

# A STUDY OF THE LIMITS OF SPIN-ON-GLASS PLANARIZATION PROCESS

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**Abstract:** Results presented in this paper demonstrate that global planarization with a SOG planarization process can not be achieved. However, local planarization on a predetermined site on a patterned wafer is possible, with a planarization factors of 0.81 for a single step process, 0.86 for a double step process, and 0.90 for a triple step process. Such planarization involves repeating the deposition and densification steps of the SOG material several times, and can be accurately modeled by a simple model described.

## Študija omejitev planarizacijske tehnike s tanko plastjo tekočega stekla (SOG)

**Ključne besede:** polprevodniki, mikroelektronika, IC vezja integrirana, planarizacija topografije, SOG plasti tanke stekla tekočega nanosenega centrifugalno, proizvodnja, modeliranje procesov, PECVD nanosi kemični s paro plazemsko izboljšani

**Povzetek:** Rezultati predstavljenih meritev kažejo, da je globalna planarizacija topografije na silicijevi rezini izven dosega metode planarizacije s tanko plastjo tekočega stekla (SOG). Vendar pa se z metodo, na določenem mestu na rezini, da doseči lokalno planarizacijo, s planarizacijskimi faktori 0.81 za enostopenjski proces, 0.86 za dvostopenjskega in 0.90 za tristopenjskega. Takšen večstopenjski planarizacijski postopek zahteva večkratno, zaporedno nanašanje in utrjevanje SOG planarizacijskega materiala in ga je možno natančno opisati s preprostim modelom planarizacije, ki je tudi opisan.

### Introduction

Device planarization, i.e. reduction of distances between topography and reduction of the side wall slopes in order to facilitate subsequent processing steps, is an important consideration in IC fabrication technologies where circuit features are scaled to submicron dimensions. It is most critical during the final steps of fabrication, when several metallization and dielectric layers are deposited, and is used primarily to enhance step coverage of these layers. Often only partial planarization (smoothing of topography), with limited step heights reduction is sought /1,2/. However, sometimes complete local planarization is required, and even complete global planarization, where the surface of the wafer is completely planarized over arbitrary topography. The latter requirement arises e.g. in LCD technologies where the globally planarized wafer surface is the lower electrode of a LC display /3/ or in ferroelectric memory devices /4/.

There are several planarization techniques used in IC processing /5/. Physical methods include polishing, which is usually applied where complete and global planarization is required, and different techniques where planarization of existing dielectric layers is attempted by film reflow, etch-back of sacrificial layers etc. Fluidic planarization techniques utilize low viscosity of certain materials, e.g. photoresists, polyimides and spin on glasses (SOG), which can

fill the trenches in wafer topography. These methods are simple to apply and usually require low processing temperatures (below 400 °C). However, compatibility of the fluidic materials with the standard dielectric materials is a serious concern, and, as a rule, only limited planarization can be achieved by such methods. In this contribution the limits of the SOG planarization methods are studied and described.

### Experimental

Planarizing characteristics of the Allied Chemicals Accuglass series 204 SOG material were studied. SOG films were deposited on 4" wafers on a Semiconductor Systems Inc. System One modular coater with an on-line drying oven, at 3000 r.p.m. and the deposited film dried at 100 °C for 60 sec. Resulting film was 315 nm thick, with better than 1 % ( $\pm 1\sigma$ ) wafer to wafer repeatability in uniformity. Densifications were performed in a Blue M, model IGF 206B-3 furnace, in a nitrogen atmosphere. A Semix Tazmo model TR 6132U (D) coater, with 3 ovens, was also used at later stages of the work, eliminating the need of a separate oven for low temperature (305 °C) densification. High temperature densification (900 °C) was performed in the Blue M oven in all cases. The results of planarization processing were photographed on a Hitachi model 405 scanning electron microscope and photographs analyzed.

The patterned wafer topography was simulated by a pattern of 10 parallel aluminum lines on field oxide. The lines were 2.5  $\mu\text{m}$  wide, 0.35  $\mu\text{m}$  thick (i.e. step heights 0.35  $\mu\text{m}$ ) spaced 1.5  $\mu\text{m}$  apart (i.e. at 4.0  $\mu\text{m}$  pitch), 3  $\mu\text{m}$ , 4.5  $\mu\text{m}$ , 6  $\mu\text{m}$ , and 7.5  $\mu\text{m}$  apart. All planarization factor data presented are an average of 5 measurements on 5 different wafers, with 2 % ( $\pm 1\sigma$ ).

## Results and discussion

Rapid evaporation of the solvent from the SOG material during the deposition process challenges detailed analysis and prediction of the degree of planarization possible with such a process. A quantitative measure of the step-height reduction, referred to as the planarization factor  $\beta$ , is given by

$$\beta = 1 - (t_{\text{step}}^f / t_{\text{step}}^i) \quad (1)$$

where  $t_{\text{step}}^f$  and  $t_{\text{step}}^i$  are the final and the initial step heights, respectively. In complete planarization  $\beta = 1$  and 0 if no planarization exists.

The rheological (fluidic) deposition model, which is often used in analysis of the spin-on processes and is based on the Navier–Stokes equations /5/, suggests that covering a patterned wafer with a fluid film (SOG, photoresist or polyimide) results in a completely flat top surface of the film, which remains flat until a considerable amount of solvent is removed from the material. After the removal of the solvent only non-volatile components of the film material remain on the wafer surface. If the proportion of the non-volatile components in the SOG material is  $k$ , the planarization factor achieved during the evaporation of the solvents is simply  $\beta = k$ , regardless of the thickness of the deposited planarizing film and the resulting partially planarized wafer topography still reflects the underlying topography. In case of Accuglass 204 SOG material, which contains 10 % of nonvolatile components (as specified by the producer), a maximal planarization factor of  $\beta_{\text{id}} = 0.1$  could thus be expected, as a result of drying of the material. However, this would only be true if during evaporation of the solvents no gross transport of the planarizing material, driven by the surface tension, occurred. This is clearly not the case: in dense topography we have been able to achieve  $\beta$  as high as 0.83 (depending on the details of the wafer topography), and less than 0.1 on isolated lines or lines separated by more than 4 to 5  $\mu\text{m}$ . This indicates that the transport of the planarizing material during evaporation of the solvents plays an important role in the SOG planarization process.

The quality of the surface underlying the planarization film also effects the planarization process and is also not predicted by the rheological model. A SOG film deposited on a bare, flat silicon wafer is not uniform across the wafer: it is generally 1.2 % thicker on the wafer center than on its edge. The situation is reversed on films deposited on wafers covered with a 1.3  $\mu\text{m}$  thick PECVD oxide film, which also has a flat surface: in this case the SOG film is 2.7 %

thinner in the center of the wafer. Also, at identical coating conditions, average thickness is 3.5 % less than on the bare wafers. SOG films deposited on patterned wafers (patterned aluminum on field oxide) simultaneously exhibit surface and topography effects: their thickness similar to those on PECVD oxide, with a 8.8 % reduction of thickness in the center. These effects are quite reproducible and are several times larger than the pertaining standard deviations of the film thickness as measured at standard positions on the wafers /6/. We conclude that both the surface quality and its structure have important influence on the local thickness of the deposited SOG films, precluding total global planarization with such a process. However, locally the topography effects prevail, which makes partial, local planarization possible.

Another difficulty in analyzing in detail the SOG planarization process arises from the rapid drying (evaporation of the solvents) and the associated thinning of the SOG film at 100 °C, the recommended temperature for this stage of processing. No further thinning due to evaporation of the solvents can be observed after only 60 sec, which makes it difficult to measure the original film thickness, unless depositions and thickness measurements are performed in an atmosphere saturated by the solvents. Such measurements have been attempted with inconclusive results: they suggest an as-deposited film thickness of 4  $\mu\text{m}$ , which can be compared to 5.6  $\mu\text{m}$ , the result of a calculation based on the rheological model, material and the deposition parameters.

As a consequence of the high volatility of the solvent system used the SOG material, the amount of solvent evaporating during the spinning and the formation of the film is considerable, thereby rapidly and locally changing the surface tension and viscosity of the spun-on material. The surface diffusion model of the planarization process, which is often used to model planarization by reflow of doped glass and is conveniently accessible in different simulation packages (e.g. SAMPLE), is therefore unsuitable for simulations of the SOG planarization process. Detailed modeling of the planarizing properties of the liquid SOG material is therefore difficult and only semi-empirical attempts in this direction have been published /7/.

After initial drying the behavior of the SOG film becomes well predictable /6/. During densification at 305 °C initially some further expulsion of the solvents from the pores of the film is observed, resulting in thinning of the film in an exponential manner, with a characteristic time of 0.50 hours. After this initial thinning, densification proper of the film can be observed; it also follows an exponential curve, with characteristic time of 1.3 hours. After 3.5 hours of baking at 305 °C the SOG film thickness does not decrease further appreciably. The quality of the deposited film is determined exclusively by the second stage of the densification and results in a porous film. Further heat treatment at a higher temperature reduces the porosity /8/, however if the planarization is applied at a stage where a

metal (aluminum) film is present on the wafer, the possibility of densification at elevated temperatures is strictly limited. Densification at 900 °C removes all traces of silanols and H<sub>2</sub>O from the film, as has been demonstrated by IR spectroscopy /9/, but still does not eliminate porosity completely. This is illustrated by our rehydration experiments in which freshly densified films at this temperature were exposed to an atmosphere saturated with water and from which the films can reversibly adsorb H<sub>2</sub>O. The degree of water adsorption has been monitored by measurements of the dielectric constant of the SOG film, which ranges from 4.6 in a dry film densified at 900 °C to 8.3 in a rehydrated film. These results closely correspond to those reported previously /10/ and indicate that moisture content (and possibly silanol content) in SOG films can be, due to possible reactions of the moisture from the film with the aluminum, potentially a serious source of quality degradation problems /11/.

In modeling of the planarization factor of the two stage densification process at 305 °C, the initial thinning due to expulsion of the solvents from the film can be, without appreciable loss of accuracy, neglected, and only the characteristic thinning time of the second stage considered. This is due to the relatively small change in the film thickness during the initial stage and the long densification times of the second one. The planarization factor for the densification step only, at specified temperature, is  $\beta_d = 0.90$ . Thus the compound planarization factor for the initial drying and densification is

$$\beta = \beta_{id} \beta_d$$

and depends strongly, as described above, on the topography: it is 0.09 for isolated lines and 0.81 in case of 0.35  $\mu\text{m}$  step heights of 2.5  $\mu\text{m}$  wide lines with 4.0  $\mu\text{m}$  pitch.

Attempts at planarization with 2 subsequent SOG depositions revealed that a SOG film dried at 100 °C is readily attacked by the solvents in the SOG material itself and is partially removed during the second deposition. This is demonstrated by the compound thickness after drying which increases by only 50 %, and a resulting  $\beta_{id}$ , which is, in case of isolated lines, not significantly different than that of one deposition only. The influence of the substrate topography on the double film planarization factor is even greater than in single film case, probably due to the fact, that the material in the trenches between the lines is less accessible to the solvent than the more exposed material. However, no regularity in the planarization factors could be observed for such a process and we therefore conclude that this is not a viable planarization procedure.

Deposition of a second film after densification of the first one (at 305 °C) resulted in doubling of the compound film thickness and an increase in the planarization factor  $\beta$  from 0.81 to 0.86, an increase of 6.2 %. This increase can be modeled by replacing  $k$ , the proportion of the non-volatile components in the SOG material, in the expression for  $\beta$ ,

by a related empirical parameter  $f$ . This characterizes the dynamic drying-out and densification processes by their end results, i.e. the thinning of the planarizing film at a particular site on the wafer, and thus takes account of all the effects governing the film thinning process at the site.  $f$  has to be determined experimentally. If the ratio of the  $f$  parameters, describing the reduction of the deposited SOG film thickness under and on a step of initial thickness  $t_{\text{step}}^i$ , is taken to be proportional to the step heights:

$$r = f_{\text{under}}/f_{\text{on}} = a \cdot t_{\text{step}}^i + 1$$

where  $a$  depends on the details of the topography to be planarized, the resulting planarization factor of a multiple-step planarization process can be predicted for a predetermined site on the wafer. In case of parallel lines of the above mentioned dimensions, and for the Accuglass 204 SOG material,  $a = 7.1$  and the model predicts a planarization factor  $\beta = 0.86$  for a double deposition of the SOG planarization material, and 0.90 for a triple deposition. Both values agree well with our experimental data. Results are summarized in Table 1. However, such an empirical model can only be used for determining  $\beta$  on a predetermined site on the wafer, with specified topography. It is of little value for estimating the degree of global planarization across the wafer. Further, multiple-step planarization is a process of diminishing returns and total planarization, even locally at a predetermined site, may not be a realistic goal of such a multi-step process.

## Conclusion

A detailed understanding of the planarization process is required to design a planarization process which results in the required degree of planarization of a production wafer. Our results demonstrate that global planarization with a SOG process is extremely difficult, if not impossible, to achieve, but local planarization with a planarization factor of 0.9 is certainly within its reach. Such a process involves repeating the deposition and densification steps of the SOG material several times, and can be, for a predetermined site on a patterned wafer, quite accurately modeled by the simple model described.

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Table 1. Planarization factors after different stages of SOG planarization process

Planarization stage	planarization factor
deposition (including evaporation of solvents at 100 °C, $\beta_{id}$ ): isolated lines	0.09
deposition (including evaporation of solvents at 100 °C, $\beta_{id}$ ): dense topography	0.9
double deposition with no densification: isolated lines	~ 0.1
double deposition with no densification: dense topography	~ 0.8, not repeatable
densification ( $\beta_d$ )	0.9
compound ( $\beta_{id} \cdot \beta_d$ ): dense topography	0.81
double planarization: dense topography	0.86
triple planarization: dense topography	0.90

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