm should be possible with an increase in the NA of the final objective. This was not done in this work because the reduced depth of field of such optics would make it difficult to maintain a tight focus over the 7.5- cm distance used to make these waveguides. With the use of an autofocus system, maintaining the entire substrate in the focal plane should not present a problem and the use of high NA optics over large distances would become a relatively easy task.

A reduction in the spun-on thickness of the film would also facilitate the fabrication of single-mode waveguides. The viscosity of Norland 61 is 350 eps at 24 °C. A lower viscosity material would produce a thinner film. Heating Norland 61 to 31°C reduces its viscosity to approximately 200 eps. This low-temperature heating will not adversely affect the polymer according to the manufacturer and should produce a thinner film when spun-on, making smaller waveguides possible.

**LOSS MEASUREMENTS**

A measure of the waveguide loss is a critical parameter in evaluating whether a waveguide structure may be adequate for applications in optical interconnects. Waveguides with losses less than 1 dB/cm are adequate for the relatively short (several centimeters) distances in which these structures are likely to be used. Loss measurements for these waveguides were obtained by a technique wherein the power of the scattered light emitting from the waveguide is measured as a function of the position on the waveguide. A schematic diagram of this technique and a typical set of data is shown in Fig. 3. Coupling of light into these waveguides is accomplished by end firing from a fiber. This technique does not control the coupling of light into the waveguide as well as prism coupling does, but it allows evaluation of guide loss in real system environments. A cutback loss measurement was not used for several reasons. In addition to being a destructive test, damage to the end of the waveguide does not guarantee consistent coupling of the light energy out of the wave-
guide. Also, the coupling of light into the waveguide will vary due to realignment after cutting the waveguide. Finally, numerous measurements are needed to resolve point defects. Careful examination of the curve in Fig. 3(b) shows two distinct slopes in the data. The steeper slope seen in the first 2-3 cm is representative of the coupling loss. The coupling loss is defined as the loss in the waveguide due to stripping of modes that will not propagate. The actual modes that are coupled into the waveguide are a strong function of how the light is launched into it. In most cases, more modes will be launched into the waveguide than were propagating in the single-mode fiber used to end fire light into the waveguide. The total length of the waveguides described here was approximately 7.5 cm and all of the nonpropagating modes were removed within the first 2-3 cm. The shallower slope seen for the remainder of the curve is representative of the waveguide loss. The waveguide loss corresponds to the loss in the guide after the nonpropagating modes have been stripped.

The loss data (measured at $\lambda = 632.8$ nm) as a function of the cross-sectional area are shown in Fig. 4. The cross-sectional area is determined by multiplying the thickness and width data from Fig. 2 for the waveguides produced at 6.4 $\mu$W. For cross referencing, the horizontal axis is also in units of the scan speed. Two curves are displayed. The top curve represents the coupling loss while the lower curve represents the actual waveguide loss. The smaller the waveguide, the fewer the modes that will propagate. Therefore, we see in Fig. 4 that the coupling loss increases with decreasing waveguide cross-sectional area due to the loss of more nonpropagating modes. The actual waveguide loss shows a similar dependence on waveguide dimensions. As the dimensions decrease, the ray angle for a given mode increases and loss mechanisms become increasingly important because of the increased optical path length. In particular, polymer phase separation at the waveguide-SiO$_2$ interface could produce scattering centers at this interface. Under certain conditions, we have seen evidence of phase separation in these materials. However, at the present time, we have not determined if the primary loss mechanism is within the material itself or at the polymer-SiO$_2$ interface. From Fig. 4 we see that waveguides with a cross-sectional area greater than $50 \mu m^2$ have guide loss less than 1 dB/cm. It should be noted, however, that a waveguide with different width and thickness but the same cross-sectional area may exhibit a different loss and that the data in Fig. 4 is valid only for the waveguides produced at the specific power level (6.4 $\mu$W).

**APPLICATIONS**

One possible use for channel waveguides at the board level is synchronous clock pulse distribution. In such a situation, a means of tapping off the optical clock pulse from the distribution bus is necessary. A simple power splitter is inadequate because too much power is split off at one junction leaving too little in the main bus for the next tap point. In conventional waveguide processing, evanescent coupling could be used. Two waveguides are brought close together, less than one wavelength apart, and the evanescent wave from one guide couples a small fraction of the light into the adjoining guide. Because the laser-produced polymer waveguides have a nonrectangular cross section due to the Gaussian beam profile, evanescent coupling is not easily achieved. However, weak coupling has been accomplished by allowing two waveguides in close proximity to merge, thereby en-
SUMMARY

We have demonstrated laser direct writing of optical waveguides using a commercially available, spin-on polymer. Curing occurs by UV photopolymerization and is a room-temperature technique. This makes this class of materials ideally suited for fabricating waveguide structures on substrate materials with low melting points. Loss measurements indicate that under the proper conditions of incident laser power and scan speed, waveguides can be fabricated with losses less than 0.4 dB/cm. This value is better than the 1 dB/cm required for board level optical interconnects. A simple power tap has been fabricated indicating the potential of using these structures for synchronous clock distribution at the board level for very-high-speed electronics. Physical measurements indicate that the laser writing can be used to vary the thickness and the width of the waveguides. Thickness variation is difficult to achieve by conventional photolithography techniques and is unique to the direct write method. Finally, the ultimate resolution of this technique is believed to be the diffraction limit. With the proper selection of optics and processing parameters, submicron features should be possible. This is smaller than the dimensions needed to produce single-mode waveguides.

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