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Fabrication of High Aspect Ratio SU-8 Structures Using UV Lithography and Megasonic-Enhanced Development

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In recent years SU-8 resist attracted a high interest for fabrication of structures with high topography or high aspect ratio structures. The reasons for SU-8 popularity can be found in its unique properties – high chemical and mechanical stability, biological compatibility, optical transparency, high aspect ratio capability and low cost of fabrication. SU-8 can be used as an alternative molding material to LIGA process; in comparison to the standard LIGA process, relatively thick (1 mm range) SU-8 layers can be processed with UV lithography and do not require expensive X-ray light source.

Nevertheless, processing of thick layers of SU-8 is not without challenges – coating high viscosity material, critical soft bakes in order of several hours, exposure requiring good contact, critical post exposure bake and extremely long development times.

One aspect of the SU-8 processing, which is explored in this paper, is improvement of the development process time – by using single wafer megasonic-enhanced development. In this paper, the experimental results from manufacturing of SU-8 structures with aspect ratio 1:23 by using UV lithography and megasonic-enhanced development will be presented. Significant development time reduction from 240 min down to 10 min was achieved.

Introduction

SU-8 is an epoxy-based, chemically amplified negative tone photoresist. After exposure to ultraviolet (UV) light, the photoacid generator decomposes to form hexafluoroantimonic acid which starts the polymerization process. With application of heat during post exposure bake, full cross-linking is achieved. Cross-linked SU-8 is mechanically and thermally stable, with a glass-transition temperature around 200 °C and a Young's modulus of ~4–5 GPa (1). Additionally, SU-8 is chemically stable in various solvents and acids and can be modified to be electrically conductive or colored.

The use of SU-8 structures in applications as optical accelerometers (2), piezoresistive mechanical sensors (3), micro fluidics channels (4) and UV-LIGA molds (5) or for die packaging (6) has been reported in literature.

SU-8 material is available in viscosities range from 2 cSt to 51500 cSt, covering the resist thickness from 1.5 µm up to 500 µm in single coated layer. The coating of SU-8 resist is not limited to the spin coating; resist casting, spray coating or lamination of dry film SU-8 sheets are alternative techniques.

The standard process flow of SU-8-based application starts with the substrate preparation – while some surfaces (Si, Ti) do not require any specific preparation, others (Ni) require the use of adhesion promoters to prevent SU-8 delamination from substrate. After coating onto the substrate, SU-8 layer is soft baked for driving the solvent out.

After exposure with the UV light and the subsequent post exposure bake, the substrates are ready for the development.

The standard development technique for SU-8 resist is immersion in a development bath for several hours to dissolve uncrosslinked SU-8. In case of ultra thick SU-8 (over 1000 µm), development times over 10 h are not uncommon.

The use of megasonic-enhanced processes (high frequency acoustic agitation) was reported as being used in the semiconductor and the MEMS technology. The megasonic-enhanced cleaning is commonly used for the particles removal from substrates surfaces during cleaning steps in the CMOS technology. In the resist development, the use of megasonic energy for improvement of the development rate, development uniformity and walls definition for high aspect ratio cavities for standard LIGA process was already reported (7). For enhancing of SU-8 development, megasonic agitation in the bath tanks was reported (8) .

Compared to the megasonic-enhanced bath process which is a batch process, not compatible with single wafer processing lithography equipment (lithography tracks), the single wafer megasonic-enhanced development process can be integrated in-line. Single wafer approach guarantees the use of fresh developer solution for each wafer, lower developer consumption and better process control (uniformity) for each processed wafer.

The setup of the single wafer megasonic-enhanced development on EVG®101 is showed in figure 1 – the megasonic transducer is mounted on adjustable arm over the wafer surface. During the process, the wafer rotates at low spin speed and acoustic power is applied uniformly through triangular-shaped transducer. A dispense nozzle supplies sufficient amount of developer to keep the space between the transducer surface and the wafer surface filled with developer. Adjustable parameters of the process are: the distance between wafer surface and megasonic transducer (flight-height), rotation speed, dispense rate, acoustic power and pulsing parameters.

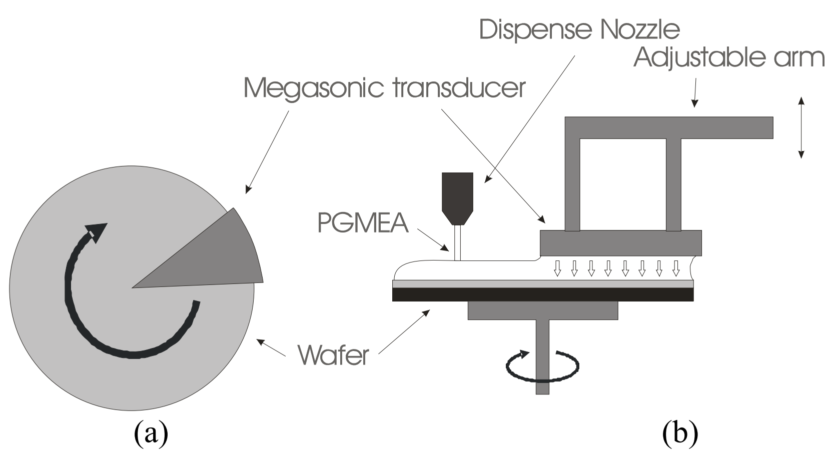


Figure 1. Schematic drawing showing the setup of the single wafer megasonic transducer: (a) view from top, and (b) cross section view.

During the operation, the acoustic power in the liquid generates the controlled cavitation, which stirs the developer. Fresh developer can be transferred to the undeveloped structures much faster than by diffusion flow and enhances the development process.

This paper describes a single wafer megasonic-enhaced SU-8 development process. Experimental results showing compared data obtained with the new process as well as with standard bath development process are presented.

Experimental

The experiments described in this paper were performed on SEMI standard 150 mm silicon wafers. Before SU-8 coating, all wafers were cleaned with acetone and isopropyl alcohol followed by a dehydration bake. The coating was performed on EVG®101 semi-automated coating system. To achieve 470 µm thick layer, SU-8 100 (from MicroChem Corp.) with viscosity 51500 cSt at 25 °C was spin coated at 600 rpm for 60s. Following the coating, the wafers were soft baked on a flat-leveled hotplate in proximity at 105°C for 10 hours, with slow ramp up and cool down. Excellent coating uniformity of ± 2% (excluding 1 cm edge bead area) has been achieved (fig. 2) by using a closed chamber system with precise ramping up and down of the spin speed.

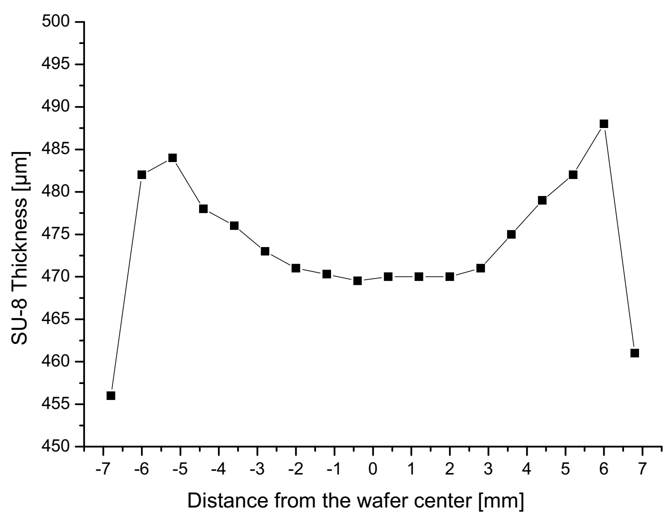


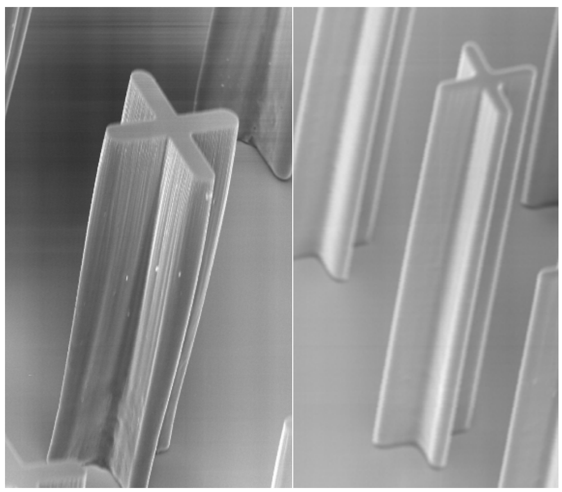
Figure 2. Coating uniformity of SU-8 over 150 mm diameter Si wafer.

A common known problem with thick SU-8 layer spin coated at low rotation speed is high edge bead that prevents the mask and the resist surface to come into contact in the active area of the wafer. One solution to this problem is use of a chemical edge bead removal (EBR) – wafer is spinning at low spin speed and the EBR solvent is streamed to the edge of the wafer to remove excessive material. In case of thick SU-8, if EBR is done directly after the coating, the resist is still liquid and cleaned edge is immediately covered with SU-8 resist flowing due to the centrifugal force. If spin speed is lowered to reduce resist flow, EBR solvent starts to penetrate into the SU-8 layer due to the concentration gradient. The EBR can be done also after the soft bake, nevertheless long EBR time is needed to remove the dried SU-8 of several hundreds of micrometers.

Air gap compensation technique can be used in the experimental setup when no structures are located in the edge bead area or when thickness variation in the edge area is not critical for device performance. The technique which uses soft cushion between the wafer and the chuck to bend the wafer for topography compensation was already reported (9). Another approach is the use of liquid with similar refractive index to SU-8 between the mask and the wafer to compensate the air gap (10). In current work, a flexible foil mask has been used to compensate the edge bead and SU-8 topography.

The use of a flexible mask brings several advantages over traditional glass mask – significantly lower price, ability to compensate the wafer topography and easy release from the wafer surface after vacuum contact. The high resolution masks down to 5 µm are nowadays available on the market.

The vacuum contact exposure with flexible foil mask (from J.D. Photo Tools) was performed on EVG®6200 Infinity mask aligner. As Yang, R. and al. (10) reported, presence of i-line (365 nm) peak in exposure spectrum results in lines widening on the top part of the structures. Figure 3 illustrates the difference in sidewall profile depending on exposure spectrum.



(a) (b)

Figure 3. Structure profile (470 µm high structures) depending on the exposure spectrum: structures exposed with 365 nm and 405 nm (a) show widening of top part of the structure; exposure with 405 nm only (b) leads to uniform line width on entire pattern height.

The reason for this phenomenon lies in the high absorbance of 365 nm wavelength in SU-8: the high energy photons in the 365 nm radiation are absorbed in the top layer close to the surface of the SU-8 and cannot penetrate in the depth of the thick resist layer. Absorption of 405 nm radiation photons is very low, they can uniformly expose the entire SU-8 thickness.

The post exposure bake has been performed on the flat-leveled hotplate at 95 °C for 20 min with slow ramping up and cooling down. Afterwards, the first set of wafers has been immersed into propylene glycol methyl ether acetate (PGMEA) bath without any agitation; the second set was puddle developed enhanced by the single wafer megasonic development. After development, wafers were rinsed by isopropyl alcohol and dried on a hotplate.

The megasonic-enhanced development has been performed with single wafer megasonic transducer (from ProSys, Inc.) integrated on EVG®101 semi automated developer (fig. 4).

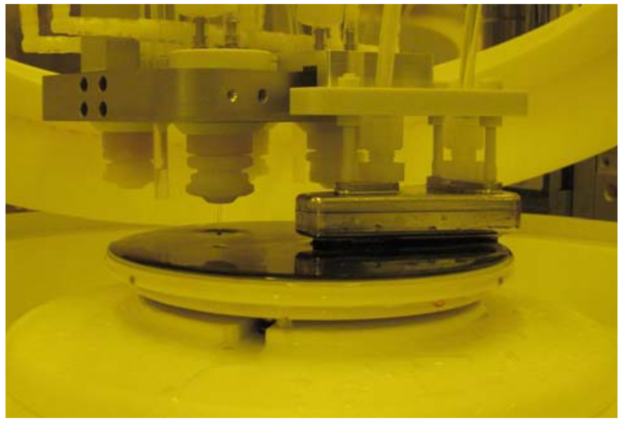


Figure 4. 150 mm single wafer megasonic-enhanced development system. Megasonic transducer integrated on dispense arm of EVG®101 with adjustable horizontal position. Side view during development process. Dispense nozzle maintains constant flow of developer.

For optimum operation, the distance between transducer and wafer surface has to be adjusted to minimize reflected power and to maximize active forward power. Figure 5 shows the reflected power as a function of the distance between megasonic transducer and the wafer in PGMEA.

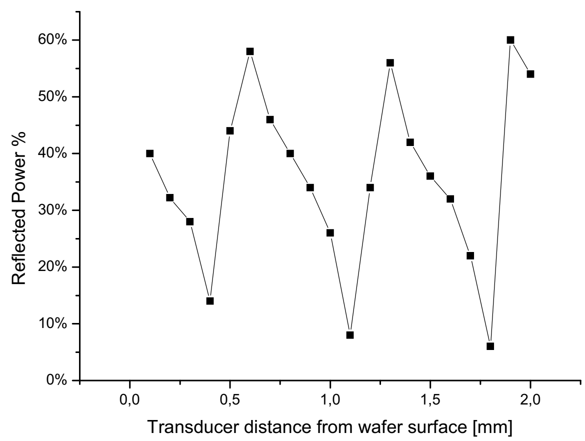


Figure 5. Reflected power as a function of the distance between megasonic transducer and the wafer surface.

The development time was increased for each following wafer in 2 min steps, and structures were inspected for residuals. For the wafers developed in bath tank, development time was increased in 30 min steps for each following wafer.

Results and Discussion

After rinsing and drying, wafers were inspected for pattern definition, residuals and delamination. On the wafers developed in the bath, the residuals close to the structures base were visible after 210 min of development time. Wafers developed with megasonic agitation were residuals-free after 10 min of development. No delamination or deformation was observed on structures with 20 µm sidewall thickness. Figure 6 shows the results of two development techniques.

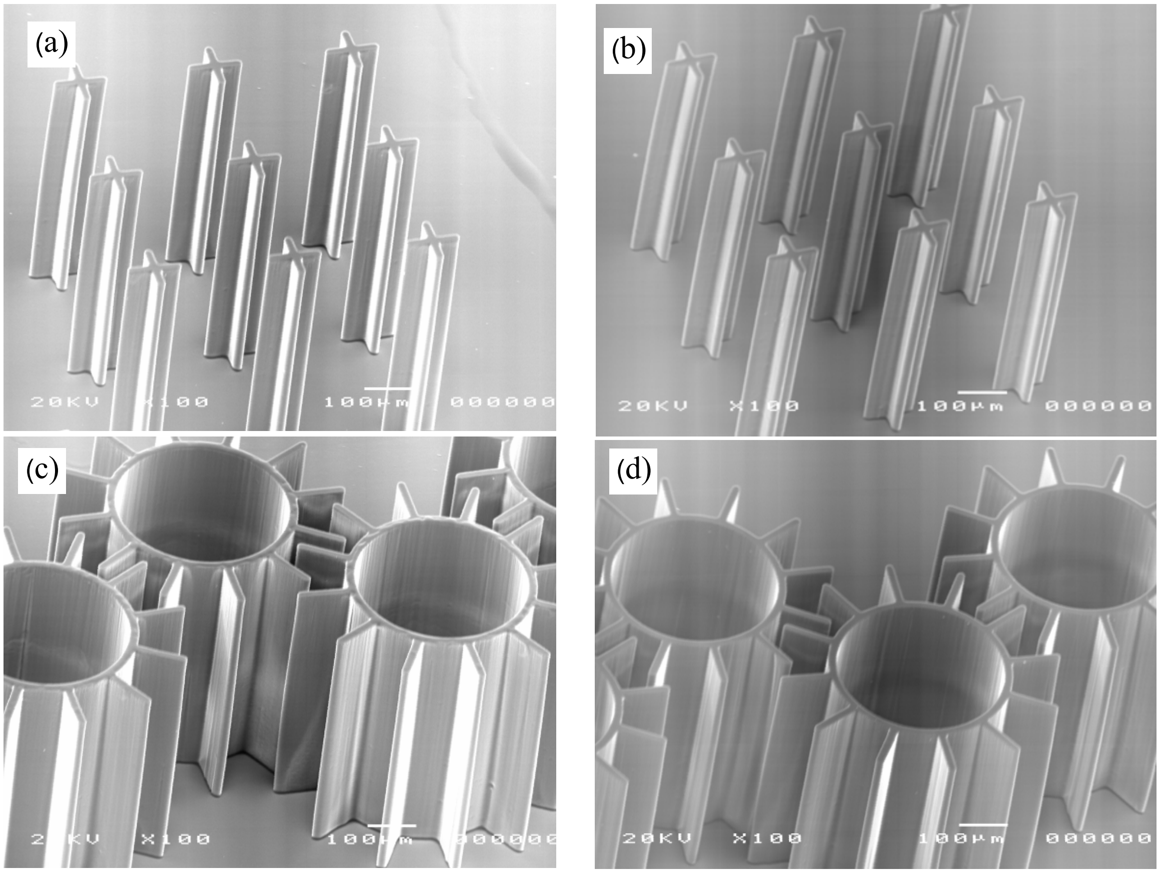


Figure 6. Free standing 470 µm high SU-8 structures. Structures with sidewall thickness 20 µm, aspect ratio 1:23. Structures on (a) and (c) were developed in PGMEA bath in 240 min, structures on (b) and (d) developed with single wafer megasonic-enhanced development in 10 min.

The structures with sidewall thickness below 20 µm were distorted (fig. 7) regardless the development technique – adhesion of SU-8 structures to silicon surface was sufficient but structures were not enough mechanically stable. The reason for distortion is not yet clarified, but it may come either from mechanical stress during post exposure bake or from the forces induced during wafer drying. Further experiments will be conducted to minimize this phenomenon.

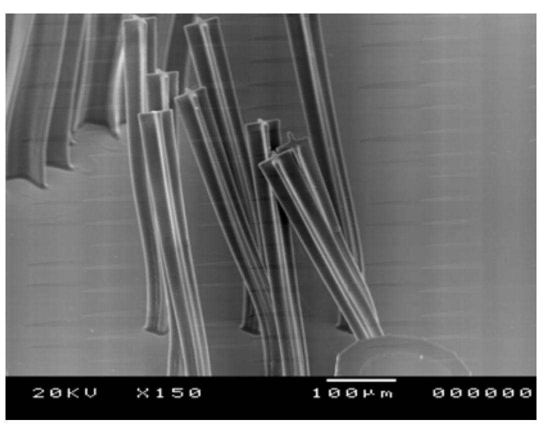


Figure 7. Distorted SU-8 structures, 470 µm high with side wall thickness 10 µm.

Conclusion

This paper reports on fabrication of high aspect ratio SU-8 structures by UV lithography and megasonic-enhanced development. The development time can be significantly reduced by megasonic-enhanced development. Open space structures of comparable quality were fabricated by two development techniques: in conventional bath for 240 min of development, with megasonic-enhanced process in 10 min for equivalent results.

Structures with vertical sidewalls and aspect ratio 1:23 were obtained in 470 µm thick SU-8 resist by using the foil mask exposure with filtered UV light. The foil mask can be good compensation technique for the topography and edge bead of thick SU-8 layers.

Correct selection of exposure spectrum is critical to achieve vertical sidewalls of high SU-8 structures. Although generally recommended, it is not sufficient to suppress the intensities below 350 nm, as the presence of 365 nm in exposure spectrum causes widening of the upper part of high SU-8 structures.

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