The Novel Formation of Photodefinable Porosity to Fabricate Direct-Write Waveguides for Optoelectronic Applications

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Introduction:

As the microelectronics industry continues to follow Moore's law, interconnects have become an obstacle to improving integrated circuit (IC) performance. Optoelectronics solutions are being considered for improving interconnect efficiency. As illustrated in Figure 1, a direct-write waveguide can be fabricated by the creation of microporosity in a rigid spin-on-glass (SOG) matrix via selective decomposition of a templated photodefinable sacrificial material (porogen). The porous regions are less optically dense due to refractive index mixing of the matrix and air.

Experimental Procedure:

Photoacid molecules can catalyze the decomposition of photodefinable sacrificial polymers by attacking the linkages between the repeating units releasing volatile products [1]. By templating the polymer in a matrix, porosity is formed as air replaces the decomposition products escaping from the matrix. To study the photoacid-catalyzed decomposition behavior of the porogen and determine appropriate processing conditions for the novel direct-write system, thermogravimetric analyses (TGA) were performed on mixtures of sacrificial polymer and photoacid generators (PAGs). As shown in Figure 2, UV-exposed PAG/porogen mixtures were less stable than the unexposed PAG/porogen mixtures, thus indicating that sacrificial polymer in a direct-write system could be selectively decomposed via UV radiation.

However, it was found that all PAGs tested were unstable at the glass transition temperature (Tg) of the SOG, meaning that thermally curing the SOG to achieve rigidity would activate the PAG, uniformly decomposing the porogen and precluding selective creation of porosity. To avoid blanket decomposition of the sacrificial polymer, the matrix was hardened below the Tg of the SOG. This was achieved by the use of bases, which catalyzed the hydrolysis of silane bonds into highly reactive silanol bonds. The silanol groups condensed to form crosslinked siloxane bonds, hence increasing the film rigidity [2].

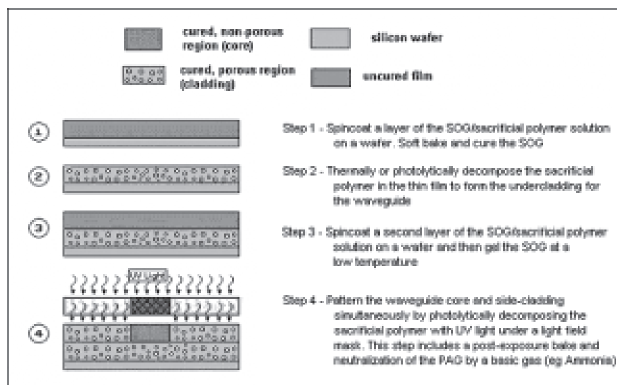

Figure 1: Basic sequence of the direct-write process based on photodefinable porosity.

FTIR spectroscopy was used to track the formation of network siloxane bonds in 0.7-1.2 μm thick gelated films. In the FTIR spectrum of the SOG matrix, two separate stretch peaks centered at 1130 cm^{-1} and 1070 cm^{-1} correspond to the Si-O caged and Si-O networked bond energies respectively [3]. As the extent of gelation increased, the network siloxane stretch peak grew larger and the extent of gelation was evaluated by comparing the relative area of the siloxane peaks (the Si-O cage/network ratio) [4].

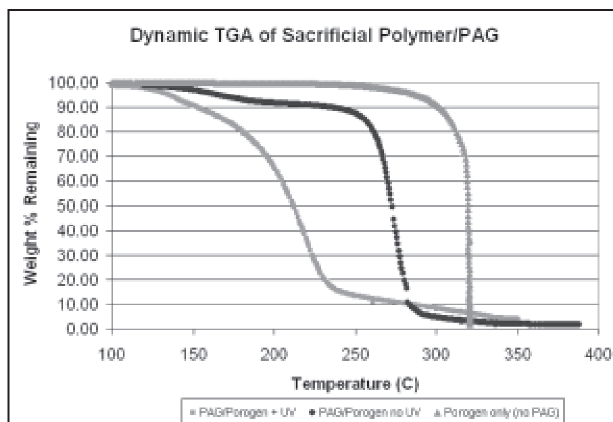

Figure 2: Dynamic TGA for determining PAG compatibility.

Nanoindentation tests were performed after the FTIR study in order to confirm the rigidity of the SOG matrix after different gelation treatments. The results of both studies, shown in Figure 2, showed that the reduced modulus (Er) of gelled films increased as the cage/network peak area ratio decreased. This confirmed that as the relative amount of networked siloxane bonds increased during gelation, the SOG matrix did indeed become more rigid.

Two processes using two different photobase generators

were developed to gel the SOG in a direct-write system without the activation of any PAG. For the first process, PBG 1 was mixed into solutions with the SOG matrix and spin-coated to form films. The PBG1 species in these films were thermally activated to release free base by heating films at 160-170°C for 30 minutes. TGA results showed that at 170°C, only trace amounts of the PAG were activated, indicating that PBG1 could be activated without activating the PAG.

In the second process, PBG 2 and a photosensitizer were mixed into solutions with the SOG matrix and spin-coated to form films. The films were exposed to 5 J/cm^2 of filtered 365 nm radiation, followed by a 30 minute post-exposure bake (PEB) at 120°C and then a 30 minute bake at 170°C to volatilize residual photobase. The PAG used is very weakly sensitized at 365 nm [5], hence in principle a compatible direct-write process involving mid-UV initiated gelation followed by 248 nm (DUV) initiated acid-catalyzed decomposition of sacrificial polymer is possible.

Results and Conclusions:

To test if porosity could be selectively produced, the films were exposed to 5 J/cm^2 of DUV radiation after gelation and then post-baked at 170°C for 1 hour in order to decompose the sacrificial polymer. Half of the wafer was covered during the exposure step so that the exposed and unexposed regions could be compared. The remaining PAG was deactivated by exposing the entire wafer to 1 J/cm^2 DUV radiation and immediate neutralization with a basic vapor. Finally, a 30 minute bake at 250°C was used to volatilize the residual reactants that might degrade the optical properties of the film over long periods of time. An ellipsometer was used to determine the refractive index (RI) of the film after each processing step. As shown in Figure 4, there was a refractive index difference of 0.0583 between the exposed and unexposed parts of the wafer for a dual-tone system with PBG 1.

For a dual-tone film with PBG 2, the RI difference between the exposed and unexposed sides was only about 0.0153. This suggests that not all of the porogen was decomposed. Processing conditions for films containing PBG2 must be modified to increase their final RI difference.

The ability to selectively lower the refractive index of the SOG films suggests that, in principle, a direct-write waveguide can be made using a photomask to define waveguide patterns in a dual-tone process. Greater RI differences between core and cladding regions could be achieved by increasing porogen loading, which will require optimization of process conditions.

Future testing of the resolution limitations of photo-defined patterns must be done to ensure that features can be patterned at sizes useful to waveguide fabrication. The optical and mechanical properties of porous SOG waveguides must be thoroughly tested to determine the viability of this system as an alternative to current direct-write waveguides.

References:

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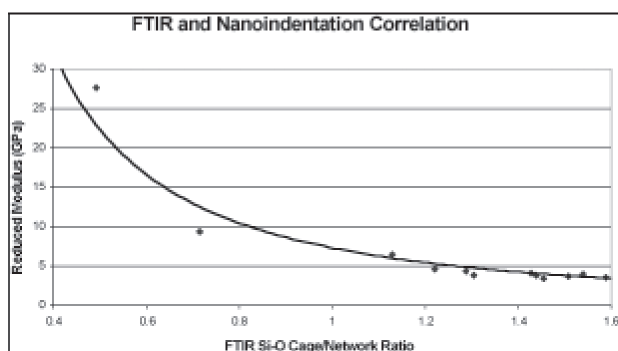

Figure 3: Comparison of FTIR and nanoindentation experimental results.

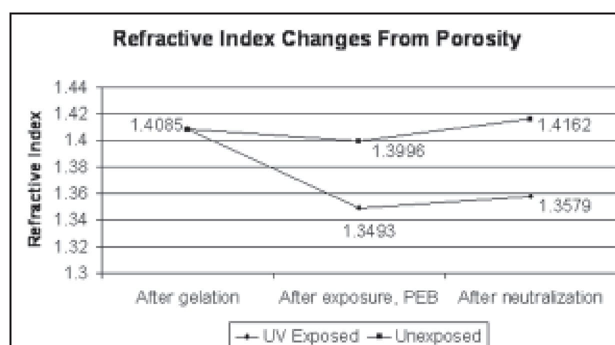

Figure 4: Refractive index values for two halves of a wafer of the PBG 1 dual-tone system.