1X Lithography for a Micromachined Accelerometer

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1.0 ABSTRACT

The objective of this project is to explore opportunities for a lower cost lithography solution for an integrated MEMS (microelectromechanical systems) process without degrading the lithographic parameters of the current process, and at the same time, qualify the new approach for full production. In particular, the key lithography step used to fabricate an accelerometer sensor will be discussed. Characterization of resist wall angles and depth of focus, together with control of etched profile, critical dimensions and monitored process stability, will be analyzed.

The results of this study showed that 1X stepper lithography provides a solution to the requirements of surface micromachining and integrated accelerometer manufacturing. This study also demonstrates that the 1X stepper process improved on photoresist and etch image stability and process latitude at the most critical process step compared to the previous method.

Key words: surface micromachining, 1X stepper lithography, integrated airbag accelerometer, polysilicon micromachining

2.0 BACKGROUND

Over the last four years several papers have been published on the development and manufacture of fully integrated micromachined sensors [1, 2, 3, 4, 5]. The approach discussed in this paper represents a departure from the main body of discrete designs that are typically machined directly from intrinsic silicon and subsequently packaged with separate signal processing electronics [6]. The surface micromachined product used for this evaluation, an airbag accelerometer, is one of a family of fully integrated MEMS devices manufactured by Analog Devices.

In this approach to MEMS technology, the electromechanical sensor elements as shown in Figure 1 are constructed from deposited polysilicon on silicon wafers concurrently with the signal processing electronics. The micromachining process is achieved through a short series of lithography steps which allow the moving element of the sensor to remain locked in place and protected until the Bipolar/CMOS (BiMOS) IC process has been completed.

3.0 INTRODUCTION

This paper examines the effectiveness of 1X stepper lithography in meeting Analog Devices requirements for the 30 lithography levels required to manufacture their integrated MEMS devices. This device manufacturing process combines conventional IC processing with the special fabrication techniques required for the surface micromachined electomechanical elements.

To determine the feasibility of an initial proposal, a 1X stepper was installed in the Analog fab. This fab was in the process of establishing a lithography area consisting of full field scanners and an i-line 5X reduction stepper, together with both negative and positive resist tracks and an optical metrology tool. The installed performance of the 1X and 5X steppers is compared in Table 1.

Parameter	1X Stepper (test results 1/4/96)	5X Stepper (test results 7/11/96)
Resolution	0.91 - 1.06 µm	0.7 µm
DOF	1.5 µm	0.75 µm
NA	0.31	0.38
Illumination Intensity	1656 mW/cm^2	98 mW/cm^2
Uniformity	2.80%	2.86%

Table 1: 1X and 5X stepper installed performance.

For Analog Devices the key benefits from a successful 1X stepper evaluation would be the simplification of the lithography process (i.e. 1X steppers could replace both the full field scanners and the 5X lithography system), throughput improvements and the resultant cost reduction, particularly with respect to photomask tooling.

A full evaluation required that all 30 levels in the process be exposed successfully on the 1X stepper. When establishing priorities, it was assumed that the 1X stepper should provide fully capable lithography for the process layers currently defined by the full field scanner. This assumption could be confirmed at electrical test on finished devices. The key evaluation should be an assessment of the 1X stepper's performance at the 5X reduction stepper lithography stages. This would validate the 1X stepper's ability to match or improve upon the resolution, critical dimension (CD) control, and alignment capability of the existing lithography tools. Analog's integrated airbag accelerometer was chosen as the test case product because it represents a substantial proportion of production.

It was a precondition that the evaluation must not impact established process flows on the other lithography tools. This requirement evaluation was particularly important because the fab was in its start up phase with an overiding requirement to rapidly qualify the performance of the sensor IC process flow and concurrently ramp production quantities.

To initiate the evaluation, Analog Devices and Ultratech Stepper process and reticle engineering groups worked together to produce a process plan for the accelerometer device which allowed this product to be fully (and quickly) qualified on the 1X stepper. The only changes required to the previously qualified mask data were the addition of alignment structures and the preparation of the design data for reticles compatible with the 1X stepper format. No modifications to the electrically active areas were required. As a result, normal mask design checking methods assured Analog Devices that the defined patterns on the new 1X reticles would yield electrically functional devices if processed correctly. As a result, within four weeks of the start of this program the first product lot was underway and sixteen weeks later, the first silicon reached final test.

The established program allowed no process changes in order to accommodate the proposed 1X lithography toolset. All specifications developed for the accelerometer product using the older toolset remained in effect. Fundamentally, only the process functions directly controlled by the 1X stepper could be optimized to provide the required resolution, critical dimension (CD) control and alignment capability. This optimization included focus, exposure dose, alignment strategies and reticle manufacturing parameters. In particular, the critical BEAMS structure mask biasing was optimized for use with the 1X stepper. All resist processes and etch processes remained unchanged.

Of particular importance was the need to study the effect of changing exposure wavelengths from i-line (365 nm) to the broadband gh-lines (390-450 nm) used by the 1X stepper on a resist characterized only for i-line.

This paper concentrates on the technical capability requirement by reporting the lithography results for the BEAMS level, identified as the most critical process because it is key to the fabrication of the micromachined sensor element. The results obtained using the 1X stepper are compared with the process results from the 5X tool as qualified in the same process, (the 5X process had been developed and used for some time). Characterization includes SEM cross sections of resist profiles and etch profiles and inline optical metrology of CD’s and sidewall angle.

The results of a ten day stability test on this process will be discussed in section six. To rapidly establish process capability, “short loop” wafers were used that closely approximated actual product conditions at this critical micromachining level, the capacitive flexure element. Sample quantities of these wafers were processed each day for ten days, on both the 1X stepper and the 5X reduction lithography tool. Process stability for both tools was measured during this test. The photoresist and etched images of the polysilicon sensor element, produced on the 1X and 5X steppers, were characterized for resist wall angle, depth of focus (DOF) and etch profiles as a function of focus and dose, uniformity and process stability.

4.0 BEAMS EVALUATION

In order to obtain as much information as possible about BEAMS level processing, the first group of reticles took advantage of the multifield format of the 1X stepper reticles to produce three fields, side-by-side on the same reticle, with different BEAMS level geometry CD biases as shown in Table 2. It was decided to concentrate efforts into looking at the process window for the 1.2 µm and 1.05 µm space features. The BEAMS reticle used with the 5X stepper had 1.05 µm space features. Results with the 1X stepper showed a better process window as indicated by the smaller CD variation (Table 2 and Figures 3 and 4) with the 1.2 µm space feature, using lower doses than required for the smaller 1.05 µm space features. Dose vs. CD analysis (Figure 2) indicates that use of the smaller features requires a 150 mJ/cm^2 higher dose and shifts the operating point on the dose curve to the less desirable asymptotic region where increasing dose no longer changes CD linearly.

Reticle Field	Pitch	Mask Line	Mask Space	3 σ CD variation*
1	5 µm	4.10 µm	0.90 µm	not tested
2	5 µm	3.95 µm	1.05 µm	0.378 µm
3	5 µm	3.8 µm	1.20 µm	0.298 µm

Table 2: Geometry CD biases provided on the 1X stepper beams reticle.
*Three standard deviations of five date points per field from -1.5 µm to 1.5 µm focus range with a focus increment of 0.5 µm.

The resist process used for the evaluation on both the 1X and the 5X stepper, was as detailed in Table 3.

Process Step	Sequence
Substrate	6 inch silicon wafer with 2µm deposited polysilicon
Resist prime	HMDS
Resist	2.07 µm positive acting dyed I-line resist
Soft Bake	60 seconds 110°C on contact hot plate
Exposure	1X stepper
Dose	400 - 800 mJ/cm^2
Post expose bake	45 seconds at 125 °C on contact hot plate
Develop	Metal ion free developer for 85 seconds

Table 3: BEAMS processing conditions.

The conclusion from this first phase of BEAMS optimization is that the 1.2 µm space feature exposure field on the 1X reticle performs better and subsequent processing results for BEAMS level on the 1X stepper reflect use of this 1.2 µm space reticle field.

Resist wall angle is the single most crucial concern when determining suitability of the 1X stepper for BEAMS processing. This is the case because etch CD variation is directly related to the cosine of the angle of the resist profile, leading to an ideal case of a 90° resist wall angle. The resist coating and developing sequence was designed for use with the 5X i-line stepper and not the gh-line broadband 1X stepper. It was unknown at the beginning of the program whether the resist wall angle achieved by the 1X stepper would be as steep as that achieved during the 5X process. Focus exposure matrices were run on bare silicon with both 1X and 5X steppers to evaluate resist wall angles. Resist wall angles were analyzed using both optical metrology and SEM cross sections. The wall angles were first derived by comparing optical CD measurements made at the top and the bottom of resist features. Measurements with polysilicon wafers yielded the results in Figure 5, which are summarized in Table 4.

5X Stepper	1X Stepper	Target
73.6° +/–0.6°	75.5° +/–1.1°	>73°

Table 4: Optical metrology measurement with polysilicon wafers.

Wall angle results using the optical metrology tool are very sensitive to the program used for measurement. For comparative results it is necessary to measure all test wafers at the same time.

The SEM cross sections yielded quite different values for wall angle from those found by the optical methods. The results of the SEM profiles are plotted in Figure 6 showing a process window for the 1X stepper. The group of SEM cross sections of resist profiles in Figure 7 were made for process optimization purposes for the 1X stepper on polysilicon. Direct comparison between the 1X and 5X stepper resist images are seen in SEM photographs in Figure 8. Resist wall angle measurement SEM results provide a more accurate picture than the inline optical system measurements. However, as a practical matter, the optical measurement represents a more viable method of inline process control. Although readings from the optical metrology tool varied from test to test and from the SEM results, a consistent pattern emerges which shows that the resist sidewall angles for both steppers are somewhat similar. The SEM results show a steeper resist sidewall angle with the 1X stepper.

5.0 DEPTH OF FOCUS

An important consequence of the NA (numerical aperture) difference between the 1X and 5X steppers is the impact on depth of focus. Table 5 summarizes the specifications of both lithography tools:

Stepper Type	Numerical Aperture	Exposure Wavelength	Field Size
1X Stepper	0.31	390 - 450 nm*	15 x 30 mm
5X Stepper	0.38	365 nm	15 x 15 mm

Table 5: NA, exposure wavelength and field size details.

*Resist testing of the i-line resist at gh exposure wavelengths indicate that the resist sensitivity is much higher at the H line (centered at 404 nm.

The depth of focus and process stability, closely related subjects, were evaluated at BEAMS level. Figures 9 and 10 show the depth of focus in developed resist images and after etching, derived from optical CD measurements

The points in Figures 9 and 10, where large fluctuations in the data begin, result when the resist profile changes sufficiently so that the optical metrology tool focus setting no longer captures a sharp image. At this point, the quality of the data degrades quickly. Note that the upper bound on focus for the 1X stepper after etch is not a change in CD but rather a rounding off of the BEAM ends (the area circled on the SEM in Figure 11). It would appear from the after-etch data that the depth of focus continues much beyond the accepted limits ultimately set for this process. BEAM end rounding degrades the electrical performance of the device, and though not quantitatively specified, it remains the limiting factor for depth of focus for positive focus values.

The observed differences in depth of focus between the 1X and 5X steppers is in close agreement with the result predicted by the Rayleigh criteria:

$$\text{Resolution} = \frac{K\lambda}{NA} \qquad \text{DOF} = \frac{K\lambda}{NA^2}$$

Table 6 compares the predicted and observed depth of focus, expressed as the ratio between the 1X and 5X steppers. The depth of focus advantage resulting from the lower NA of the 1X stepper is apparent.

Depth of Focus Ratio	Predicted	Actual
DOF (1X stepper) : DOF (5X stepper)	1.89 :1	1.7 :1

Table 6: 1X to 5X depth of focus ratio results.
*Resist testing of the i-line resist at gh exposure wavelengths indicates that the resist sensitivity is much higher at the h-line (centered at 404 nm).

Practically speaking, processing steps involved in surface micromachining cause somewhat more topography and wafer distortion than is normally found with standard microelectronics processing. Therefore lithographic DOF at fairly large feature sizes is a greater concern than for standard microelectronics processing. Another difference is that the physical tolerances of the electromechanical elements are not necessarily the same as those for electronic circuitry. In the current case, BEAMS geometries require tighter process control than the electronics circuitry. Again, a case where the 1X stepper’s large DOF greatly improves manufacturability.

6.0 PROCESS STABILITY – THE “10 DAY TEST”

A ten day test was undertaken to assess process stability of both lithography systems. For this test, short loop wafers were constructed with the surface micromachined topography up to the BEAMS level. Three wafers per day were coated on a single track, split through each stepper and rejoined for developing, resist metrology, etching and post etch metrology. Optical metrology was used to measure CD’s at the top of the BEAMS feature before and after etch. Each wafer was measured at five exposure fields and five sites per field. This measurement pattern was repeated on ten wafers for each test group. The results of this test are summarized in Table 7:

	3σ CD Variation After Etch	CD Mean After Etch*	3σ CD Variation Resist	CD Mean Resist*
1X Stepper (0 µm Focus)	0.085	3.864	0.0948	3.303
1X Stepper (-1 µm Focus)	0.197	3.847	0.3069	3.280
5X Stepper	0.3285	3.794	3.363**	3.166

Table 7: CD variation over ten day for 1X and 5X stepper processing.
*Measured at the top of the profiles using optical metrology tool. **High values indicates presence of numerous suspect readings probably due to changes in resist profiles at the top edge of the resist feature. This is not an accurate forecaster of after etch process variation results.

It was observed that at an optimum focus setting, the 1X stepper reduces after etch CD variation by a factor of four over the 5X stepper (refer to Table 7). The measured resist CD variation for the 5X stepper is probably not physically accurate but rather reflects a difficulty in obtaining optical measurements when resist profiles change beyond the tolerances of the 1X metrology tool.

7.0 CONCLUSIONS

The 1X stepper lithography compares favorably to the 5X lithography used previously in all areas evaluated including DOF and resist wall angle. The observed 1X process stability is a consequence of the greater DOF available with the 1X stepper, which in turn is related to the lower NA of the 1X stepper system. The greater resolution of the 5X stepper is achieved at the expense of DOF which is demonstrate to be a more critical factor in determining lithographic performance for the surface micromachined devices. The improved CD control achieved by the 1X stepper both before and after etch stems from its ability to maintain the steepest possible wall angles in the resist over a greater range of surface topography and focus settings.

The other areas evaluated including cost effectiveness, throughput, alignment and electrical test; also proved favorable to the 1X stepper. As a result of this evaluation, Analog Devices is phasing out its current lithography toolset and is replacing it with the newly installed 1X steppers. The first lot through the 1X stepper yielded electrically verifiable chips and subsequent lots had normal yields.

8.0 REFERENCES

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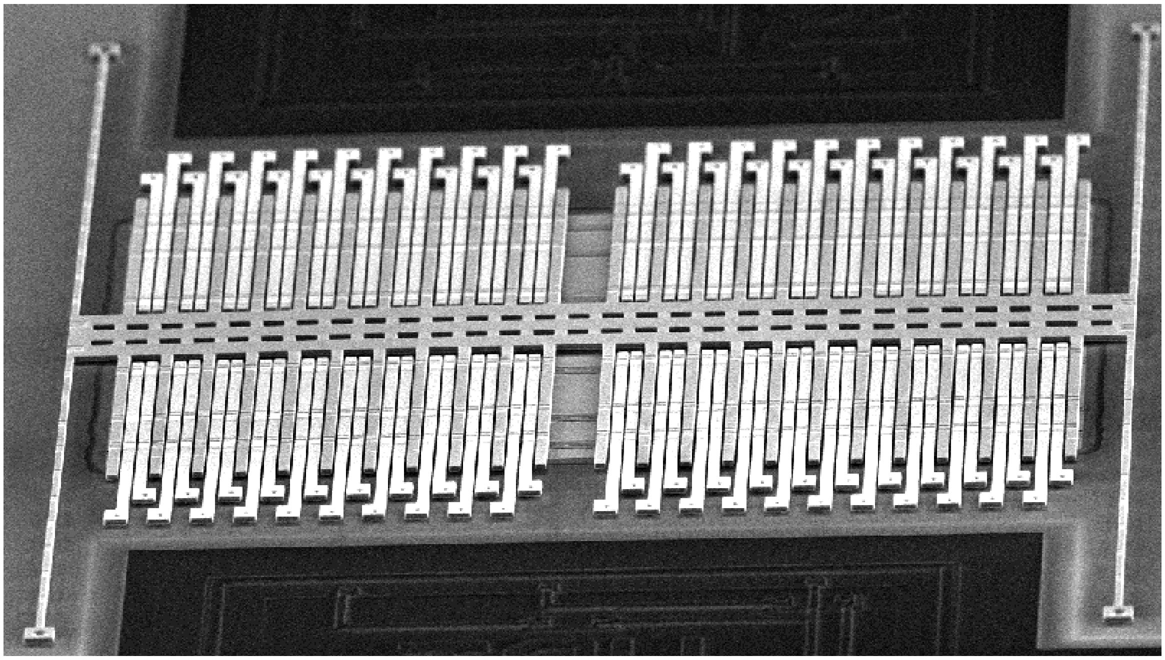

Figure 1: Photograph showing the electromechanical sensor element of an intregrated MEMS device.

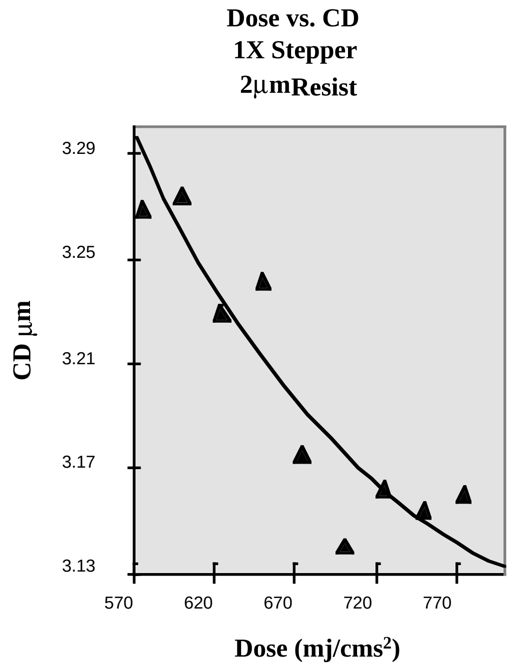

Figure 2: Plot of CD versus dose for the 1X stepper. This graph illustrates that higher exposure doses are necessary for smaller CD values. For this reason, the 1.2 µm biased pattern field, which results in a larger initial feature size and therefore requires less exposure, was selected for detailed process studies.

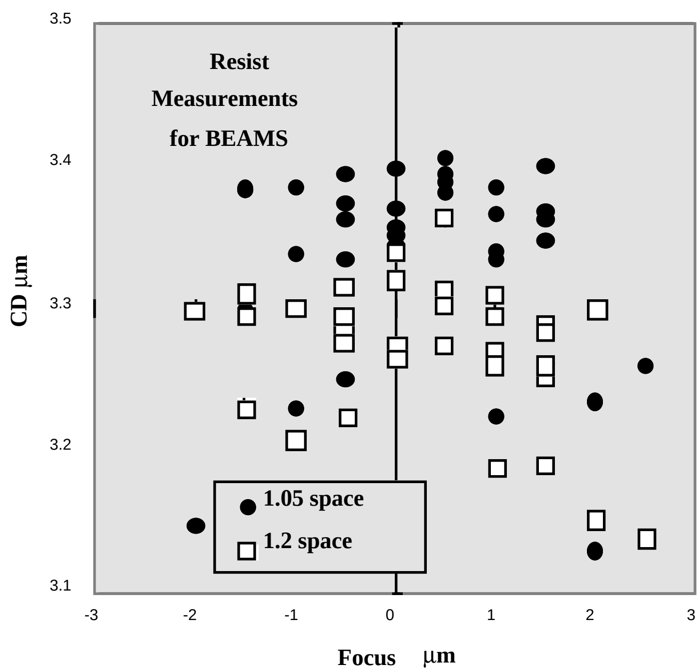

Figure 3: Plot of CD versus focus on the after develop process results for the 1X stepper. The 1.2 µm biased pattern feature has a better controlled distribution with focus.

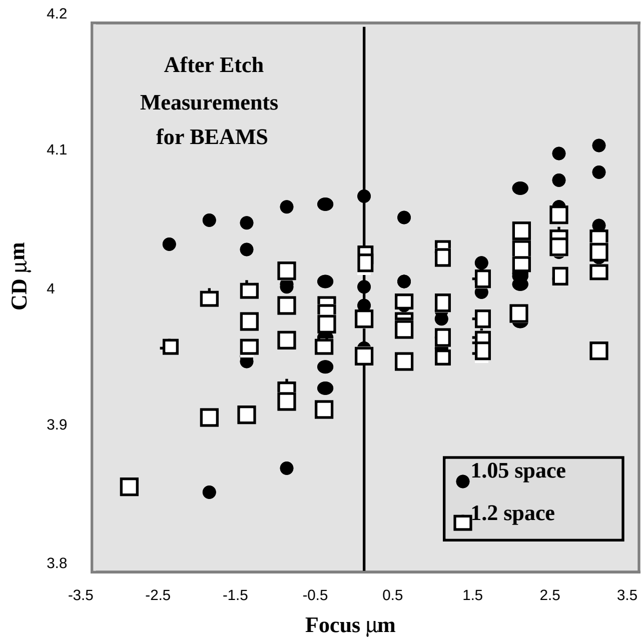

Figure 4: Plot of CD versus focus on the after etch process results for the 1X stepper. The CD results obtained for the 1.2 µm biased pattern field in resist are further improved after etch.

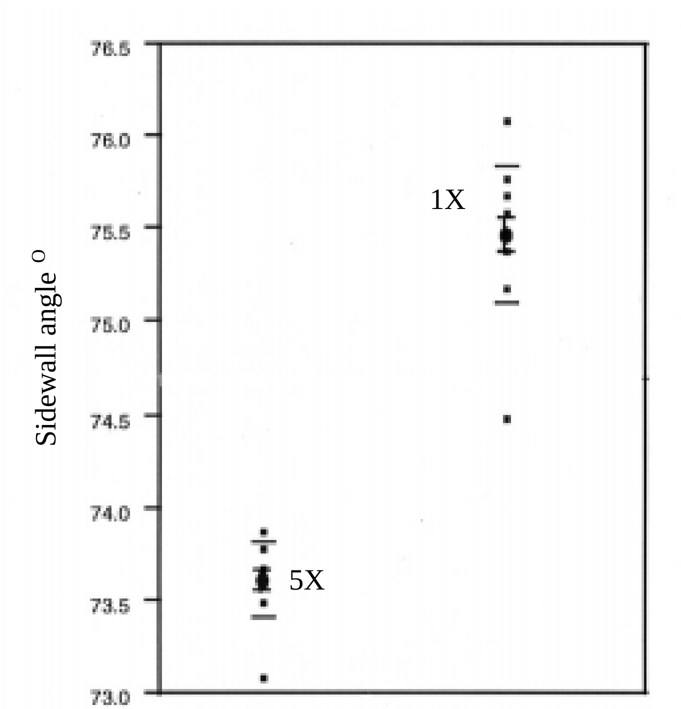

Figure 5: Resist sidewall angles for the 1X and 5X steppers calculated from optical CD measurements. The target value of >73° wall angle established for the Beams process is met by both systems, however the 1X result is significantly improved by the lower operating NA of the 1X stepper.

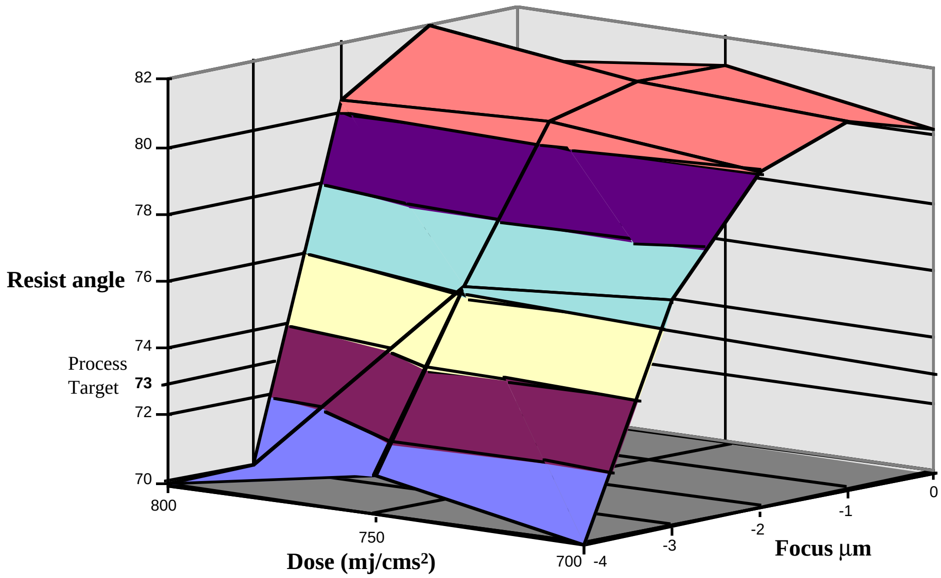

Figure 6: The process window for the 1X stepper plotted from SEM studies of wall angle studies. The process target of 73˚ wall angle is maintained across a range of exposure and focus settings providing a large operating window.

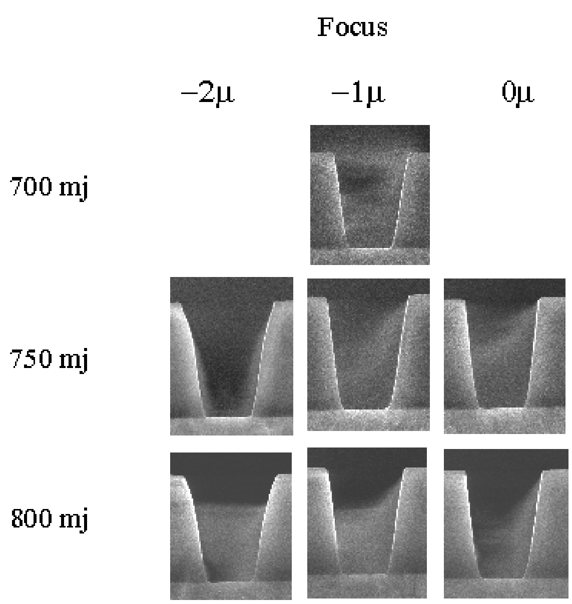

Figure 7: 1X stepper resist images showing the effect of focus and exposure on side wall angle.

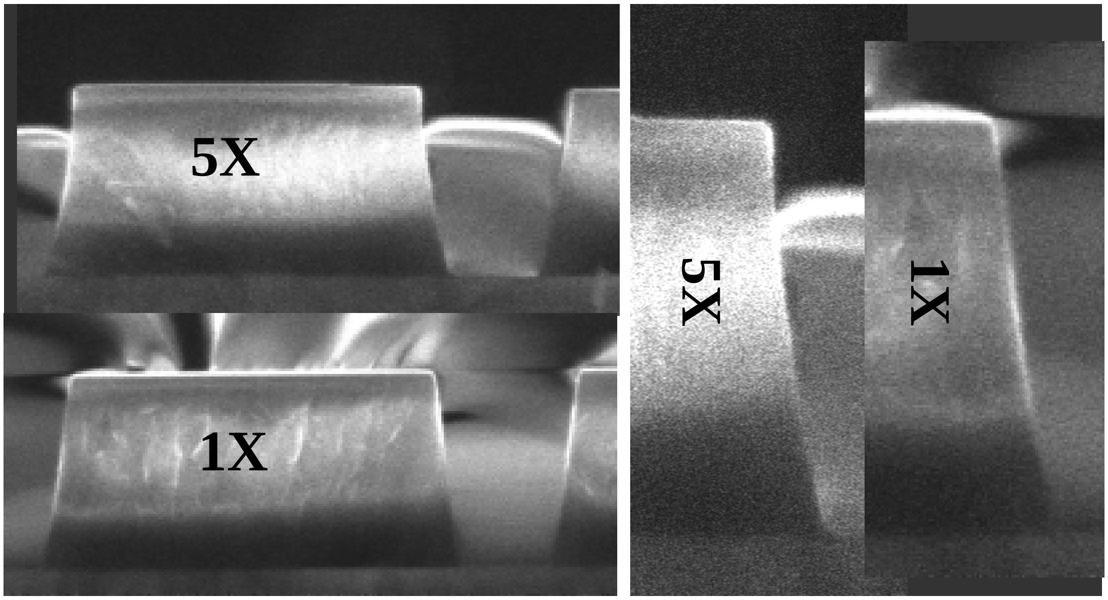

Figure 8: Comparative SEM photographs of 1X and 5X resist images, illustrating wall angle differences. These images typify the wall angle results shown in Figures 5 and 6.

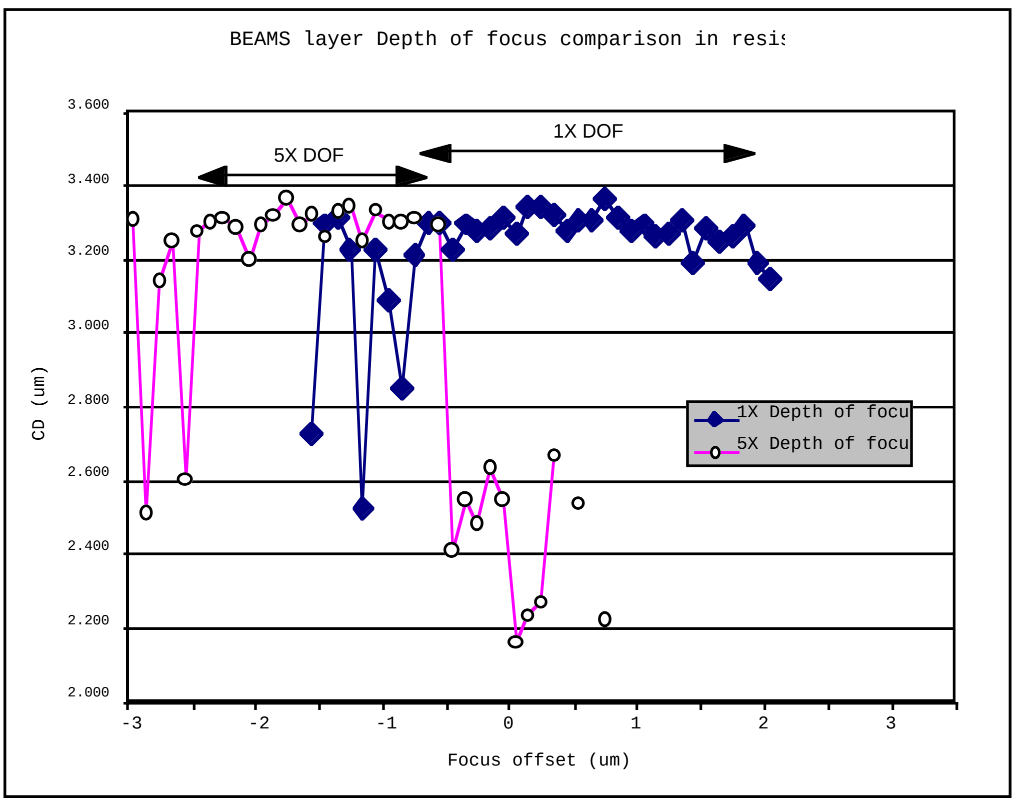

Figure 9: Depth of focus in developed resist images, derived from optical metrology. The location where the repeatability of the CD measurement data degrades indicates the limits of the stepper's depth of focus. The measurements show the depth of focus provided by the 1X stepper to be significantly larger than for the 5X.

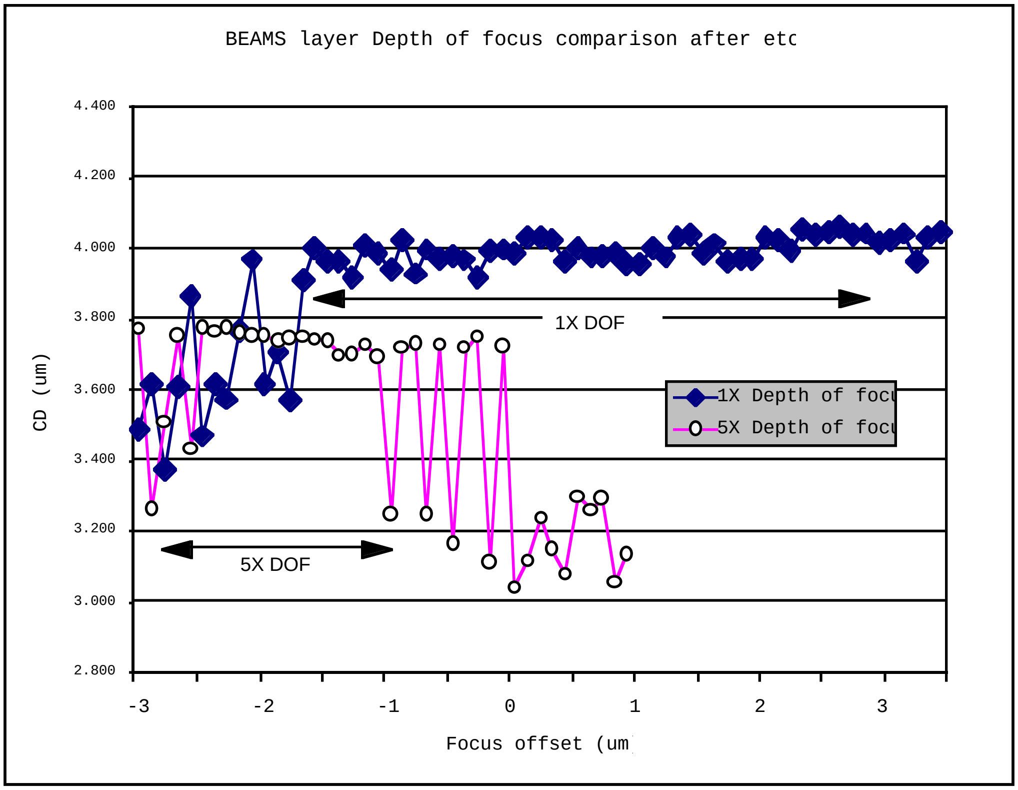

Figure 10: Depth of focus after etch, derived from optical metrology. Again the greater depth of focus available from the 1X stepper lithography is evident.

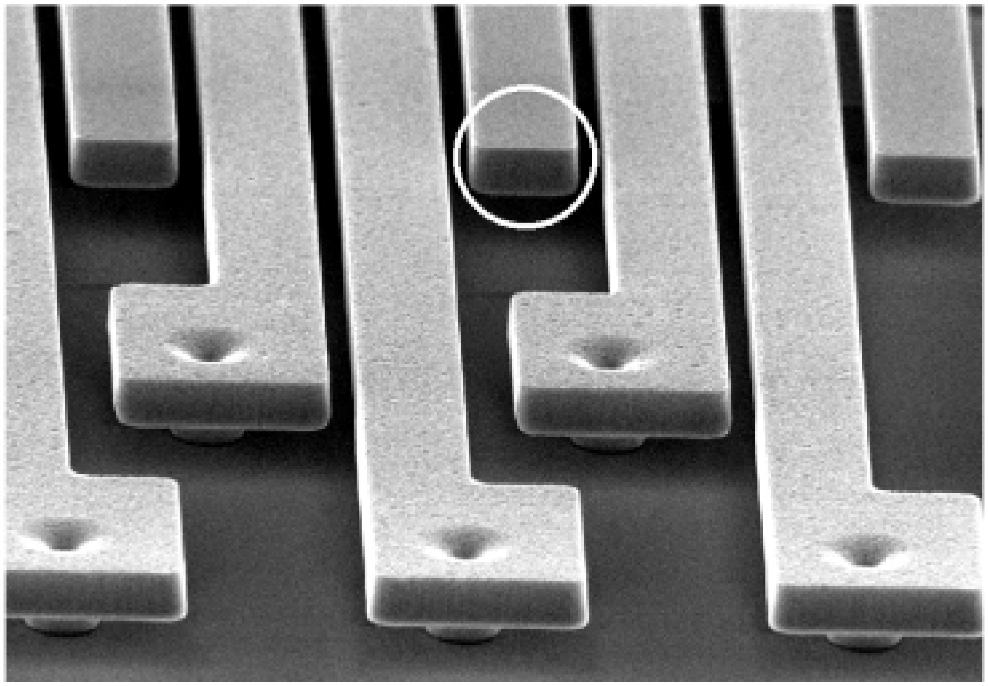

Figure 11: SEM photograph of Beam structures showing the areas sensitive to edge rounding.