Photoresist Coating Methods for the Integration of Novel 3-D RF Microstructures

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***Abstract*—This paper presents three coating methods of photoresist on large three-dimensional (3-D) topography surfaces. Two special methods, spray and electrodeposition (ED) are introduced and investigated for the fabrication of 3-D microstructures and RF-MEMS devices. Characteristics of each method as well as its advantage and disadvantages are outlined. A comparison is made to point out the most suitable coating method in terms of complexity, performance and type of application. The potential of these coating methods is demonstrated through several applications such as fabrication of multilevel micromachined structures and RF MEMS devices. [1031]**

***Index Terms*—Electrodeposition (ED), lithography for MEMS, patterning 3-D structures, photoresist coating, spray coating.**

I. Introduction

THE growing interest in the development of microelectromechanical systems (MEMS) and the increasing use of truly three-dimensional (3-D) microstructures requires new techniques and processes to fulfill the demand for further miniaturization and higher integration density. For several MEMS applications, pattern transfer onto silicon wafers with extensive topography requires a uniform photoresist layer over nonplanar surfaces. To date, three photoresist coating techniques have been introduced for the fabrication of MEMS devices. Spin coating is the most conventional coating method, which is applied to standard flat wafers. It is not always desirable and can only be used for some MEMS applications with certain modifications [1]. Alternatives such as electrodeposition and spray coating of photoresist should be considered. Electrodeposition of photoresist has been reported as an attractive method for 3-D stacks of chips [2], [3], but it requires a conductive layer. Recently, a new coating method, direct spray coating of photoresist, [4] has been introduced as another photoresist coating technique for microsystems. Although this technique is still in the early stages of exploration, it appears to be a promising technique for coating irregular surfaces as it presents some advantages over spin coating and electrodeposition of photoresist.

In this paper, we report on the use of these three coating techniques to coat highly nonplanar wafers, i.e., wafers with anisotropically etched grooves or cavities with a depth up to 400 μm. Potentials and limitations are pointed out and a comparison of the three coating methods is presented in order to identify the most suitable coating technique for a specific application.

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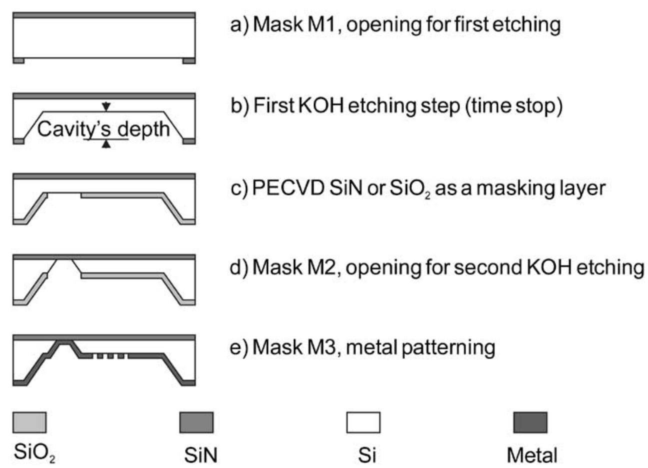

Fig. 1. Schematic drawing of the preparation of the wafers for coating experiments.

II. Test Mask Design and Wafer Preparation

The photoresist coating methods are used to transfer patterns in and across deep etched cavities. This highly nonplanar surface is often encountered in the fabrication of multilevel micromachined structures [5] and several RF-MEMS components. In order to evaluate all three coating methods, lithographic steps have been performed on micromachined silicon wafers. Deep anisotropically etched cavities of varying sizes and shapes have been anisotropically etched in KOH solution. The processing scheme used to evaluate the coating techniques is schematically illustrated in Fig. 1. Although cavities between 75 and 400 μm have been investigated [6], in this paper we focus on wafer with cavity's depth close to 400 μm.

A set of test masks has been designed to study pattern transfer on these wafers. A first mask (M1) is needed to define the deep cavities and grooves. This mask consists of blocks of structures being repeated on different areas of the wafer. Each block contains several groups of rectangles or squares with different dimensions and with an H/V ratio varying between 0.6 and 5 (H and V indicate parallel and perpendicular orientation with respect to the flat of the wafer, see Fig. 2). Group A consists of several rectangles with dimension of 1 mm $\times$ 3 mm and 2 mm $\times$ 3 mm, which are placed both parallel and perpendicular. Group A' has the same distribution of structures, but their dimensions are 2/3 of the ones in group A.

A second mask (M2) contains the structures to be patterned on the bottom of the grooves or cavities etched using mask M1.

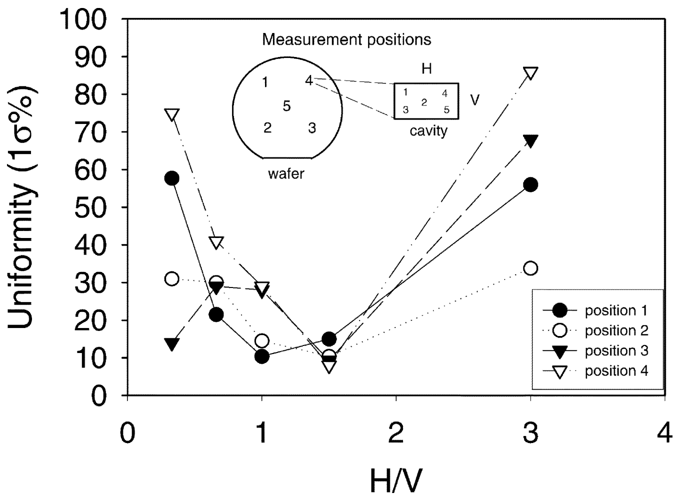

Fig. 2. Uniformity of photoresist spin coating versus the shape of cavities (cavity depth: $375\ \mu\mathrm{m}$).

These structures also vary in size, shape and separation distance. This mask is generally used to define the openings for the second etching in the two-level bulk micromachining process. A third mask (M3) containing structures that run across the entire micromachined wafer (i.e., both surface and through several etched levels) is used to further evaluate the potential of this process, particularly the metal patterning process. The evaluation of the geometry and shape of these structures is also used to measure the photoresist thickness and its uniformity. To evaluate the three coating methods, the following steps are investigated:

— photoresist coating;
— photoresist exposure and development;
— evaluation of the patterns.

In all cases, a contact mask aligner, an EV420 [4], is used for the exposure of the photoresist. The thickness of the photoresist is measured through the opening by an Alpha-step 200 surface profiler (Tencor Instrument). For all three coating techniques, spin, spray and ED coating, we study the photoresist thickness and uniformity at the bottom of the etched cavity using the following procedure. The thickness value is averaged over five measurement points at each of the four corners and in the center of the cavity. This is repeated in five different positions on the wafer as illustrated in the schematic drawing inserted in Fig. 2. The data in Fig. 2 uses only four data points, while later for spray and ED photoresist coating all five locations are reported. The photoresist coating layer is evaluated through the uniformity $(1\sigma\%)$

$$1\sigma\% = \frac{\sigma}{\text{average}} \tag{3-1}$$

where σ is the standard deviation of the measurement values and *average* is the average value over all measurement points. This uniformity value reflects the quality of the coated layer, which has a great influence on the quality of the printed image.

III. Spin Coating

A. Spin Process and Photoresist

Spin coating of photoresist is the standard coating method for flat wafers in IC technology. Spin on photoresist applied to irregular topographies wafers has been reported for some application such as for flat panel displays [7] or with a modified equipment to coat wafers with through holes [1]. Spin coating can be used for wafers with deeply etched cavities even with conventional equipment if the spinning program is appropriately modified. As recently reported in [6], a suitable photoresist and coating program can be chosen for coating high topography structures. Best results are achieved using the thick positive photoresist AZ4562 [8]. The coating procedure starts with flooding photoresist onto the wafer in order to cover the whole surface. A pause after the dispense step allows additional time for the solution to flow into the deep features. A slow acceleration and spin speed is applied to allow time for the solution to flow and spread prior to drying. A second step with a fast spin speed promotes the drying of the film and reduces the further flowing of photoresist that can result in nonuniformal coating. After coating, wafers are baked on a hot plate at 95 °C for 3 min. The wafers are then exposed with the second (M2) mask. High exposure energy is required to assure that all the structures are opened. Generally an exposure energy of 675 $\mathrm{mJ/cm^2}$ is used. The wafers are then developed in a solution of AZ400K [8] and DI water (1:4). This developer solution provides a high-contrast image. No post bake is required for this photoresist.

In spin coating of 3-D structures, the photoresist thickness and uniformity depend a lot on the size and shape of the cavity. Fig. 2 shows the dependence on the H/V ratio of the uniformity of the photoresist layer on a wafer with 375 $\mu\mathrm{m}$-deep micromachined cavities.

Using the special coating procedure described above, the best uniformity of photoresist $(1\sigma\%)$ is obtained for cavities with an H/V ratio from 1 to 2, i.e., when the shape of cavity is a square or a large rectangle. The uniformity value for this type of cavities is between 10–20%. This value is reasonable for patterning large structures at the bottom of these deep cavities.

B. Advantages

Spin coating is a mature technique and uses commercially available equipment and photoresists. The process is compatible with the IC technology and can be used at all stages of processing on all types of substrate layers. There are only two parameters, i.e., the photoresist solution viscosity and the spinning speed that strongly influence the layer forming. Therefore, the process optimization focuses only on these two parameters.

C. Disadvantages

The main obstacle is caused by the centrifugal force when spinning. The deeply etched features cause a physical obstruction to the solution flow, preventing complete coverage and often causing striation or photoresist thickness variation such as the variation on the near and far sides of a cavity or between cavities at different positions on the wafer. Sizes and shapes of the cavities also have influence on the photoresist uniformity and coating defects. Experiments investigating the effect of cavity's size to photoresist layer are performed on wafers with cavities of rectangular and square shapes fabricated by the test mask M1 as described in Section I. The measured photoresist uniformity $(1\sigma\%)$ versus H/V ratio is depicted in Fig. 2. Each set of points corresponds to an area of the wafer (upper left,

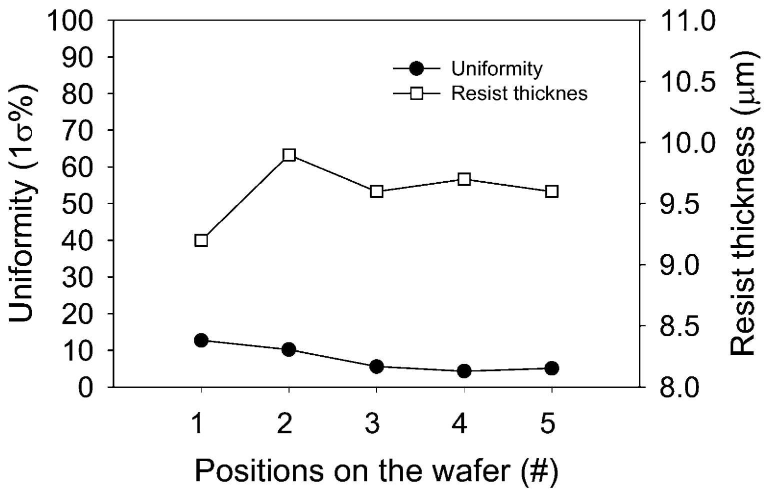

Fig. 3. Photoresist thickness and uniformity at the bottom of a 375-$\mu\mathrm{m}$-deep cavity with $H/V = 2/3$ at different positions on the wafer using spray coating.

upper right, lower left and lower right, with respect to the wafer flat). The lowest uniformity variation can be observed at $H/V = 2/3$, 1, 3/2, which indicates a better photoresist uniformity in the square or large rectangular cavities.

Coating defects related to poor coverage of corners of etched structures are evaluated as well using two long rectangular structures (with $H/V = 1/5$), placed perpendicularly with respect to each other. The separation between these two pits is 100 $\mu\mathrm{m}$. After the second etching step—generally used to open windows in the bottom of these pits—the corners of both pits are damaged. This indicates that when two such structures are placed close to each other, poor corner coverage of the photoresist is observed. This poor coverage is caused by the obstruction of features to the solution flow. Consequently, the masking layer in the separation area is locally etched during the patterning step thus undermining the masking effect crucial to proper pattern transfer during wet or dry etching steps. For cavities with $\mathrm{H/V} > 1/5$, even if the separation between corners is still 100 $\mu\mathrm{m}$, no such problem appears. Therefore, spin coating can be used to transfer patterns into the bottom of deep cavities with large size as the larger cavities present better photoresist uniformity. Despite the modified procedure, the spin method is less convenient for patterns running across cavities as the variation of photoresist over the sidewalls (top and bottom corner of the cavities) are rather severe.

IV. Spray Coating

A. Spray Process and Photoresist

The direct spray coating is performed in an EVG 101 system [4]. Compared to spin coating, spray coating operates on a different principle and it does not suffer from the photoresist thickness variation caused by the centrifugal force. The direct spray system includes an ultrasonic spray nozzle, which generates a distribution of droplets of micrometer size. It can reduce the effect of fluid dynamics of photoresist on the wafer as the photoresist droplets are supposed to stay where they are being deposited. The central part of the aerosol is forwarded to the dispense nozzle which is constructed to reduce the carrier gas pressure and to redirect the photoresist spray perpendicular to the substrate surface. During spray coating, the wafer is rotated slowly while the swivel arm of the spray coating unit is moved across the wafer. The low spinner speed (30–60 rpm) is necessary to minimize the centrifugal force. The rotation allows photoresist coverage of all angles in the cavities.

To get the proper droplet size distribution of photoresist, a photoresist solution with viscosity of less than 20 cSt is necessary. Several available photoresists cannot be used directly, as their viscosity is too high for the EV101 system or they are only suitable for flat surfaces. Therefore, we have investigated a number of photoresist solutions that are made by adding solvent to the original photoresist solution. Due to gravity, a flowing effect can occur while spraying photoresist on wafers with high topography, resulting in the accumulation of photoresist at the bottom and reduction at the top corner of cavities. To minimize this effect, the solvent's evaporation should be accelerated. One way to achieve this is to select a solvent with a fast evaporation rate at room temperature.

Initially, photoresist solutions, such as AZ4823 (Clarian Corp.) and AZ4562 (Clarian Corp.) [8] diluted in PGMEA (propylene glycol methyl ether acetate) have been investigated but the flowing effect observed could not be sufficiently reduced. This is probably due to the lower evaporation rate of the PGMEA solvents contained in both photoresists. Much better results are achieved using solutions of AZ4562 photoresist diluted in MEK (Methylethyl ketone) with solid contents of 10%. We have found that this is a proper photoresist solution for sufficiently conformal coating of wafers with high topography as the MEK solvent has a faster evaporation rate than PGMEA. Lower viscosity solutions can form a smoother layer but it may flow easier into high aspect ratio features and therefore can cause a photoresist thickness variation at the top and bottom of cavities. The choice of the photoresist composition, i.e., the amount of solvent included and the solution viscosity, is very important.

Several experiments are performed to optimize a few parameters of the spray system as well as the spray solution in order to get a good uniform photoresist layer on the wafer. Key parameters that influence the quality of the coated layer are as follows:

— solid content of the spray solution;

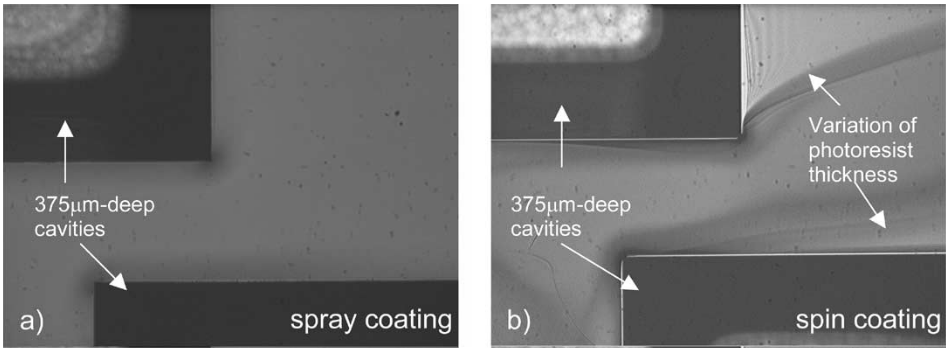

Fig. 4. Image of photoresist coated wafer surface between two cavities: a) using spray coating and b) using spin coating.

— photoresist dispensed volume;
— angle of the atomizer;
— scanning speed of atomizer;
— spray pressure.

The first two parameters are related to the photoresist solution while the other three are related to the spray system. Especially for the optimal values of the solid content and the dispensed volume of the photoresist solution several tests are required. By optimizing the coating process and using a diluted AZ4562 photoresist, a good uniform photoresist layer has been deposited on wafers with 375 $\mu\mathrm{m}$-deep cavities. In all type of cavities, the uniformity $(1\sigma\%)$ is around $\pm 10\%$ as illustrated in Fig. 3. The uniformity of photoresist layers obtained by this spray coating technique is clearly better than with the spin coating.

B. Advantages

For coating nonplanar surfaces, spray coating presents some advantages over the spin method. First, this technique uses much less photoresist than spin coating. In fact, for spin coating, the wafer is flooded with photoresist but due to the high rotation speed, only a small amount of photoresist remains on the wafer. For spray coating, the very fine droplets of photoresist are deposited directly on the wafer and form the layer. The amount of resist loss is only the small part that sprays out to the air or to the exhaust system. According to the manufacturer, the spray process requires no spin off photoresist so that it can result in up to 70% less photoresist consumption as compared to the spin process. This brings a clear benefit in cost saving and waste disposal reduction as well. Second, the reproducibility of spray coating is much better than spin coating. The photoresist thickness is repeatable over all cavities with the same size, regardless the position of cavities on the wafer. Due to an even distribution of photoresist over the wafer while spraying, the shape of the cavity and the H/V ratio have a negligible influence on the photoresist uniformity. Spray coating has no thickness variation caused by directional effect of spinning, thus no striation and no damaged structures are observed. Fig. 4 shows two images of a photoresist layer on the surface between two cavities: a) using spray coating and b) using spin coating. The spray coated photoresist layer is clearly uniform while the spin coated surface shows some striation caused by photoresist thickness variation. Thirdly, the direct spray coating does not require a special underlayer and can be applied on both insulating and conductive layers. Thus, spray coating can be used at all stages of the process and gives rather encouraging results, especially for patterning structures at the bottom of deep cavities.

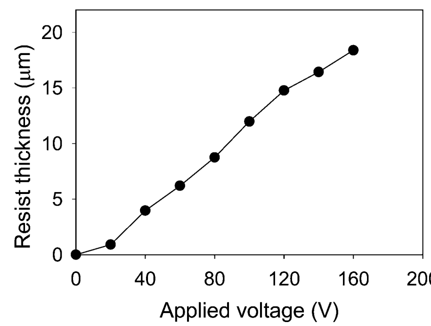

Fig. 5. Photoresist thickness as a function of the applied voltage at $45\ ^\circ\mathrm{C}$.

C. Disadvantages

Although the spray technique gives better results than spinning, small variations in photoresist thickness are observed if cavities with a large difference in size are present on the same wafer. The photoresist thickness at the bottom of a small cavity is thicker than the one in a large cavity. If the difference in dimension of cavities is large, it will lead to a large variation in photoresist thickness between cavities. Consequently, this may affect the resolution of printed patterns in the photoresist when using the same exposure energy on the wafer. Hence, it will be easier to control the patterning process if the dimensions of cavities on the same wafer are comparable. Another challenge is the flowing of photoresist due to its gravity, resulting in a thicker photoresist layer at the bottom corner and a thinner one at the top corner of the same cavity. This flow effect will be of great influence for patterns that run in and across cavities. A solution to this problem is the use of a higher dose of exposure energy to remove excess photoresist at the bottom corner of the cavity. At the top corner the photoresist tends to be thinner due to surface tension at a sharp corner. Sometime this results in very poor coverage of photoresist at the top corner. That effect will be minimized by applying a rounding-off corner step prior to coating. This step is only a short etch of silicon in a TMAH solution [9].

Although dedicated spray photoresist coating equipment is commercially available the spray technology is not as developed as spin coating and specific photoresist solutions are still under development.

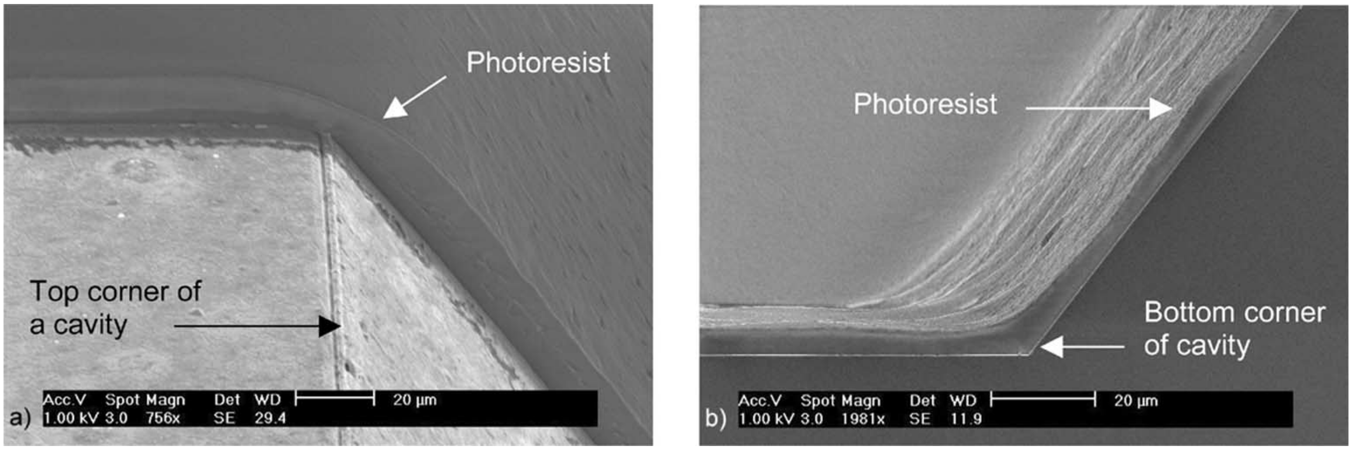

Fig. 6. SEM photographs of electrodeposited photoresist: a) at obtuse corner of a cavity and b) at the bottom corner of the cavity.

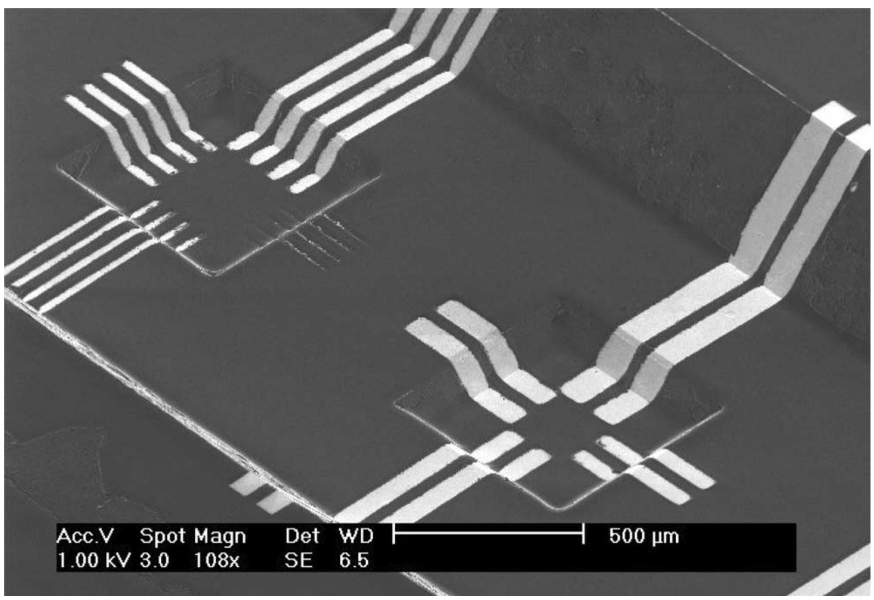

Fig. 7. Set of 10–80-μm-wide lines reproduced in a two-level-bulk micromachined cavity with the depths of 375 and 150 μm.

V. Electrodeposition (ED) of Photoresist

A. ED System and Photoresist

Electroplating of photoresist or photoresist electrodeposition (ED) is a powerful technique employed for several years to coat 3-D structures. ED coating uses special photoresist. Both positive and negative type photoresists developed by Shipley Ltd and known as PEPR 2400 and Eagle 2100 ED are available.[1] In this work, negative type Eagle 2100 ED photoresist is used. Experiments on photoresist electrodeposition are performed in a coating system developed by MECO Equipment Engineers B.V. [10]. It requires a special plating equipment and cataphoretic photoresist emulsion. To deposit a photoresist layer, the wafer surface must be coated with an electrically conductive material. The wafer to be coated faces an inert, planar stainless steel anode at a distance of 50 mm. In order to obtain regular coating and avoid pinholes in the deposition, the coating solution must be free from any gas bubbles. Therefore, the photoresist tank, coating cell, and overflow weirs are designed in such a way that inclusion of air during recirculation of the photoresist is minimized. During the coating process, carboxylate anions are neutralized by hydrogen ions generated by the electrolysis of water. As photoresist solids are removed from the bath at the cathode, there is a gradual build up of ionizer in the bath. Therefore, to maintain bath chemistry, free acid must be removed by ultrafiltration.

The process is self-terminating and the deposition takes place in only a few seconds. The photoresist thickness is highly dependent on the voltage and the temperature of the bath. The photoresist has a solids content of about 10%. The solids are in the form of stable organic particles with the size from 50 to 200 nm and soluble in water. The photoresist can be operated with a bath temperature between 35 °C–45 °C and applied voltage from 20 to 160 V.

After applying voltage, positive charged micelles are drawn to the cathode. The conductivity of the aqueous solution permits controlled electrolysis, and water decomposes to raise the pH at the cathode and lower the pH at the anode. When the micelles reach the cathode, their positive surface charges are neutralized

[1]Shipley Europe Limited, Herald Way, Conventry, U.K.

TABLE I
CHARACTERISTICS OF PHOTORESIST COATING TECHNIQUES

	Spin coating	Spray coating	ED coating
Process	- Simple - Difficult to automate trench coating process	- Simple - Batch fabrication	- More complex - Batch fabrication
Surface material	Insulating or conductive	Insulating or conductive	Conductive Electrical contact to wafer
Photoresist	- Several commercially available types - High photoresist consumption	- Photoresist solutions with viscosity < 20cSt - Very low photoresist consumption	- Special ED resists - Frequent refreshing of photoresist bath - Moderate photoresist consumption
Resist uniformity	- Difficult to control - Poor reproducibility - Dependent on shape, size and position of cavities on the wafer	- Controllable - Reproducible - Independent on shape and position of the cavities	- Controllable - Reproducible and good uniformity - Independent on shape, size and position of cavities
Parameters	- Viscosity - Spin speed	- Solid content of solution - Resist dispensed volume - Scanning speed - Spray pressure	- Voltage - Temperature - Bath condition
Suitable applications	- Transfer patterns to the bottom of etched cavities - One level etched and large cavities are preferable	- Transfer patterns to the bottom of etched cavities - Cavities with comparable size are preferable	- Transfer patterns that run in and across cavities - Metal patterning is preferable - Coating over vertical walls are possible

by hydroxide ions produced by the electrolysis of water. The micelles then become destabilized, and coalesce on the surface of the cathode to form a self-limiting, insulating film.

The photoresist thickness increases with the increase of applied voltage at an optimum bath temperature (at $45\ ^{\circ}\mathrm{C}$). Previous experiment [11] showed that coating at temperatures of $40 - 45\ ^{\circ}\mathrm{C}$ gives the best thickness reproducibility. Photoresist thickness versus applied voltage when coating at $45\ ^{\circ}\mathrm{C}$ is shown in Fig. 5. The uniformity of an ED coated layer is better than a spin or spray coated layer. For example, a layer coated at $45\ ^{\circ}\mathrm{C}$ and 70 V has a thickness of about $8.8\ \mu\mathrm{m}$ and the uniformity $1\sigma\%$ is 4.4%. These values refer to photoresist at bottom of a 375-$\mu\mathrm{m}$-etched cavity, and are measured using the same procedure for the spin and spray coating. As ED the coating is very conformal, uniformity variation are less significant and therefore not explicitly shown in Fig. 5. Due to the nature of ED coating, the photoresist thickness and uniformity do not depend on the H/V or the depth of etched cavity. Very conformal coating from top down to the sidewalls and to the bottom of the etched cavities can be obtained as illustrated in Fig. 6.

B. Advantages

The main advantage of this ED coating is the conformal photoresist layer being independent of the geometry of the nonplanar features. The most critical part to be coated like the obtuse top corner and concave bottom corner of the cavities are covered by a layer of practically the same thickness as on the surface of the wafer. A very conformal photoresist at the bottom and top corner of the etched cavity can be observed in Fig. 6a) and b). This is an obvious advantage over spray and spin coating. For that reason, ED coating is the most suited technique to pattern structures that run in and across cavities or when a smaller line width is required. An example of a patterned structure running over a wafer after a two-level micromachining process is shown in Fig. 7. Compared to the two methods previously described, this is the only technique that can coat etched cavities with vertical walls.

C. Disadvantages

This technique always requires a conductive (metal) surface. Therefore this technique is not convenient for all stages of the process, while it is perfectly suited to pattern the metal layer. The set up and process handling are more complicated than the other two coating techniques. The coating bath should be checked and maintained frequently in order to get a reproducible process.

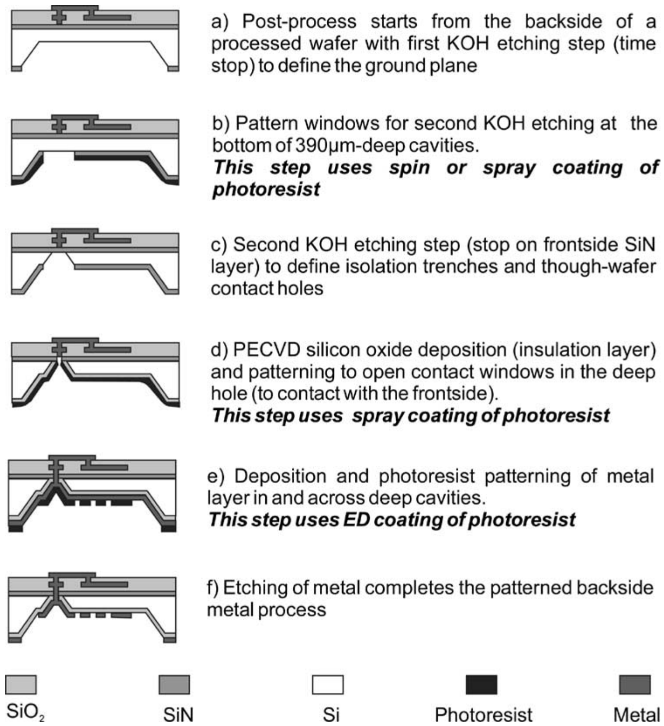

Fig. 8. Process flow of the postprocess module using three coating methods to transfer patterns in and across high topography surface.

VI. Comparison Coating Methods and Applications

A. Comparison

The spin coating, spray coating and ED coating of photoresist each have their own advantages and disadvantages when employed to coat wafers with high topography. Their major characteristics, summarized in Table I, offer a comparison between these techniques and can be of help to identify the most suited technique to transfer a specific pattern on a wafer with a known topography. Equipment cost and wafer throughput are also factors to be considered. However in this paper we limit our evaluation to the performance of these techniques on high topography wafers and compare them specifically for their use in coating 3-D structures.

B. Application

The three coating methods mentioned above can be used for a lot of MEMS applications. One of the main applications is transferring lithographic patterns onto micromachined wafers. That is a major step toward the realization of high-density through-wafer interconnects, wafer-scale packaging of microsystems and integration of passive RF components.

Based on the characteristics of each coating method, we have combined different coating procedures into one process to realize 3-D RF devices. A postprocess module for RF device realization has been developed using these coating techniques. The module is applied to the backside of the processed wafer and is used to fabricate two-level bulk micromachined structures and patterned metal at the backside of the wafer. A schematic drawing of the process sequence is illustrated in Fig. 8.

A number of RF structures have been realized using this module such as: low-loss microstrip transmission line, conductor-backed inductor, crosstalk barrier, subsurface inductor and through-chip transmission line. The process has improved the performance of RF devices as reported through the electrical characterization in ref [12]. As described in Fig. 8, spin and spray coating can be used to fabricate the two-level bulk micromachinined structures. An example of two-level bulk micromachined structures is shown in Fig. 9a). A close up of a micromachined structure with 8 through-wafer holes reaching the wafer frontside is depicted in Fig. 9b). The squares patterned at the bottom of the cavities have the correct shape after the second etch, indicating a good patterning of the nitride-mask layer. Moreover, even the through-holes that are positioned quite close to the edge of the cavities and have narrow spacing are well defined and no under etch of the corner or of the spacing is observed.

In the module described in Fig. 8, ED photoresist coating is used at the last step for metal patterning. This method makes use of the active device metallization layer as a plating base for coating. Further, the very conformal character of this coating technique allows the definition of fine lines running over multi-level etched surfaces. In Fig. 10 devices realized with this module are shown. Patterned fine lines running over two-level micromachining from backside to frontside, together with patterned lines on the frontside surface, form a 3-D solenoid inductor [see Fig. 10a)] with the turns running from front to backside of the wafer. Another example is a spiral inductor at the bottom of 375-μm-deep cavity. This inductor is contacted to the frontside by the patterned lines over the through-wafer holes as illustrated in Fig. 10b). A very high inductor Q of 17.5 was achieved for a 4-nH inductance by employing a 4-μm-thick Al layer and a high-resistivity (3000-Ω-cm) silicon substrate. Fig. 11 is a measurement result of this inductor.

VII. Conclusion

Three coating methods, spin coating, spray coating and ED photoresist coating, have been introduced for the realization of 3-D structures. Experiments are carried out to evaluate the applicability of each coating method as well as its advantages and drawbacks for MEMS applications. In summary, we can conclude that spin coating and spray coating can be used for all types of surface material and are preferable for patterning the contact windows or structures at the bottom of deep cavities. The spin coating can be performed in standard equipment but the reproducibility is difficult to control. Spray coating, on the other hand, requires special equipment and photoresist but it brings controllable and better results. The last coating method, ED photoresist coating, is more suitable for metal patterning because the method needs a metal layer as a seed layer for plating. So this technique is usually used as a back-end process. By combining different coating methods into one process, we have successfully fabricated several 3-D structures. Examples of some innovative 3-D structures for RF devices and its electrical characteristics have been demonstrated in [11], [13]. Furthermore, these coating methods can be beneficial to other new applications in MEMS and in microelectronics as well.

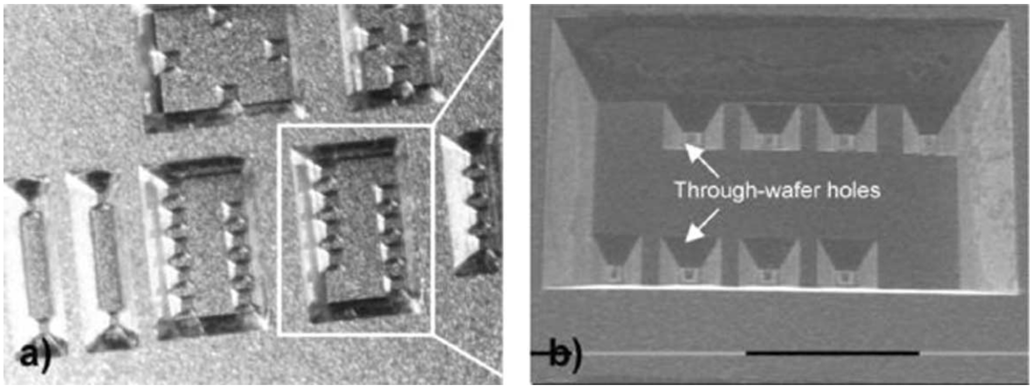

Fig. 9. Two-level-bulk micromachined structures: a) optical image showing different microstructures; b) SEM image (magnification $\times$ 39) of one structure with eight through-wafer holes realized using the a pattern transfer process to 375-$\mu\mathrm{m}$-deep cavities and KOH etching.

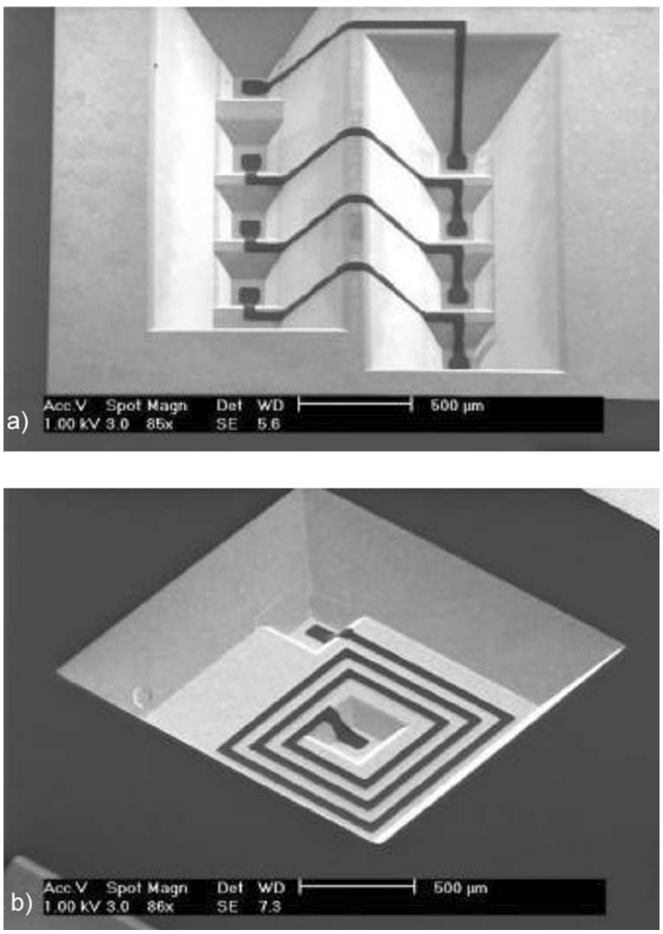

Fig. 10. Device realized using the postprocess module: a) 3-D solenoid inductor with turns running from the front to the backside of the chip; b) a spiral inductor at the bottom of 375-$\mu\mathrm{m}$-deep cavity. The inductor is contacted to the frontside by metal line through 130-$\mu\mathrm{m}$-deep vias.

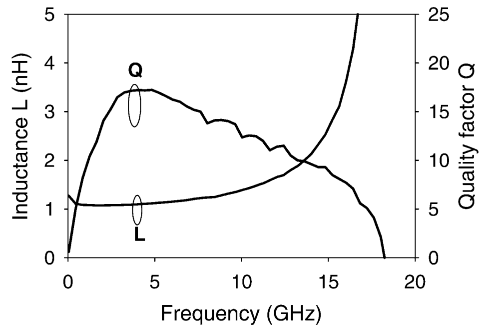

Fig. 11. Measured quality factor (Q) and inductance (L) of a sub-surface inductor with pattern metal vias fabricated by ED coating photoresist as illustrated in Fig. 10b).

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