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Novel Photolithography Yield-Enhancement Technique: Megasonic-Enhanced Development

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MEMS-specific processes required to adapt standard IC manufacturing technologies in order to accommodate its custom requirements. Photolithography is one of the standard techniques which had to adapt particularly to the use of thick resists needed for high aspect ratio features fabrication.
In order to work with resist thickness varying between few tens and up to few hundreds of micrometers the standard process flow had to be changed to multiple-layers coating, customized (and very long) baking times, special exposure techniques and development.
This paper introduces a megasonic-enhanced method used for developing resists. In case of MEMS applications this method brings not only a major yield improvement (better quality features) but also a major decrease of process time.

Introduction

Photolithography is one of the best known technologies common to Micro- Electro-Mechanical Systems (MEMS) and microelectronics fabrication. The process flow is well defined and consists of coating a photosensitive material (photoresist or simply resist) onto a substrate, bake the substrate for solvent removal from resist layer, expose to UV using a pattern generator (mask), develop the exposed features and then move to the next process, typically a thin film deposition (e.g. a lift-off process) or an etching step. The process is straight forward and for microelectronics industry the main challenge remains the shrinkage of the features and adapting the lithography to the new requirements by adopting new techniques.

In the MEMS field the challenges are of a different nature and refer mainly to the use of thick photoresists (typically by thick resist is meant the range from 5 to few hundreds of micrometers) requiring new processing techniques or transparent substrates mainly impacting on UV exposure.

In the current work will be addressed one aspect of resist processing, post-exposure development using a large area megasonic transducer, as a major yield and throughput influence factor.

Acoustic energy in the megasonic range has been used over the past decade to enhance uniformity of, and accelerate the resist develop process, initially in LIGA applications and eventually in the challenging MEMS area. Initial focus of megasonic enhanced develop work was in the reduction of boundary layer through acoustic streaming. At a given megasonic amplitude, cavitations are induced in the process fluid. The imploding cavitations and subsequent shock waves extend the fluid exchange below the streaming boundary layer. As the positive effect of megasonic induced cavitation in the sub-boundary area was observed, efforts were directed to the control of density and uniformity of the cavitation and thus reduction of develop process time and increased uniformity.

This paper presents a new method of photoresist development based on the use of a large area megasonic transducer: MegPie® [1].

Theory

Initial work on megasonic-enhanced development was accomplished in immersion type configurations in which the substrate to be processed was submerged in a tank filled with the process fluid (developer). Megasonic energy was introduced to the fluid either indirectly through a coupling fluid layer, or directly with a resonator in direct contact with the process fluid.

Such configurations exhibited significant improvements in the ability to resolve very high aspect ratio structures as well as marked reduction in the developing process time but suffered from severe limitations in uniformity across the substrate (die to die). Efforts were then made to improve the acoustic transmission uniformity through various resonator designs and placements (position/angle) of substrate in relation to the resonator. These measures were limited by irregularities in field caused by acoustic wave reflections endemic to a tank type system with wafer present [2].

The die to die non-uniformity was caused in part by the replenishment rates of "fresh" process fluid. The process fluid exchange in the sub-boundary area caused by megasonic induced cavitation simply exchanges diffused fluid from the surface region with fluid from outside the boundary layer. When the fluid outside of the boundary layer has not been exchanged for fresh process fluid on the macro level due to flow restrictions, eddy currents, or depletion of the process fluid in the whole system, the local effectiveness of the megasonic enhancement is reduced considerably.

In order to minimize or eliminate the process irregularities and variances of the immersion method, the system type was changed to a single substrate spin method. The substrate to be processed is held to a spinning chuck with the surface to be processed facing up and process fluid applied to the top surface only (figure 1).

In this spin system, megasonic energy is introduced to the process fluid via a wide area megasonic transducer, the MegPie®. This transducer couples acoustic energy into the process fluid filled gap formed by the substrate and the transducer face. The centrifugal forces created by the spinning substrate expel the spent process fluid off of the wafer and provide for a constant refreshment of the process fluid outside the boundary layer.

The uniform acoustic field of the MegPie® resonator is shaped to provide radial uniformity. In a rotating substrate system, the outer portion of the substrate is moving faster than the inner portion when referenced to a fixed point. The form of the MegPie® assures that every portion of the substrate receives the same amount of megasonic dosage with each substrate rotation. This dosage uniformity is assured without the requirement of mechanical scanning, the transducer remains at a fixed position and height above the substrate throughout the whole process.

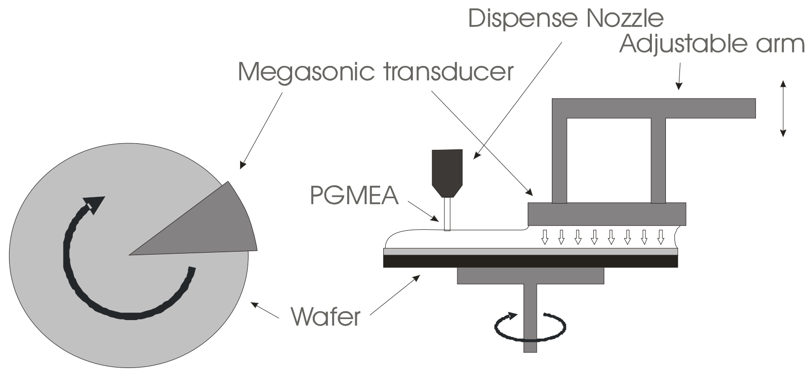

Figure 1. Horizontal spinner chuck system with fluid delivery and MegPie® transducer.

The combination of an adjustable uniform megasonic energy field and a fresh supply of process fluid provide optimal conditions for controlled and reproducible cavitation densities and uniformity (figure 2).

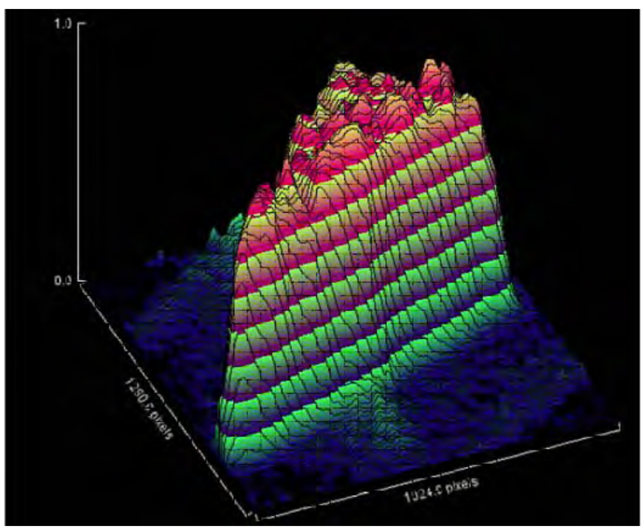

Figure 2. Sonoluminescence imaging indicating cavitation density and uniformity in the acoustic field of a 300 mm MegPie Transducer, energy 2.9 W/cm^2 at 925 kHz. Each color cycle = 10%.

Experimental

<u>SU-8 processing</u>

A high radial uniformity area megasonic transducer, the MegPie®, was used in these experiments (figure 1). This transducer couples acoustic energy into a fluid filled gap formed by the substrate and the transducer face.

Two different studies were performed: the impact of megasonics on process yield when using thick SU-8 photosensitive polymer and the impact on development process time for using a thin polymer (SINR^{TM} from ShinEtsu MicroSi [3]).

The experiments described in this paper were performed on SEMI standard 150 mm diameter 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. [4]) 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 hot plate in proximity mode at 105°C for 10 hours, with slow ramp up and cool down.

Excellent coating uniformity of ± 2% (excluding 10 mm edge bead area) has been achieved (figure 3) by using a closed chamber system with precise ramping up and down of the spin speed.

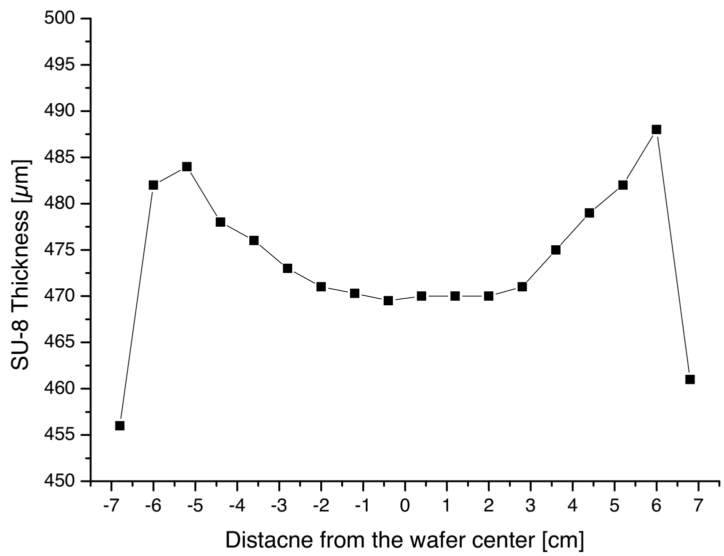

Figure 3. SU-8 coating uniformity over 150 mm diameter Si wafer.

A common 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 a to perform 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 edges are immediately covered with SU-8 resist flowing due to the centrifugal forces. 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. For UV exposure a flexible foil mask was 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 vacuum contact exposure with flexible foil mask (from J.D. Photo Tools) was performed on EVG®6200 Infinity mask aligner. The presence of i-line (365 nm) peak in exposure spectrum results in lines widening on the top part of the structures.

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 with isopropyl alcohol and dried on a hotplate.

The megasonic-enhanced development has been performed with single wafer megasonic transducer, the MegPie® integrated on EVG®101 semi automated developer (figure 4). For optimum operation, the distance between transducer and wafer surface has to be adjusted to minimize reflected power and so 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.

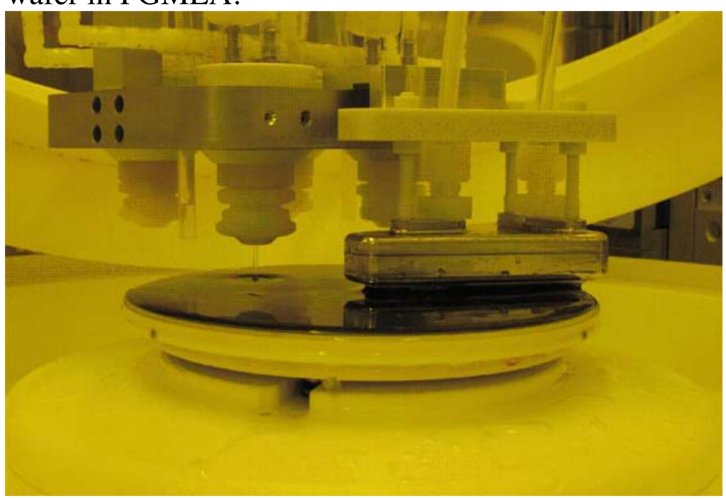

Figure 4. 150 mm single wafer megasonic-enhanced development system. Horizontal position of megasonic transducer and constant flow of developer are ensured.

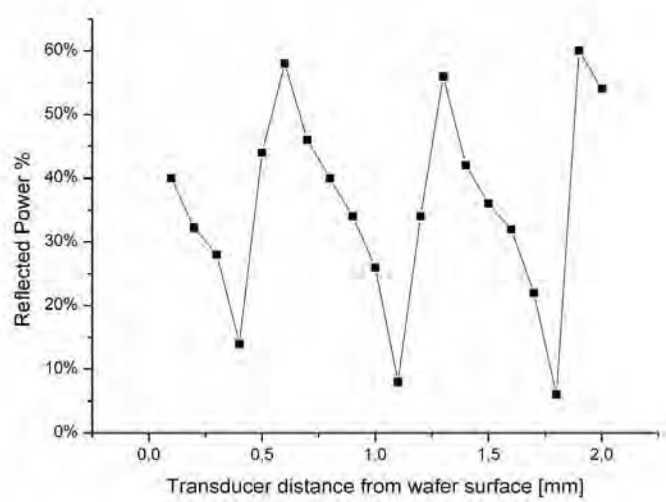

Figure 5. Reflected power as a function of the distance between megasonic transducer and the wafer surface.

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.

SINR™ processing

Si-wafers, 150mm diameter, (100)-oriented were used for tests. Spin-on deposition and baking were performed on an EVG®150 automated spin-/spray-coating equipment. Figure 6 shows the layer thickness and layer uniformity vs. spinner speed.

For the patterned layers preparation substrates coated with SINR™ material were exposed with UV in an EVG®620 mask aligner (dose: 1500 mJ/cm^2) using a test mask containing different patterns with known dimensions. Two types of development processes were used for efficiency comparison: puddle development and megasonic-enhanced development.

For puddle development the developer solution is sprayed onto substrate surface, left there for specified times and then spun off rinsed with isopropanol. In the megasonic-enhanced development process a MegPie® megasonic transducer providing high radial uniformity is placed in proximity to the wafer (in millimeter range) and a developer layer is maintained between the resist surface and the transducer surface.

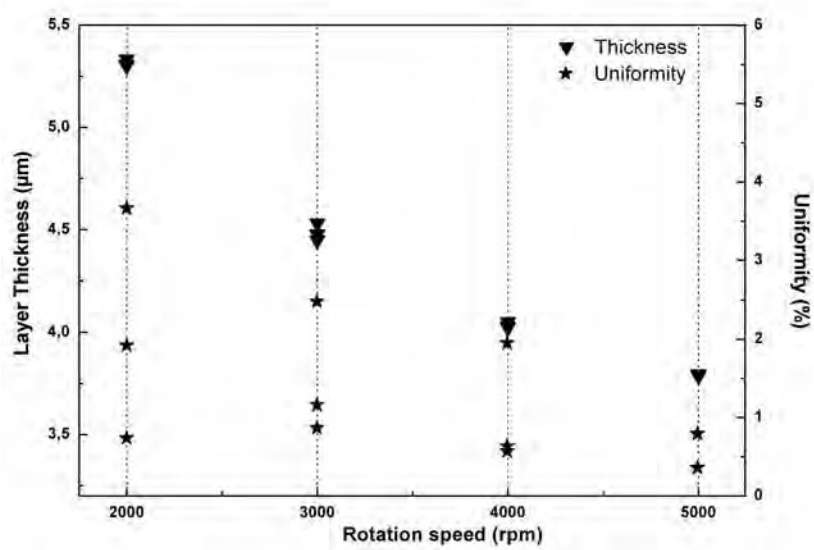

Figure 6. SINR™ layers thickness and thickness uniformity vs. rotation speed.

Results

SU-8 results

After rinsing and drying, wafers were inspected for pattern definition, residuals and delamination. Wafers developed in the bath showed still after 210 min residuals close to the structures base. 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 7 shows the results of both development techniques.

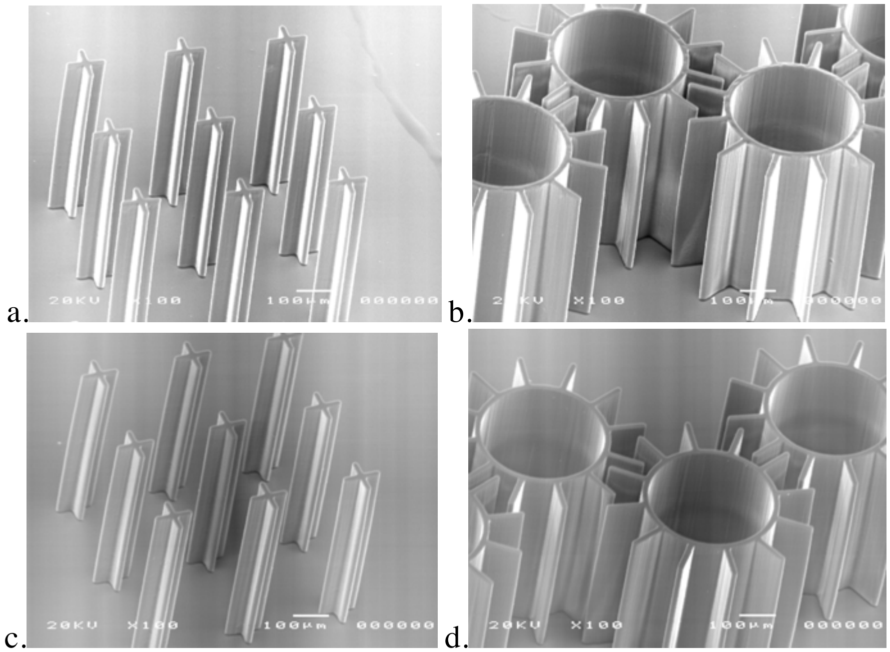

Figure 7. Free standing SU-8 structures: 470 μm high, 20 μm sidewall thickness, 1:23 aspect ratio. Structures a. and b. were developed in PGMEA bath for 240 min, structures c. and d. were processed with megasonic-enhanced development in 10 min.

SINR^{TM} results

A test mask with known feature sizes was used for patterning. The test mask consisted of alternative bright field/dark field areas, each area containing line patterns. The polymer layers were prepared as described above for spin curve study and soft baked material was exposed in a mask aligner. For the first tests the polymer thickness (5 μm) and UV exposure condition (1500 mJ/cm^2) were maintained constant and development conditions were varied in order to check the impact of the two processes on pattern quality. In a first approach the development process efficiency was evaluated by using development times of 30 sec and 60 sec. After rinse and pattern investigation with optical microscope the development was continued by using additional 30 sec or 60 sec steps.

In the current work megasonic development was studied as a potential technique to improve pattern definition in a shorter time compared to puddle development. Both the dark field as well as the bright field exposure modes were investigated as the test mask used offered this possibility. Table I summarizes the results of the development process for bright field exposure and table II shows results for dark field areas exposure. The features dimensions which were considered for evaluation of development efficiency for this set of experiments were ranging from 15 μm to 50 μm. In tables I and II the “+” sign means feature was resolved (well developed) while the “-“ sign shows features which couldn’t be resolved by specific process condition.

Table I. Development results (bright field).

Run no.	Development method	Process type (n x sec)	Total develop. time (sec)	Feature size				
				50 μm	40 μm	30 μm	20 μm	15 μm
1	Puddle	1x60	60	+	+	-	-	-
2	Puddle	2x60	120	+	+	+	-	-
3	Puddle	3x60	180	+	+	+	-	-
4	Puddle	4x60	240	+	+	-	-	-
5	Puddle	3x30	90	+	+	+	-	-
6	Megasonic	1x60	60	+	+	+	+	-
7	Megasonic	2x60	120	+	+	+	+	-
8	Megasonic	3x60	180	+	+	+	+	+
9	Megasonic	4x60	240	+	+	+	+	+
10	Megasonic	3x30	90	+	+	+	+	+

Table II. Development results (dark field).

Run no.	Development method	Process type (n x sec)	Total develop. time (sec)	Feature size				
				50 μm	40 μm	30 μm	20 μm	15 μm
1	Puddle	1x60	60	-	-	-	-	-
2	Puddle	2x60	120	-	-	-	-	-
3	Puddle	3x60	180	+	+	-	-	-
4	Puddle	4x60	240	+	+	-	-	-
5	Puddle	3x30	90	+	+	-	-	-
6	Megasonic	1x60	60	+	+	+	-	-
7	Megasonic	2x60	120	+	+	+	+	-
8	Megasonic	3x60	180	+	+	+	+	-
9	Megasonic	4x60	240	+	+	+	+	+
10	Megasonic	3x30	90	+	+	+	+	-

Megasonic-enhanced development was able to resolve features as low as 15 μm while the minimum feature size resolved after puddle development for identical UV exposure and similar development time was 30 μm (bright field) or 40μm (dark field).

Conclusion

Megasonic-enhanced development technique was introduced. Two process examples were presented: SU-8 thick resist development and SINR^{TM} thin resist development.

The development time can be significantly reduced by megasonic-enhanced development. Open space SU-8 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 1:23 aspect ratio 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.

Megasonic-enhanced development of SINR™ resist resulted in shorter process time, and using the same development time the resolved features size was much smaller compared to the puddle development.

As illustrated by these two examples the application potential of this new method is significant. Applications based on thick resists suffer for both yield and long process time. If there is not much room to decrease the baking and exposure times, significantly decreasing development time would result in a significantly shorter total process time. Thick resist mold applications or thick resist for electroplating (bumping) were identified as applications which may potentially benefit from using this method.

Besides its technical advantages of allowing fabrication of accurate structures in thick or thin resist materials this newly introduced process brings also major cost of ownership decrease not only due to the improved yield per substrate processed but also by consistently reducing process time and developer consumption.

All above mentioned benefits of this new technique recommends MegPie® as a very useful component of MEMS manufacturing toolbox.

References

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