Process development for 3D laser lithography

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Abstract

The field of micro-electro-mechanical-systems (MEMS) grew out from the integrated circuit (IC) industry. So far the main fabrication techniques used in MEMS are planar technologies, which set limitations to the sensor/actuator design. Therefore greyscale (3D) technology seems to be the method for fabrication of three-dimensional structures in a single lithography and etching step. The idea in fabricating a 3D photoresist structure is the controlled transmission of UV light intensity during the exposure process. The result of this work is to provide a preliminary process solution for the formation of nearly arbitrarily shaped 3D forms in photoresist using Heidelberg Instrument DWL 66FS direct writing lithography tool. For this purpose, the investigation results of the exposure tool possibilities of the photoresist selection for 3D applications and as a real greyscale application, slopes with different angles, which will be used for making a tactile sensor, are provided.

Keywords: MEMS, greyscale, direct laser writing, 3D photolithography, tactile sensor, medical application.

1 Introduction

Greyscale photolithography is a method for realizing three-dimensional structures in the photoresist, which is usually transferred to the substrate by dry anisotropic etching. In planar technologies used in fabrication of MEMS usually only one exposure dose is applied. In greyscale photolithography the exposure light intensity needs to be controlled. Depending on the properties of the photoresist and available exposure dose values, different structure depths (also

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called grey levels) can be achieved. For achieving greyscale structures, several photolithography methods like multiple-step exposure, pixelated mask exposure and direct writing can be used [1].

In this paper we provide the main research results of the process solution for the formation of nearly arbitrarily shaped 3D forms in photoresist using Heidelberg Instrument DWL 66FS direct writing lithography tool. First, the capability and properties of the lithography tool for exposing 2D and 3D structure were investigated. Second, the suitable photoresist was chosen and characterized for finding the best possible parameters for greyscale applications. Third, the real application and the demonstration of greyscale process and different slopes in photoresist were produced for iVIEW project (Preparation Enhancement for Visually Impaired people). The idea of the iVIEW project is to develop a system, which could describe the environment to visually-impaired or blind people in a sense-physiological way. The 3D structures achieved in this work will be used for making one part of a tactile sensor. In the future, an array of these sensors would represent an image through the surface which can be sensed by visually-impaired people by touching it.

2 The problem

The main goal is to fabricate silicon wafers with cone or pyramid shaped chambers, which will be a part of the actuator used in iVIEW project. On the side of the larger opening an actuator is used for pushing the liquid inside the chambers in the direction of the smaller openings. The cone shaped chambers act like amplifiers which cause the polymer push-up effect on the other side of the chamber. Different structure sizes are needed in order to find the most suitable dimensions for the whole application. The characterized cross-section and description of the wafer with chambers is presented in fig. 1.

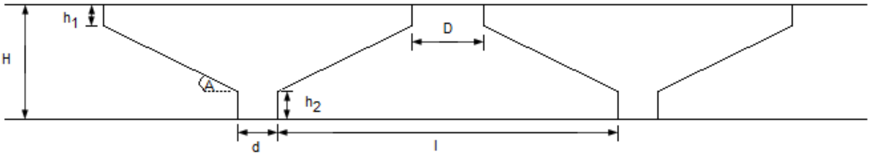


Figure 1: Overview of the cross-section of expected results in silicon (H is the standard silicon wafer of 525 µm; h_1 is the front side step of about 50 µm; h_2 is the back side step of about 100 µm; A is the etched angle of 30°, 45°, 60°, 75°, l is the distance between the bottoms of adjacent chambers: from 1 mm to 2.5 mm; d is the length of the chamber bottom: 100 µm < d < 1000 µm; and D is the area controlled by l and A, but the adjacent openings are not allowed to overlap).

3 Description of the method

In standard lithography the two dimensional structures with straight sidewalls are expected. For this purpose, photoresists with high contrast value must be used. In the case of greyscale lithography, the photoresists with low contrast are preferred to be used because of wider range of exposure doses between unexposed and exposed development rates. It means the lower the contrast of the photoresist the wider the transition range of realizing more grey levels. The next important aspect is the thickness of the photoresist. Firstly, the attainable photoresist thickness and selectivity has to be suitable for etching of 3D structures for standard Si wafer applications. Secondly, it has to be considered that thick positive resists (> 5 μm) give much higher application flexibility than thin (< 2 μm) ones because of the exposure light penetration depth. In the case of resists with the photoactive component DNQ (DiazoNaphthoQuinone), the exposed part becomes UV transparent and therefore the deeper exposure inside of the resist is possible. The dose relations between penetration depth and development rate give improved usability for greyscale applications.

In published literature the large diversity of properties and application possibilities of photoresists used in different greyscale and direct laser applications can be detected (e.g. [2–5]). The determination of the thickness of the photoresist is one of the most critical steps in the process development. The needed photoresist thickness depends on the application and etching method. In this research, DRIE etching as a first approximation has been chosen, because the photoresist structure is transferred and amplified into silicon, without needing any special compensation inside the resist structure. Etching process used in this work will provide 1:80 etching selectivity for AZ 4562 photoresist with silicon wafer. This selectivity means that during the same time one part of photoresist and 80 parts of silicon wafer will be etched.

Photoresist thickness of approximately 7.4 μm was chosen in order to ensure that after etching through the silicon there still will be some resist left to protect the areas which were not supposed to be etched. The overall process flow steps include the prime coating (used for the improvement of adhesion), substrate baking, photoresist coating, exposure, softbake, solvent evaporating, and development. In the research the attention will be put on the used coating parameters, solvent evaporation, and softbake parameters, which are the main influencing parameters for the 3D process.

4 Results and discussion

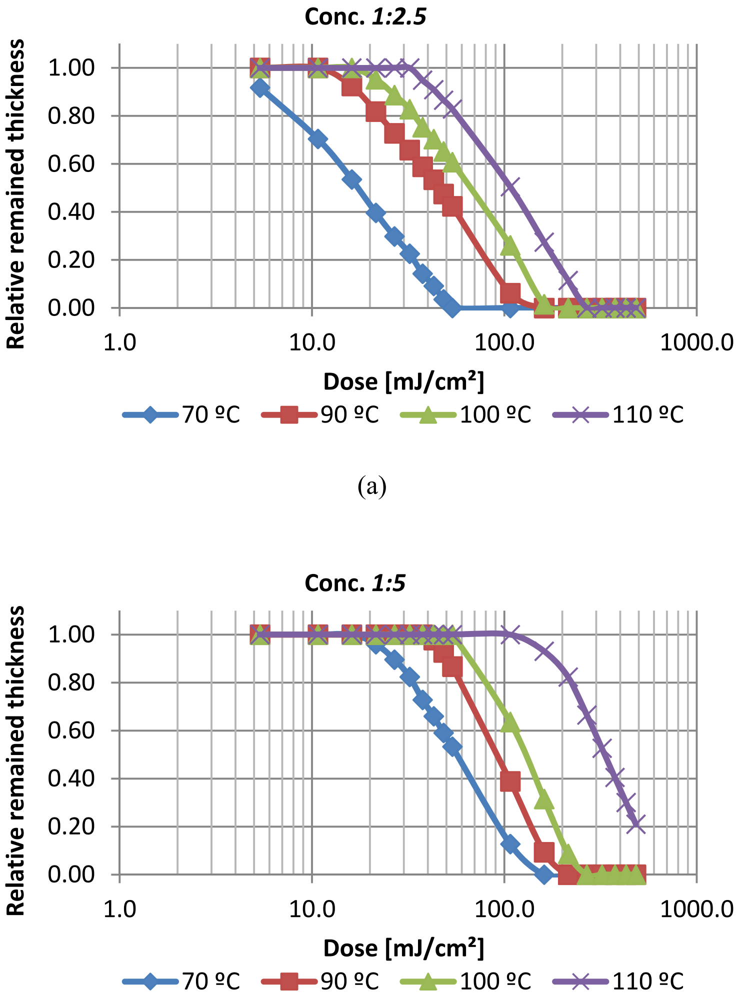
4.1 Photoresist characterization

The influence of softbake temperature and developer concentration on contras curves has been investigated. In standard applications, for achieving high contrast, it is recommended adjusting the exposure dose in a way that in the case of 100°C softbake, the development rate would be about of 2 μm/min using 1:4 developer concentrations [6]. On the contrary, greyscale applications require low contrast. The most effective possibility to lower the contrast is to use rather "cool" (70–90°C) or "hot" (100–120°C) softbake. Another option is to use higher developer concentrations, which increases the development rate and decreases contrast due to dark development at the same time. Four different prebake temperatures were applied: 70°C, 90°C, 100°C, 110°C. All softbake steps were done with the hotplate using 7 minutes 30 seconds baking time. The test was repeated four times using 1:2.5, 1:3, 1:4 and 1:5 developer concentration with according developing times of 1 min 30 sec, 1 min 42 sec, 3 min 45 sec and 5 min 49 sec.

The results of the experiments show the shift of the contrast curves from lower to higher doses by increasing the softbake temperature, irrespective to the developer concentration used. Furthermore, the higher the softbake temperature, the wider transition range occurs. In respect of greyscale the wider transition range is preferred as it allows realizing more grey levels. The behavior of contrast curve graphs is explained by the chemical changes inside of photoresist during the softbake. When applying rather "cold" softbake approach, relatively high concentration of the PGMEA solvent stays inside the photoresist. The alkaline developers react with the remaining solvent and form acetic acid, which increases the resist dissolution rate. As a result of higher dissolution rate, lower exposure doses are needed. In the contrary, during "hot" softbake, most of the solvent evaporates from the resist and most of the photoactive component decomposes. This results in decreased dissolution rate, which means that higher exposure doses are needed. However, due to low developing rate, also the wider range of intensities can be used. In fig. 2, the softbake influence on the contrast curves for the concentrations 1:2.5 and 1:5 is shown. On the contrast curve graphs dark development is neglected, as it is expected to be lower than 40 nm/min [6].

The results from the experiment also show the shift of the contrast curves from lower to higher doses by decreasing the developer concentration irrespective of the softbake temperature. This means that by using lower developer concentration higher exposure doses are needed. However, in the case of 1:4 concentration for every softbake temperature the transition range is sharper, which indicates to higher contrast. In fig. 3 the developer concentration influence on the contrast curves for the softbake temperatures 70°C and 110°C is shown.

In fig. 4 the influence of the softbake temperature on contrast value is illustrated. It can be seen that for all developer concentrations the highest contrast value is achieved with 100°C softbake, which agrees with the theory and confirms with the information given in the datasheets. The contrast value decreases when using either lower or higher softbake temperatures. However, rather "cool" softbake temperatures ensure lower contrast value than "hot" temperatures.



(a)

(b)

Figure 2: Softbake temperature (from 70°C to 110°C) influence on contrast curves: (a) developer concentration 1:2.5; (b) developer concentration 1:5.

The developer concentration influence on contrast values is illustrated in fig. 5. It can be seen from the graphs that irrespective of softbake temperature the contrast value rises by decreasing the developer concentration. The reason is that high developer concentration decreases developer selectivity which results in a lower contrast. This means also shorter times for developing process.

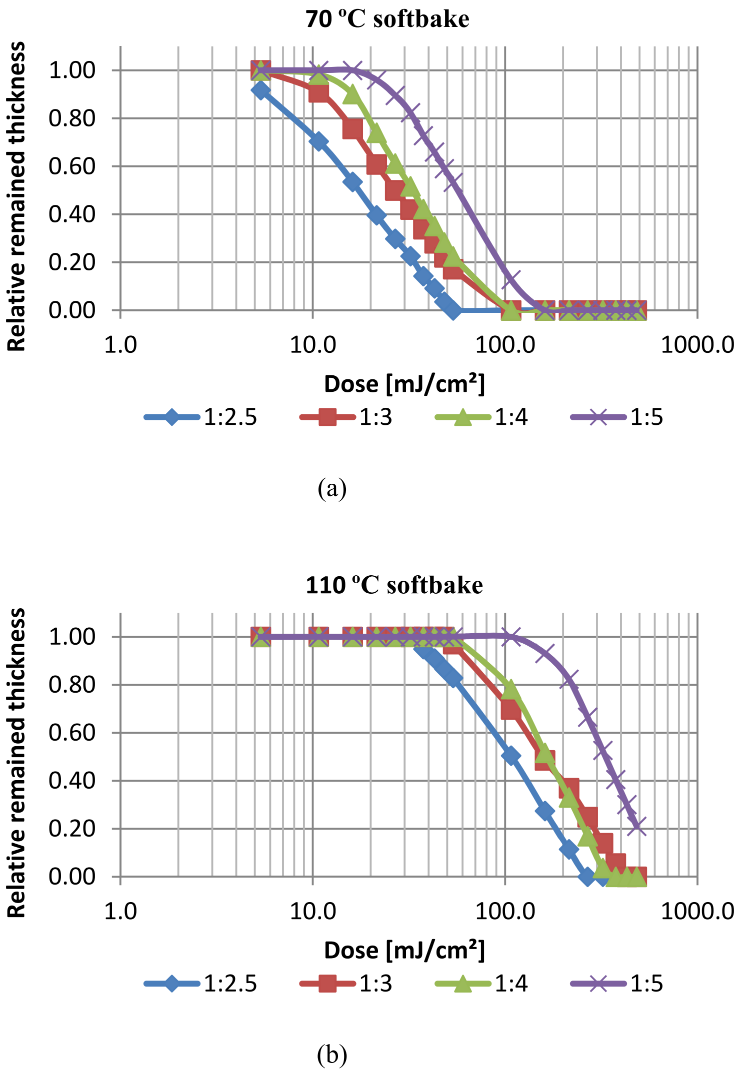


Figure 3: Developer concentration influence on contrast curves: (a) 70°C softbake; (b) 110°C softbake.

During the experiments the softbake temperature and developer concentration influence on T-topping effect was observed at overetched structures, which has been fixed irrespective on developer concentration and softbake temperature. However, minimum effect was observable in standard conditions with AZ 400K developer (fig. 6). The T-topping effect does not have big influence on the greyscale application used in this research because of very low underetching

(~ 290 nm). However, depending on the greyscale application, it could be remarkable obstacle for achieving the desired design. The T-topping is caused by the inhibitors on the surface of the resist which decrease the development rate from the top.

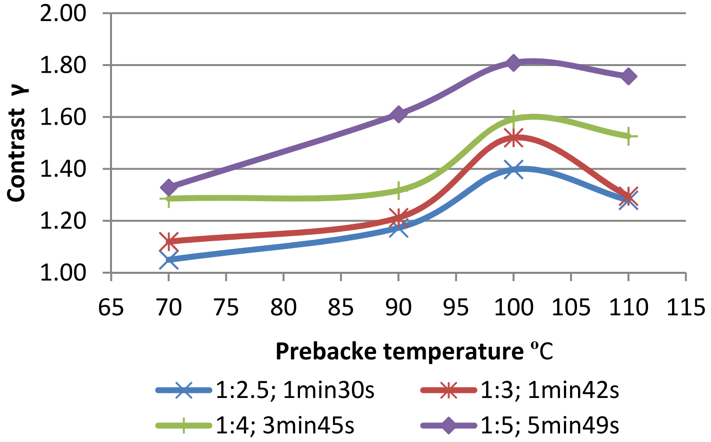


Figure 4: The influence of the softbake temperature (70°C to 110°C) on contrast value for different developer concentrations (1:2.5 to 1:5).

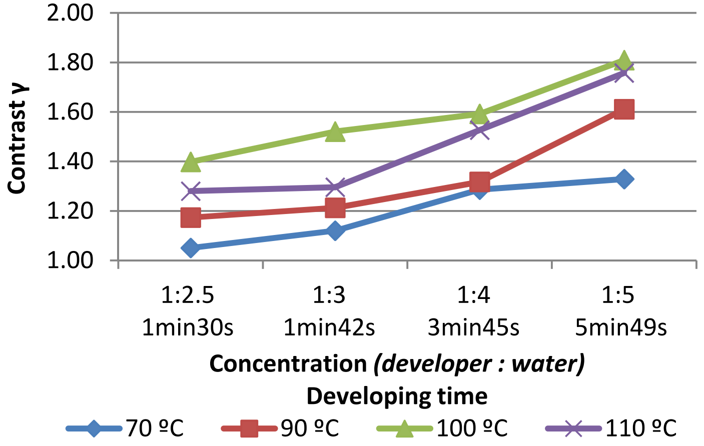


Figure 5: The influence of developer concentration (1:2.5 to 1:5) on contrast value for different softbake temperatures (70°C to 110°C).

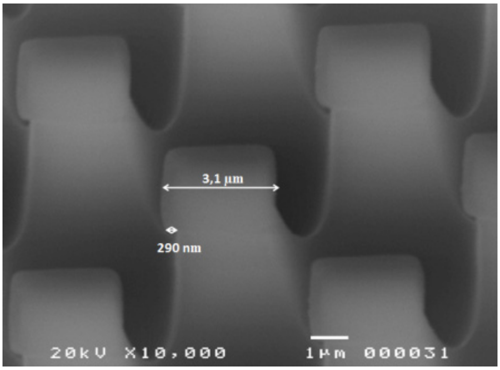


Figure 6: T-topping effect when standard (AZ 400K 1:4 developer, 100°C softbake) process flow parameters applied.

4.2 Greyscale process

DWL 66FS exposure tools uses different configuration for the greyscale mode, which means that the grey levels with fixed exposure doses has to be chosen, e.g. software intensity, filter transparency and exposure amount (n-over mode) are needed to be adjusted in a way that after the development process only structures with the highest exposed grey value are developed. In this work software intensity of 75 % together with 50 % and 10 % filters with n-over mode 4 were found to be suitable.

For finding the relation between grey levels and developed depth an additional exposure test was made. In this case a test design with 66 steps with width of 10 µm was used. The available 127 grey levels were divided between 66 design layers. The continuous grey values for the last layers were chosen for determining the exact grey level needed for clearing the photoresist. The results are shown in fig. 7.

It can be clearly seen that the behavior of the photoresist is not linear and for achieving different linear slopes the linearization is needed. For this purpose the grey value is described as a function of developed depth. The grey values resulting in zero or maximum depth were excluded and the measurement results were fitted to a 4th order polynomial, eqn. 1.

$$\mathrm{GV} = 0.00957 * \mathrm{r}^4 + 0.10031 * \mathrm{r}^3 - 0.20094 * \mathrm{r}^2 + 7.81122 * \mathrm{r} + 8.91228 \qquad (1)$$

where r is the desired structure depth in µm and GV is the acquired grey level.

For applying the eqn. (1) the transfer equations from 3D silicon structures to 3D photoresist structures are required. In this research, DRIE process is used, which means that all the vertical dimensions in the photoresist have to be adapted accordingly to the selectivity (the horizontal structure dimensions will stay the same). The cross-section view of the photoresist and a standard wafer for achieving iVIEW project requirements is shown in fig. 8.

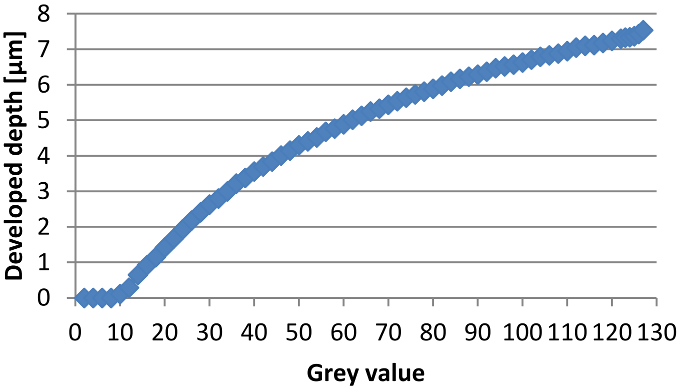


Figure 7: Grey value versus developed depth.

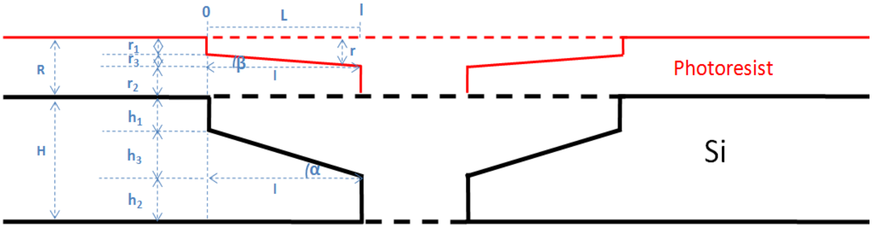


Figure 8: The cross-section view of the photoresist and a standard wafer for iVIEW project requirements.

Fig. 8 shows the two important process parameters (r and l) to be defined. The eqn. (2) describes the slope in photoresist from the surface, which ensures that irrespective of the thickness of the photoresist. Only the height of the last step r_2 will depend on the real thickness of the photoresist.

$$r = -\frac{\tan\alpha}{S_{DRIE}} * L - \frac{h_1}{S_{DRIE}} \tag{2}$$

where r is the needed structure depth in photoresist from the surface of the photoresist, α is the required slope angle in silicon, h_1 is the required depth of front side in silicon, S_{DRIE} is the selectivity provided by DRIE etching and L is the horizontal position of the slope (from 0 to l) where the depth of the slope in photoresist is needed.

The eqn. (3) describes the horizontal length of the slope for an arbitrary slope angle in silicon.

$$l = \frac{H-h_1-h_2}{\tan\alpha} \tag{3}$$

where l is the horizontal length of the slope, α is the required slope angle in silicon, H is the thickness of the wafer, h_1 is the required depth of front side in silicon and h_2 is required depth of back side in silicon.

The horizontal length of the slope describes the length of the slope design. Before making the CAD design, it has to be decided how many grey layers (or steps) will be used for describing the slope. It has to be considered that too few grey layers will result in a non-smooth slope. However, when using too many grey layers then after calculating the grey values for each layer, several sequential layers will have the same grey value. In this research, it was decided to calculate the grey value always for the middle horizontal position of the grey layer. The position value has to be inserted into eqn. (2), which determines the needed depth from the surface in photoresist. After that, the needed depth value could be inserted into the calibration curve formula, eqn. (1), which gives the respective grey value.

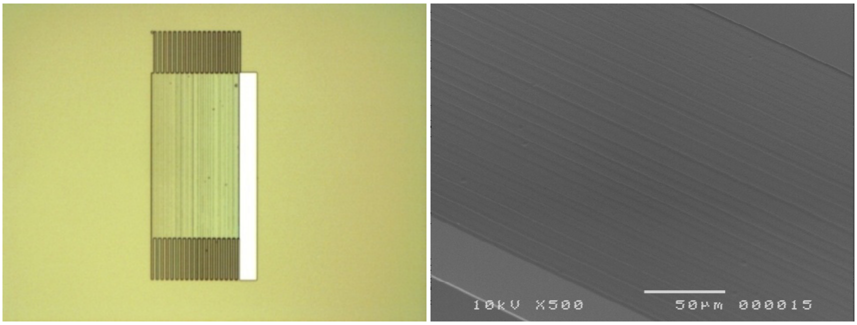
4.3 Greyscale process results

Finally we shortly stop on greyscale process results for achieving 30°, 45°, 60° and 75° slopes in silicon. According to the idea of iVIEW project and its requirements, the front (h_1) and back (h_2) step heights may vary, the primary goal was to achieve the acquired slope angles. In addition, the back side step height (h_2) will vary always because of the needed depth of the structure is calculated from the surface of the photoresist and the thickness of the photoresist will always slightly vary. Also, it has to be considered that greyscale process is very sensitive to development, which means that slightly longer/shorter development will result in a shift of the slope in horizontal direction, which leads to the change of the dimensions of the front and back side steps. The achieved slopes in silicon and their parameters are listed in table 1.

Table 1: Slope parameters for 30°, 45°, 60° and 70° slopes in silicon.

Required slope in Si	**30°**	**45°**	**60°**		**75°**	
Width of grey layer	10	10	10	6	10	3
Number of grey layers	65	37	22	36	10	33
Calculated resist slope	0° 24' 49"	0° 42' 58"	1° 14' 25"	1° 14' 25"	2° 40' 15"	2° 40' 15"
Real resist slope	0° 26' 03"	0° 47' 21"	1° 12' 16"	1° 23' 15"	2° 45' 31"	2° 55' 15"
Calculated slope in Si	31° 14' 08"	47° 46' 48"	59° 19' 56"	62° 42' 06"	75° 27' 26"	76° 14' 03"

As an example the slope in photoresist for achieving 60° slope in silicon is presented in figs 9 and 10.



(a) (b)

Figure 9: Developed design (left) and SEM picture of the slope transition quality (right) of the photoresist slope for achieving 60° slope in silicon in the case of 6 µm grey layer width.

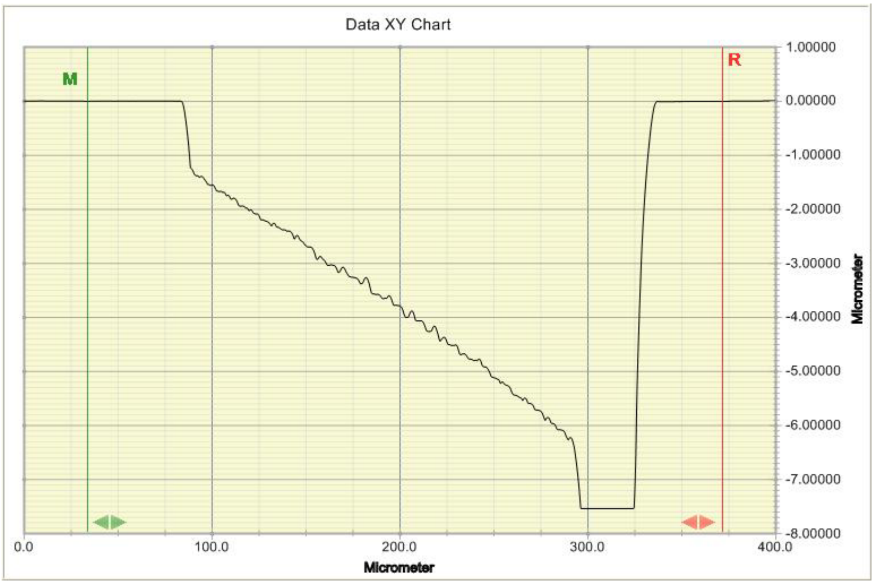


Figure 10: Profilometer measurement result of the photoresist slope for achieving 60° slope in silicon in the case of 6 µm grey layer width.

5 Conclusions

The goal of this paper was to present the investigation results of the exposure possibilities of the direct laser tool and of selection a suitable photoresist for 3D (greyscale) applications and to provide the preliminary process solution for fabricating greyscale structures in the photoresist. In addition, as a real greyscale application, slopes with different angles for iVIEW project were analyzed.

The photoresist AZ 4562 and developer AZ 351B from Microchemicals GmbH was chosen to be most suitable, because of its properties like thickness and contrast, which were easily adjustable to process parameters. For this purpose, the resist was characterized using softbake temperatures from 70°C to 110°C and developer concentration from 1:2.5 to 1:5. The 110°C softbake and 1:4 developer concentration was found to be the best for the greyscale application required in this work. The need for a rocking table for providing constant developing conditions was met, because of the high greyscale process sensitivity to developing process.

As a real application, the slopes in photoresist for achieving 30°, 45°, 60° and 75° slopes in silicon were produced. The slope structures achieved in this work will be used in the iVIEW project for making one part of the tactile sensor for visually impaired people. As a future work, the provided greyscale solution suitability for more sophisticated structures (e.g. lenses) should be investigated. The methods for decreasing the surface roughness should be under observation.

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