TECHNICAL NOTE

Vacuum-tuned graded-index polymer waveguides on silicon substrates

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A new method for producing graded-index (GRIN) profiles on type A photolime gel-based polymer waveguides with vacuum drying is demonstrated. Vacuum drying allows optical waveguides to be built on substrates with a higher index of refraction without intermediate lower-index cladding layers while keeping the concentration of various dopants unperturbed. The waveguide-loss and GRIN profiles were compared for vacuum-dried and alcohol-dried samples. Waveguide losses from 0.1 to 10 dB/cm were observed. © 1996 Optical Society of America

The refractive-index profiles of optical waveguides for polymer-based optical interconnects fall into two classes, step index and graded index. Step-index waveguides require the guiding layer to have a higher index of refraction than the cladding media. Graded-index (GRIN) films, on the other hand, can be applied on higher-index substrates and still form waveguides.[1,2] In this paper we report, for the first time to our knowledge, the formation of GRIN films by use of vacuum drying of photolime gel polymer. Typical waveguiding polymers have an index of refraction well below that of silicon. Photolime gel polymer has an index near 1.5, compared with 3.45 for Si. This means that in order to form a waveguide, a cladding layer that possesses an index lower than the waveguide polymer must be applied between the substrate and the waveguide layer. A wet-processing technique for making GRIN polymer-based waveguides on Si, GaAs, and metals was demonstrated in the past,[1] but that technique allowed chemical dopants to the polymer to be diluted by the initial water-swelling step and by the subsequent dehydration process. The vacuum-drying technique discussed here can be extended to avoid such problems and therefore provide a well-tuned index in the polymer thin film, while maintaining dopant concentrations for electro-optic uses.[3,4]

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To prepare polymer thin films, a solution with 10 g of polymer powder and 100 mL of water was prepared. This ratio yields polymer films with $n \sim 1.52$ at the 632.8-nm wavelength.[5] After sitting undisturbed in a 60 °C water bath for 3 h, the polymer solution was spin coated onto Si substrates and allowed to dry overnight at room temperature and 40% (nominal) relative humidity.

Photolime gel polymer film is known to absorb water and swell when allowed. Such a swelled film can be given a GRIN of refraction versus depth profile when the water is forcefully removed from the film.[6] The resulting mass-density gradient causes a GRIN of refraction. The alcohol-drying method reported previously[1] immerses the swelled film in increasingly concentrated solutions of isopropyl alcohol and water, chemically removing water from the film. The alcohol-drying process begins with swelling of the polymer film in water for 3–5 min. Next the film is immersed in 25%, 50%, and 75% alcohol: water baths at room temperature for 30 s each. The sample is then immersed in 100% alcohol at room temperature for 10–30 s and dried. A final immersion in 100% alcohol at 60 °C for 30 s will dry the film further.

The new method of index-profile tuning reported in this paper replaces alcohol drying and dehydrates the sample by placing it in a vacuum chamber. The film may also be vacuum dried within 30 min of film application to avoid the water-swelling step. Table 1 shows the fabrication parameters and drying conditions for two different waveguide samples prepared on the same Si wafer.[2] After thin film was prepared and dried to form GRIN profiles, He–Ne laser light was prism coupled into the films to examine the

Table 1. Conditions for Alcohol-Dried and Vacuum-Dried Polymer Waveguide Samples

Sample	Thickness after Profile Tuning	Alcohol Dry (min)	Hot Alcohol (min)	Vacuum Dry (min)	Pressure (Torr)
Vacuum-dried	8	—	—	2.5	0.5
Alcohol-dried	12	2.0	0.5	—	—

waveguiding for wet (alcohol-dried) and dry (vacuum-dried) processed films.[7] Figure 1 depicts the difference between a polymer-based step-index waveguide [Fig. 1(a)] and a polymer-based GRIN waveguide [Fig. 1(b)] on a high-index Si substrate. It is clear from Fig. 1(b) that a single-layer low-index polymer coating can be used to form waveguides on higher-index substrates.

In order to compare the GRIN profiles resulting from alcohol and vacuum drying, we measured the waveguide-mode effective indices that arise in chosen films and used these data to determine index versus depth of the film. To measure mode effective indices, we prism coupled transverse-electric (TE) polarized 632.8-nm-wavelength laser light into the films. Figure 2 shows a prism-coupled fundamental transverse-electric (TE_0) waveguide mode that is guided in polymer directly on bare Si. Si was used because of its much higher index of refraction than that of polymer (3.45 versus 1.5), so that guided modes would not normally be confined without cladding layers of lower index, or without a GRIN versus depth profile.

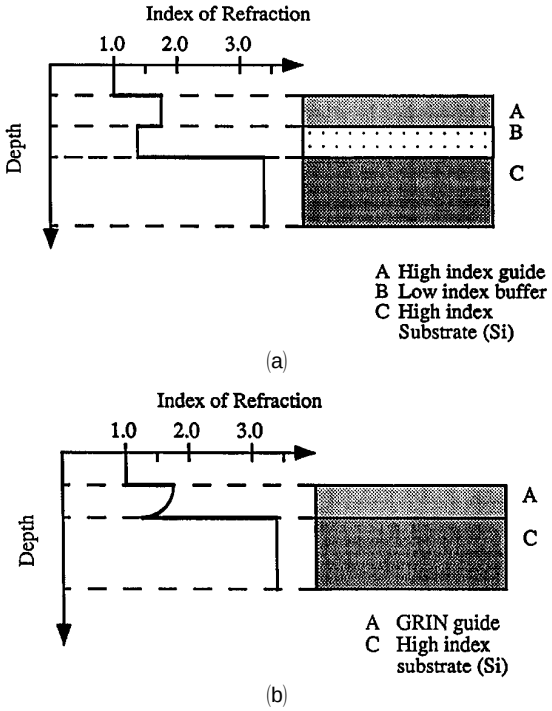

Fig. 1. Formation of optical waveguides for Si-based intrawafer optical interconnects with (a) step-index and (b) graded-index profiles.

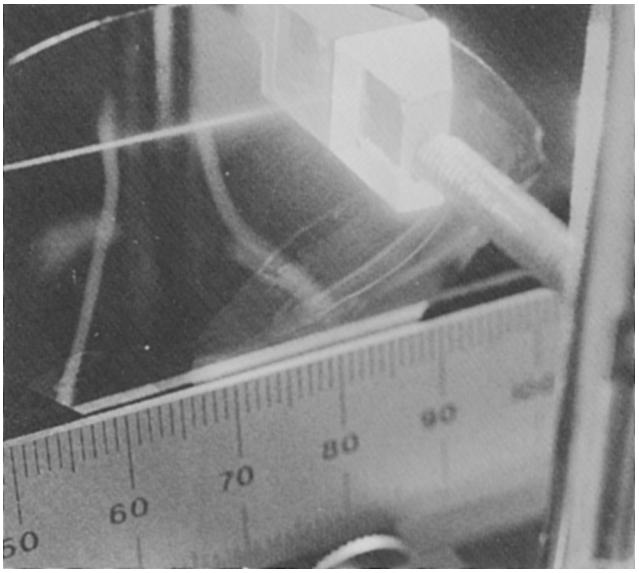

Fig. 2. Observation of the TE_0 guided mode of a polymer waveguide formed by vacuum drying ($\lambda = 632.8$ nm).

The loss of such planar waveguides was measured. A light beam from a He–Ne laser is coupled into the waveguide and a diamond scribe scratches across the waveguide to cut propagation and scatter light. The first cut is made at the point to be measured farthest from the input coupler. A 20× microscope objective and a detector are placed within 2 mm on top of the scratch to gather and measure scattered-light intensity, representing intensity in the waveguide at that distance from the input coupler. After the scattered intensity is recorded, a new cut is made closer to the coupler, and a new intensity reading is taken. The process is repeated until the cut reaches the input coupler. Thus this method measures intensity scattered from a completely cut waveguide versus propagation distance. The technique estimates waveguide loss and excludes coupling loss.

In order to maximize accuracy and minimize variability, the microscope objective was repeatedly positioned, moved, and repositioned to ensure repeatable maximum light gathering. The objective and detector were also shielded from stray light.

Figure 3 plots the intensity versus distance for vacuum-dried and alcohol-dried waveguides. Figure 3 shows that, based on the present data, the TE_0-mode waveguide propagation losses of vacuum-dried samples are higher than those of alcohol-dried samples. This phenomenon has been consistently observed. Depending on film-preparation conditions, we have observed waveguide-propagation loss varying from 0.1 to more than 10 dB/cm on Si substrates. Film cleanliness and the film's GRIN profile are the two pivotal factors in engineering the waveguide losses. The first factor determines the volume-scattering effect within the waveguide, and

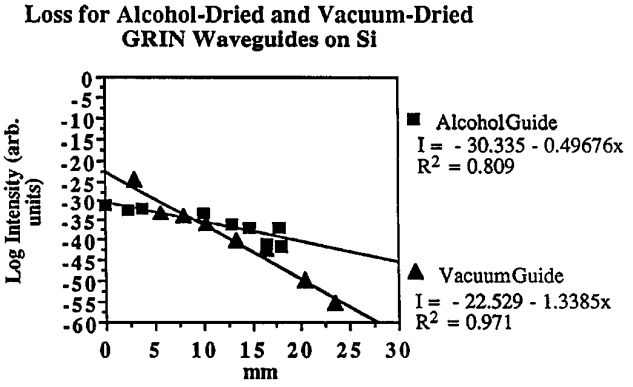

Fig. 3. Measured waveguide loss of vacuum-dried and alcohol-dried samples, working at 632.8 nm.

the second decides the strength of the interaction between the evanescent tail of the waveguide mode and the Si substrate. Note that these waveguides were used to compare the different loss and GRIN profiles resulting from vacuum drying and alcohol drying and were not optimized for low loss. The evanescent tail of the guided mode in the vacuum-dried waveguide had stronger interaction with the Si substrate than did the mode in the alcohol-dried waveguide. This caused Si to absorb more strongly and to increase the observed waveguide loss.

The mode data and the inverse Wentzel–Kramers–Brillouin[8] method were used to determine the index profile of the polymer thin film. The resulting index versus depth in the polymer is plotted for vacuum-dried samples in Fig. 4(a) and alcohol-dried samples in Fig. 4(b). Note that the samples represented in Fig. 4 were taken from the same wafer, and that their respective thicknesses were equal to within the thickness variation across one 3-in. (7.62-cm) wafer, estimated from interference fringes to be ± 1.8 μm. Vacuum-dried films have higher indices of refraction than those of wet-processed films. Because of the variation of the GRIN profile, the guided waves within vacuum-dried films were experimentally confirmed to have higher propagation loss than wet-processed waveguides.[1–3]

In summary, we present a new method for inducing a GRIN profile in photolime gel polymer by vacuum drying. Mode effective indices were measured and used to determine the GRIN profiles presented. Our investigation concludes that the alcohol-dried waveguides have a lower surface index, a more gradual index gradient, and thicker film after drying than do vacuum-dried waveguides. These results suggest that the vacuum-drying process generates a less porous microstructure and higher mass density than the alcohol-drying process. As experienced with early alcohol drying, the vacuum-dried waveguide-propagation loss could be significantly improved with pressure filtering of the polymer and optimization of the drying process to tune the index profile. In addition, the ability to induce GRIN without diluting polymer dopant concentrations is an advantage over alcohol drying. The vacuum-drying technique reported here adds to the existing alcohol-drying technique as a universal tool for waveguide formation on any substrate of interest, because of the formation of GRIN profiles.

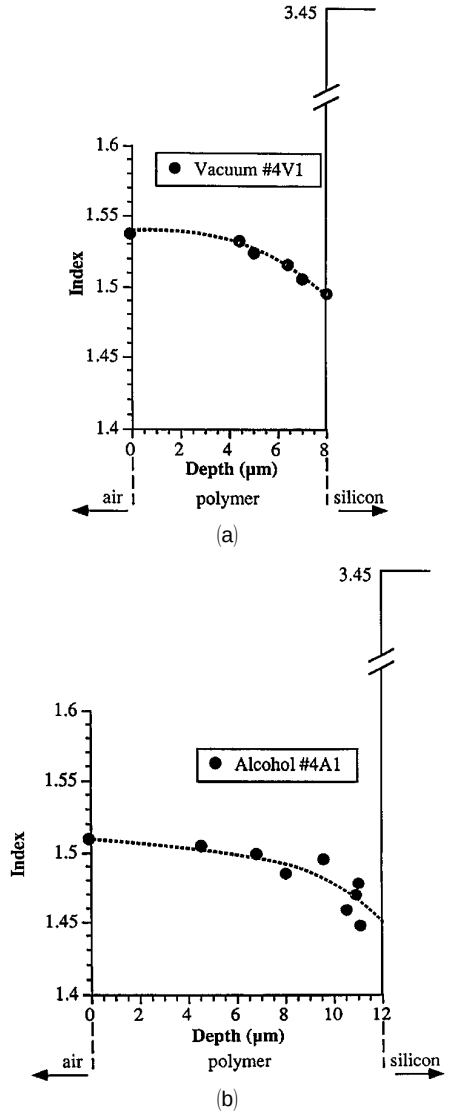

Fig. 4. Graded-index profiles of polymer thin films as a function of depth with the Inverse Wentzel–Kramers–Brillouin method, for vacuum-dried (a) and alcohol-dried (b) samples.

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