213

Vacuum-Tuned Graded Index Polymer Waveguides On Silicon Substrates

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Abstract

A new method using vacuum-drying is demonstrated for producing graded index (GRIN) profiles on type-A photolime gel-based polymer waveguides. Vacuum-drying allows optical waveguides to be built on higher index of refraction substrates without intermediate lower index cladding layers. The waveguide loss and graded index profiles were compared for vacuum-dried and alcohol-dried samples.

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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 higher index of refraction than the cladding media. Graded index 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 the formation of graded index (GRIN) films by vacuum-drying of photolime gel polymer. Typical waveguiding polymers have index of refraction well below that of silicon. Photolime gel polymer has index near 1.5, compared to 3.45 for Si. This means that in order to form a waveguide, a cladding layer possessing index lower than the waveguide polymer must be applied between the substrate and the waveguide layer. A wet processing technique was demonstrated in the past for making GRIN polymer-based waveguides on Si, GaAs, and metals,[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.

To prepare polymer thin films, a solution with 10g polymer powder and 100ml water was prepared. This ratio yields polymer films with n~1.52 at 632.8nm wavelength.[3] After sitting undisturbed in a 60 °C water bath for 3 hours, 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 graded index of refraction (GRIN) vs. depth profile by forcefully removing the water from the film.[4] The resulting mass density gradient causes graded index 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 by swelling the polymer film in water for 3-5 minutes. Next, the film is immersed in 25%, 50%, and 75% alcohol : water baths at room temperature for 30 seconds each. The sample is then immersed in 100% alcohol at room temperature for 10-30 seconds and dried. A final immersion in 100% alcohol at 60°C for 30 seconds 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 minutes 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 silicon wafer.[2] After thin film preparation and drying to form graded index profiles, HeNe laser light was prism-coupled into the films to examine the waveguiding for wet (alcohol-dried) and dry (vacuum-dried) processed films. Figure 1 depicts the difference between a polymer-based step-index waveguide (Fig. 1(a)) and a polymer-based graded-index waveguide (Fig. 1(b)) on a high index silicon substrate. It is clear from figure 1(b) that a single-layer low index polymer coating can be employed to form waveguides on higher index substrates.

In order to compare the graded index profile resulting from alcohol and vacuum drying, we measured the waveguide mode effective indices arising in chosen films and used these data to determine index vs. depth of the film. To measure mode effective indices, we prism-coupled transverse-electric (TE) polarized 632.8nm 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 vs. 1.5), so that guided modes would not normally be confined without cladding layers of lower index, or without a graded index vs. depth profile. The loss of such planar waveguides was measured using a method similar to cutback.

Figure 3 plots the intensity vs. distance for vacuum-dried and alcohol-dried waveguides. Figure 3 shows that 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 the waveguide propagation loss varying from 0.1dB/cm to more than 10dB/cm on Si substrates. Film cleanliness and the film's GRIN profile are the two pivotal factors to engineer the waveguide losses. The first factor determines the volume scattering effect within the waveguide and 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 graded index 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 (IWBK)[5] method were used to determine the index profile of the polymer thin film. Figures 4(a) and 4(b) plot the resulting index vs. depth in the polymer for vacuum-dried (4(a)) and alcohol-dried (4(b)) samples. Note that the samples represented in figures 4(a) and 4(b) were taken from the same wafer, and that their respective thicknesses were equal to within the thickness variation across one 3" wafer, estimated from interference fringes to be +/- 1.8μm. Vacuum-dried films have higher index of refraction than that of wet processed films. Due to the variation of 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 graded index profiles presented. Our investigation concludes that the alcohol-dried waveguides have lower surface index, more gradual index gradient, and thicker film after drying than do vacuum-dried waveguides. These results suggest that the alcohol-drying process generates a more porous micro-structure and lower mass density than the vacuum-drying process. Film purification and appropriate index profile tuning would significantly reduce the waveguide propagation loss. The vacuum-drying technique reported herein adds to the existing alcohol-drying technique as a universal tool for waveguide formation on any substrate of interest, due to the formation of GRIN profiles.

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Bibliography

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2 R.T. Chen et al, "Polymer microstructure waveguide on alumina and beryllium oxide substrates for optical interconnection," Appl. Phys. Lett. **56**, 8 (1990)

3 R.T. Chen, "Polymer gelatin microstructure waveguides in conjunction with HOE for electronics and VLSI optical interconnects," Final Report to U.S. Army Strategic Defense Command, contract number DASG60-90-C-0018 (1992). Gelatin film thickness of 5μm is indicated for 10g/100ml gel/water ratio 60rpm spin speed.

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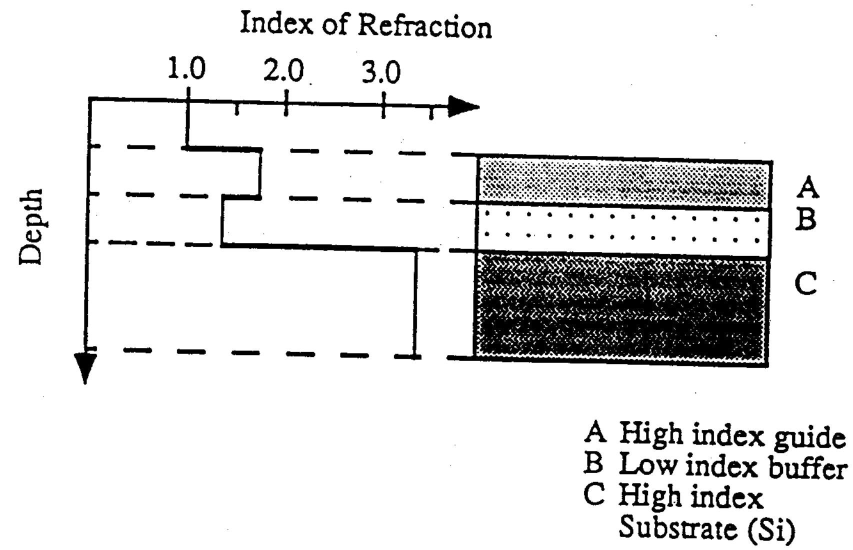
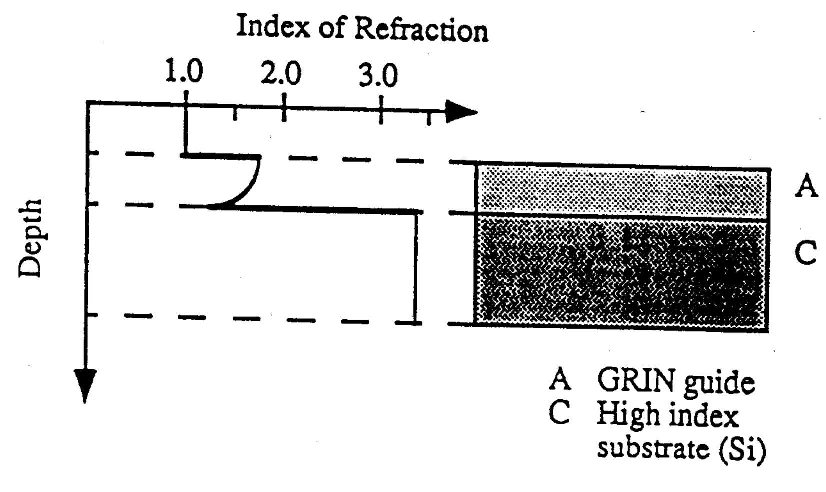
Table 1 Conditions for Alcohol-Dried and Vacuum-Dried Polymer Waveguide Samples

	Thickness After Profile Tuning	Alc. Dry (min)	Hot Alc (min)	Vac. Dry (min)	Pressure (torr)
Vacuum-Dried	8	--	--	2.5	0.5
Alcohol-Dried	12	2.0	0.5	--	--



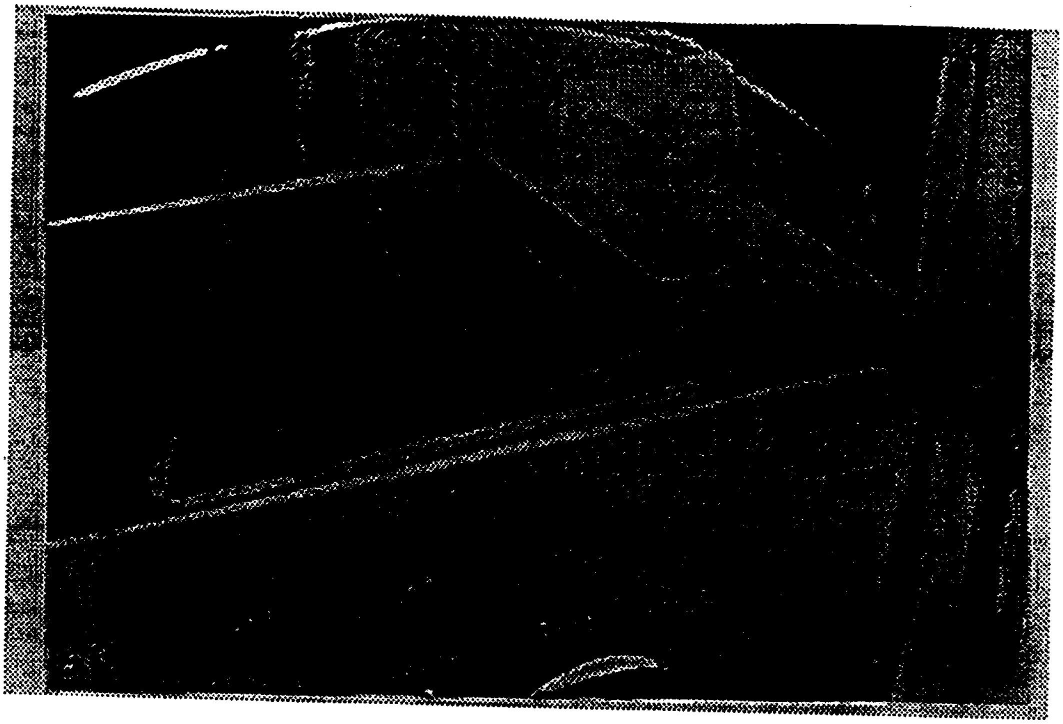
(a)



(b)

Formation of Optical Waveguides for Si-based Intra-Wafer Optical Interconnects with (a) Step Index and (b) Graded Index Profiles

Figure 1



Observation of the TE_0 Guided Mode of a Polymer Waveguide Formed by Vacuum-Drying (λ = 632.8nm)

Figure 2

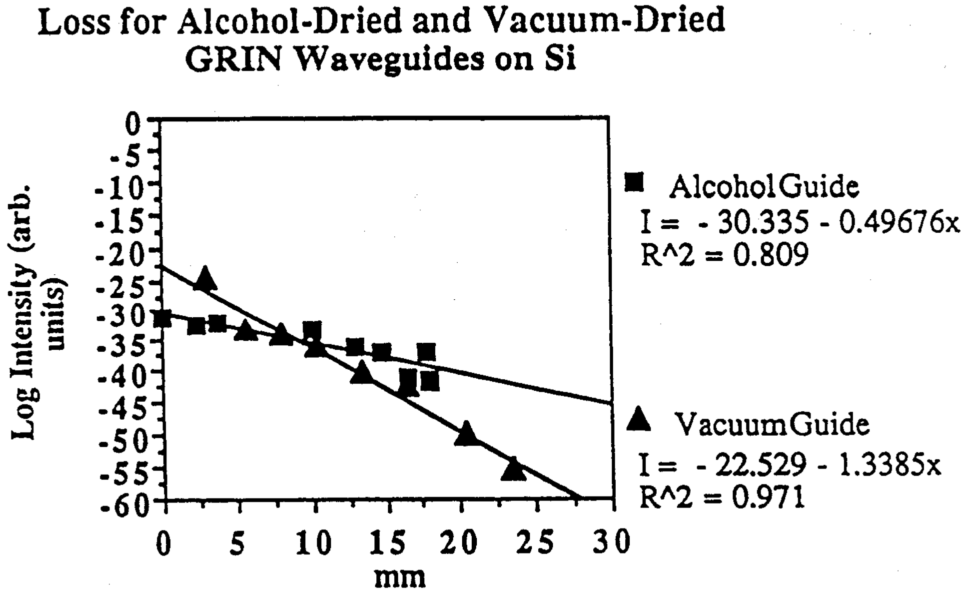


Figure 3

Measured Waveguide Loss of Vacuum-Dried and Alcohol-Dried Samples, Working at 632.8nm

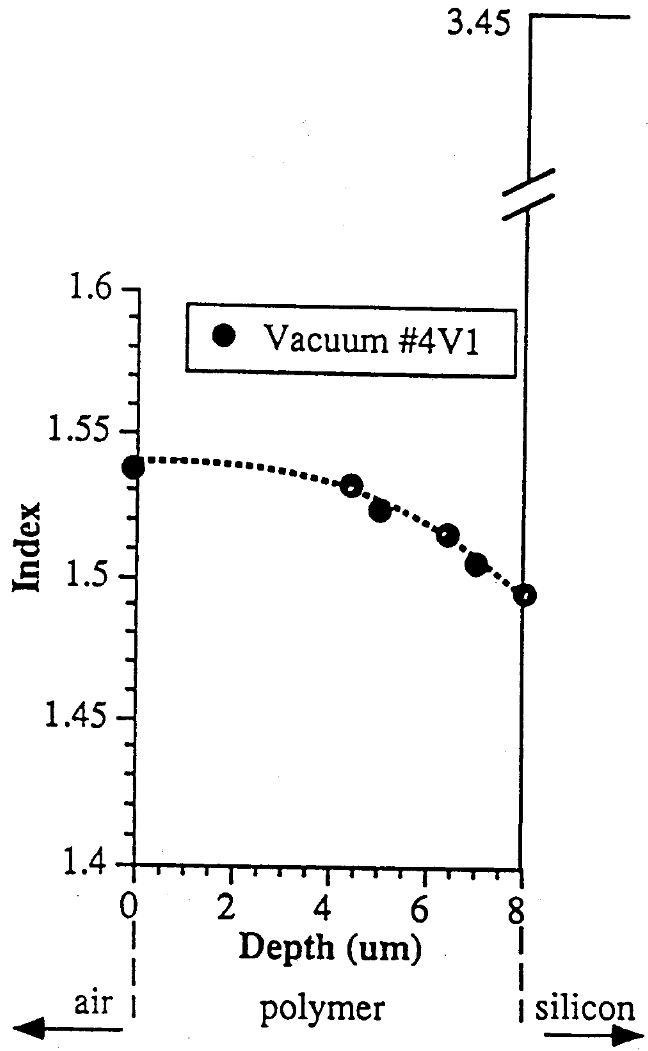


Figure 4(a)

Figure 4 Graded Index Profiles of Polymer Thin Films as a Function of Depth Using IWKB Method, for Vacuum-Dried (a) and Alcohol-Dried (b) Samples.

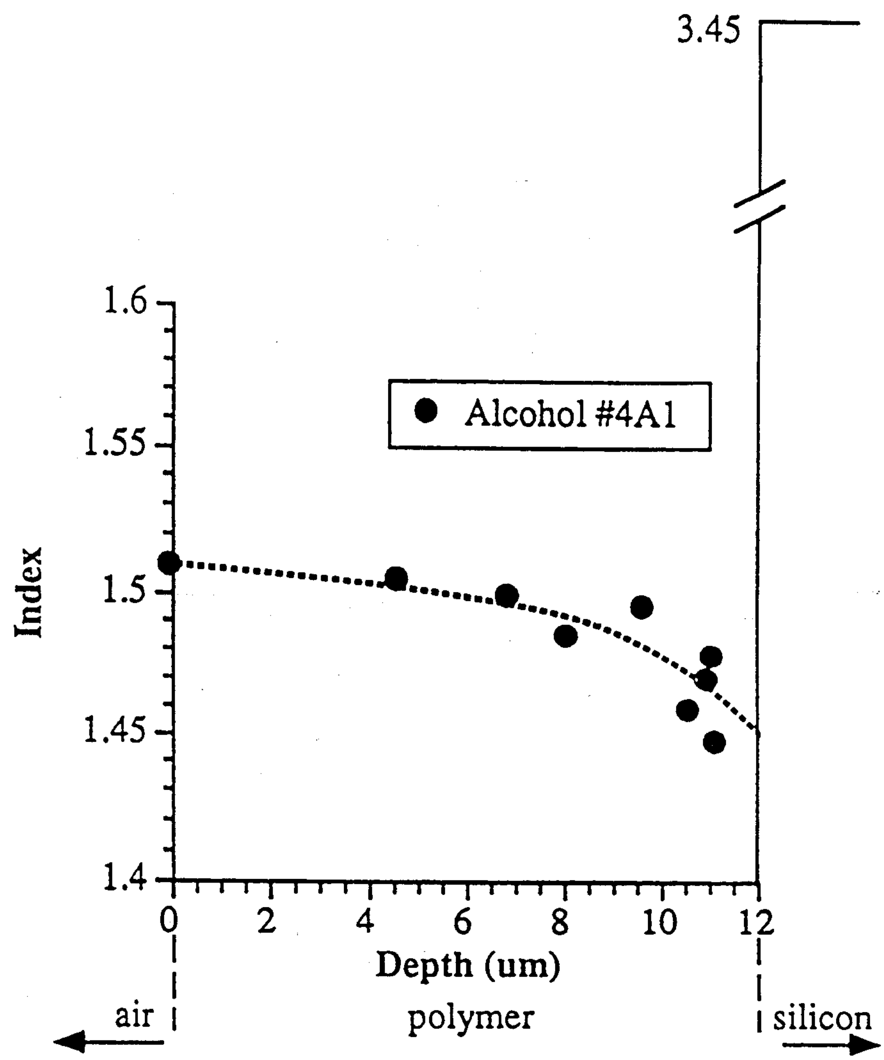


Figure 4(b)

Figure 4 Graded Index Profiles of Polymer Thin Films as a Function of Depth Using IWKB Method, for Vacuum-Dried (a) and Alcohol-Dried (b) Samples.