Development and Characterization of a RIE Process for Anisotropic Trenches in Silicon

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Abstract—**Reactive Ion Etching (RIE) is an important process widely used in the fabrication of micro-electro-mechanical-systems (MEMS) especially for microfluidic channels. The purpose of this investigation was to develop a process for anisotropic trenches in silicon using the Drytek Quad reactive ion etching system available at the Semiconductor and Microsystems Fabrication Laboratory at Rochester Institute of Technology. The etch profiles were analyzed using Scanning Electron Microscopy (SEM) and the aspect ratio dependent etching (ARDE) effect, and the etch anisotropy were characterized. At the end, this investigation demonstrated highly anisotropic trenches etched in silicon. A baseline process for etching anisotropic trenches in silicon using the Drytek Quad was established.**

Index Terms—**ARDE, etch anisotropy, etch rate, reactive ion etching, undercutting**

I. Introduction

Dry etching of silicon is preferred over wet chemical etching because it provides numerous advantages. These advantages include: the elimination of handling hazardous acids and solvents, the ability to achieve both anisotropic and isotropic etch profiles, the achievement of wanted directional etching without using the crystal orientation of silicon, high resolution, less or no undercutting, repeatable results, and better process control. However dry etching does utilize several toxic or corrosive gases. RIE is a plasma-based process that uses radio frequency (RF) power to drive the chemical reaction. RIE is a process of physical etching combined with a chemical reaction. For this process, the etching is accomplished by ionic bombardment. There are several parameters that can be changed to obtain different etch characteristics. These parameters include RF power, pressure, and gas flow. For the silicon etch, the gases pumped into the system were sulfur haxaflouride (SF_6), argon, and CHF_3. At first samples were etched using the sulfur hexaflouride gas only. Then argon and CHF_3 gases were added to the recipe and their influence on the etch depth, undercutting, and etch anisotropy were studied. Preliminary tests showed that argon was a better choice for anisotropic silicon etch profiles than CHF_3.

An important factor that determines the etch rate and depth uniformity is the aspect ratio dependent etching (ARDE) also known as the "RIE lag." Due to this effect it is expected that the opening in the mask has a significant effect on the final etch depth of the trench. One of the goals of this project was to minimize this undesirable effect.

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II. Process Development

A. Initial Tests

For this project several 4-inch wafers were used. The wafers were coated using Shipley 812™ g-line photoresist, and then exposed and developed. The resist was hard baked at standard conditions of 125°C for 60 seconds. The lithographic mask used for this investigation had lines ranging from 0.6μm to 10μm. In some regions of the mask the lines are isolated, while in other regions the lines are dense.

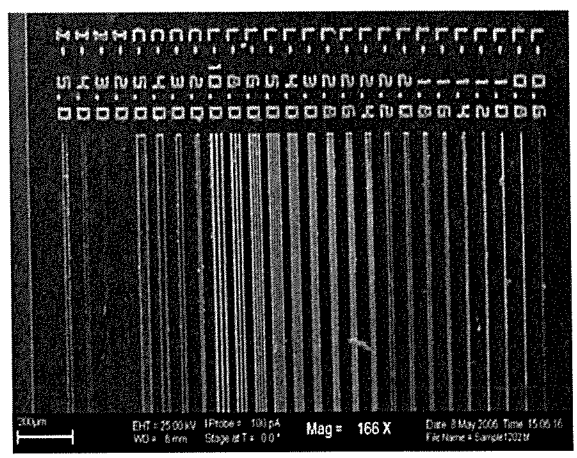

Fig. 1. Top view of an etched sample showing the lines on the mask

At first, it was desired to observe if photoresist alone would be able to act as an etch mask. A time evolution check showed that photoresist alone was not sufficient to mask the etch for longer than 5 minutes. The conditions for this etch were: chamber pressure 80mtorr, SF_6 gas flow of 50 sccm, power of 200 watts, resulting in a DC Bias of 63Volts. All etches in this investigation were done in chamber 1 of the Drytek Quad.

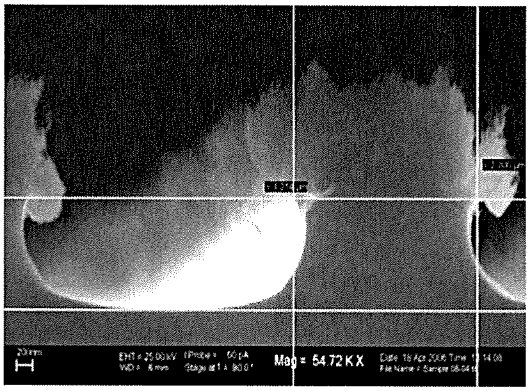

Fig. 2. Time evolution etch using photoresist as an etch mask after 2 minutes of etching

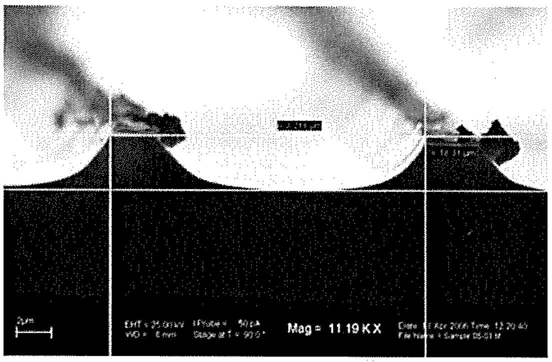

Fig. 3. Time evolution etch using photoresist as an etch mask after 5 minutes of etching

B. New Etch Mask

The most commonly used masking material for silicon trench etching is silicon dioxide (SiO_2). Silicon dioxide is preferred over other masking materials such as silicon nitride or photoresist, because of its high selectivity. Thermal oxide is preferred over PECVD oxide or TEOS because of its higher density. About 1.6μm of thermal oxide was grown on several wafers. Lithography was performed and the resist was hard baked at a high temperature of 270°C for 5 minutes for etching purposes. The thermal oxide was etched using the following recipe: chamber pressure of 80mtorr, a CHF_3 gas flow of 70 sccm, and a power of 220 watts, resulting in a DC Bias of 451 volts. The etch time was 30 minutes long.

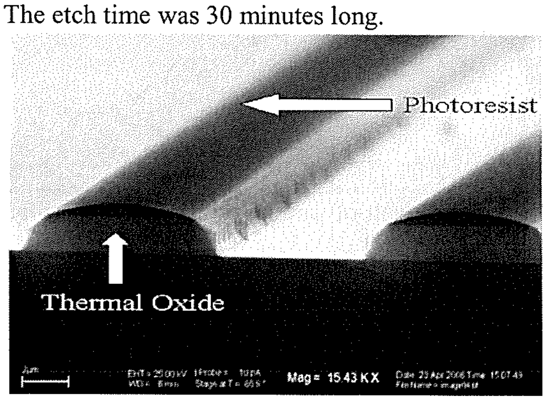

Fig. 4. New etch mask: thermal oxide with hard baked resist

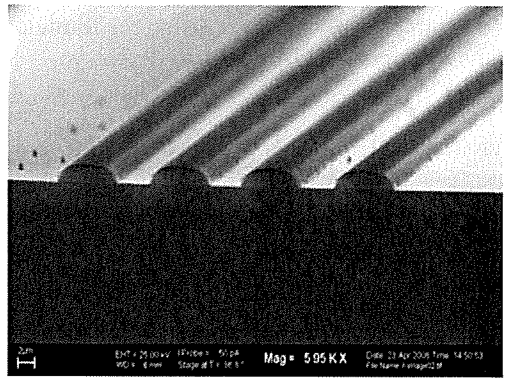

Figure 5. New etch mask: 5μm array lines

C. Preliminary Tests

Several samples were etched using the conditions shown in Table 1. Rather than etching full wafers, the wafers were cleaved and just a piece of silicon was used for each etch. When introduced in the etch chamber, the piece of silicon was sitting on top of a real wafer in order to reduce loading effects. At first the samples were etched using the SF_6 gas only. A low pressure is required for an anisotropic etch. Considering the gas flow rates used, the lowest pressure accepted by the Drytek Quad was 30mtorr. The first three samples were used to observe an etch time evolution for 5, 10, and 15 minutes. For this the etch conditions were: chamber pressure of 30mtorr, a SF_6 gas flow of 60 sccm, and a power of 240 watts. Sample #4 was etched using a lower power of 160 watts. In order to make the etch anisotropic other gases must be added to the recipe. For this investigation, the gases used were argon and CHF_3. After analyzing the results using the SEM, it was observed that the sample etched using argon exhibited a higher anisotropy than the sample etched using CHF_3. The next samples were etched using different ratios of SF_6 and argon gas flows and the etch anisotropy was calculated. Sample #9 was etched using a higher power of 320 watts, and it was compared to sample #7, which used a lower power of 240 watts.

Sample #	Power (watts)	Pressure (mtorr)	SF_6 gas flow (sccm)	Other Gases (sccm)	DC Bias (volts)	Etch Time (min)
1	240	30	60	None	270	5
2	240	30	60	None	273	10
3	240	30	60	None	270	15
4	160	30	60	None	220	10
5	240	30	60	CHF3 30	326	10
6	240	30	60	Argon 30	375	10
7	240	30	60	Argon 60	373	10
8	240	30	30	Argon 60	439	10
9	320	30	60	Argon 60	463	10

Table 1. Preliminary tests

D. *Etch Anisotropy*

The etch anisotropy was calculated using the formula below, where a is the undercut, and b is the etch depth.

$$\text{Etch Anisotropy} = 1 - \frac{a}{b} \quad (1)$$

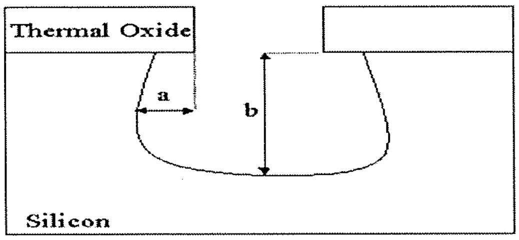

Fig. 6. Etch anisotropy diagram

III. Preliminary Tests Results

The results obtained for the preliminary tests are shown in Table 2. A small opening refers to an opening of 2 to 4μm, while a larger opening refers to an opening of at least 8μm. The samples etched using the SF_6 gas only exhibited a much higher undercut than the samples etched using SF_6 and argon. As the argon flow rate was increased, the etch profile became more and more anisotropic.

Sample #	Smaller Opening Si Etch Rate (μm/min)	Larger Opening Si Etch Rate (μm/min)	Estimated etch anisotropy
1	0.367	0.446	0.782
2	0.281	0.431	0.735
3	0.279	0.420	0.693
4	0.253	0.363	0.684
5	0.251	0.391	0.782
6	0.294	0.419	0.779
7	0.301	0.388	0.812
8	0.222	0.309	0.909
9	0.482	0.622	0.834

Table 2. Preliminary tests results

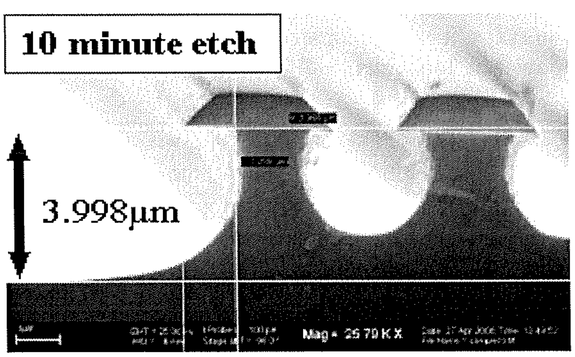

Fig. 7. Micrograph of Sample #2, also showing the ARDE effect

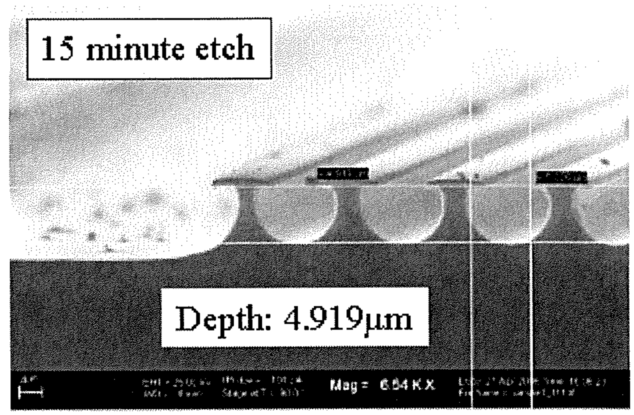

Fig. 8. Micrograph of sample #3

Sample #4 was etched using a lower power, which resulted in a lower etch rate and higher undercutting as expected.

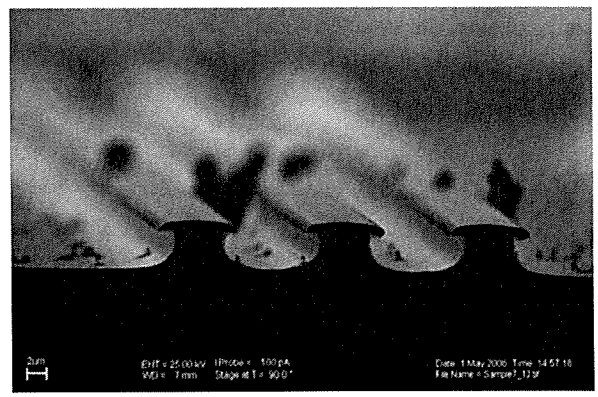

Fig. 9. Micrograph of sample #7

When the argon gas flow rate was doubled compared to the SF_6 gas flow, highly anisotropic etch profiles of array lines were observed. When the higher power of 320 watts was used, a higher etch rate, therefore deeper trenches were obtained. However, this came at a cost of a lower etch anisotropy.

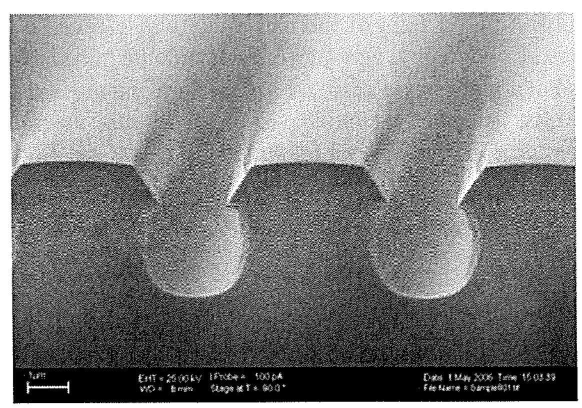

Fig. 10. Micrograph of sample #8: highly anisotropic etch profile

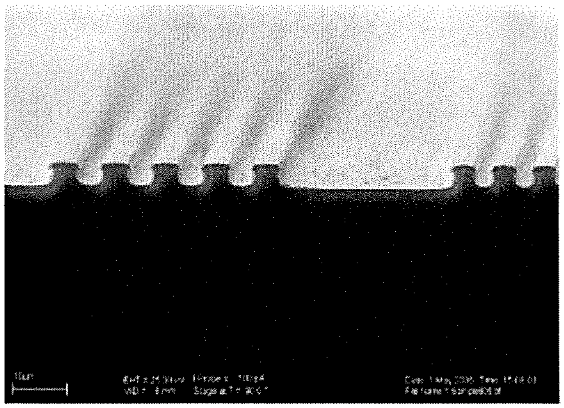

Fig. 11. Micrograph of sample #8: highly anisotropic etch profiles of array lines

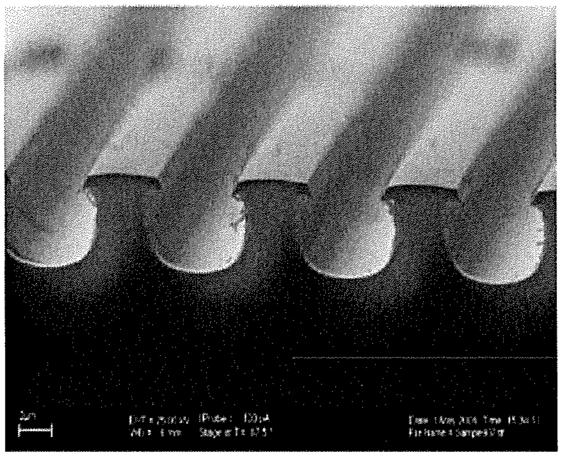

Fig. 12. Micrograph of sample #9, higher power etch

IV. Experimental Design

In order to gain a better understanding of the process a design of experiments was performed. The design was a 2-level, 3-factor, full factorial with two center points. This is illustrated in Table 3, where runs #1 and #10 represent the center points. The three factors were power, pressure, and argon gas flow rate. The SF_6 gas flow rate was kept constant at 40 sccm, and the etch time for each run was 15 minutes.

Run #	RF Power (Watts)	Pressure (mtorr)	Argon gas flow (sccm)
1	300	45	75
2	280	40	60
3	320	40	60
4	280	50	60
5	320	50	60
6	280	40	90
7	320	40	90
8	280	50	90
9	320	50	90
10	300	45	75

Table 3. Experimental design

To reduce run-to-run variations, the runs were not performed in the order shown in Table 3.

V. Results

A. *Summary of Experimental Design Runs*

The results obtained for each run in the experimental design are illustrated in Table 4. The etch rate of silicon was calculated for small, medium, and larger openings. In this case, a small opening refers to an opening of 2 to 3μm, a medium opening refers to an opening of 4 to 7μm and a larger opening refers to and opening of 8μm or greater. The etch anisotropy was calculated for each opening.

Run #	Small Opening Etch Rate (μm/min)	Small Opening Etch Anisotropy	Medium Opening Etch Rate (μm/min)	Medium Opening Etch Anisotropy	Large Opening Etch Rate (μm/min)	Large Opening Etch Anisotropy
1	0.253	0.776	0.337	0.862	0.391	0.954
2	0.315	0.798	0.339	0.833	0.350	0.970
3	0.294	0.815	0.297	0.867	0.358	0.969
4	0.323	0.807	0.361	0.832	0.372	0.958
5	0.259	0.818	0.327	0.796	0.365	0.936
6	0.303	0.844	0.351	0.851	0.371	0.960
7	0.262	0.799	0.344	0.821	0.368	0.973
8	0.308	0.811	0.349	0.847	0.373	0.963
9	0.320	0.825	0.343	0.855	0.415	0.961
10	0.248	0.787	0.323	0.860	0.402	0.959

Table 4. Summary of experimental design runs

B. *SEM Images of Experimental Design Runs*

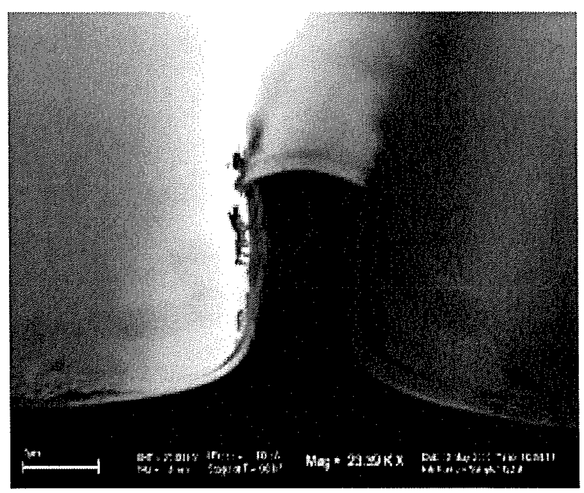

Fig. 13. Micrograph of run #1: highly anisotropic etched 2μm isolated line

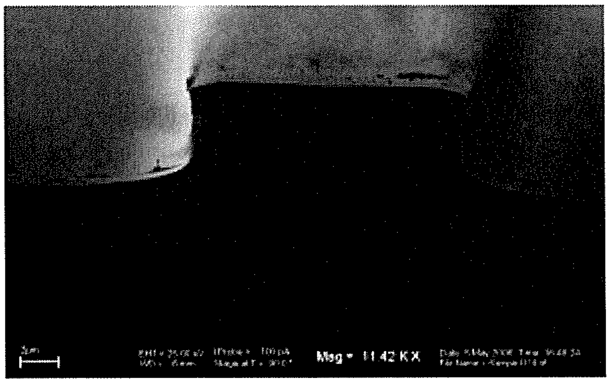

Fig. 14. Micrograph of run #1: highly anisotropic etch for 10 μm line

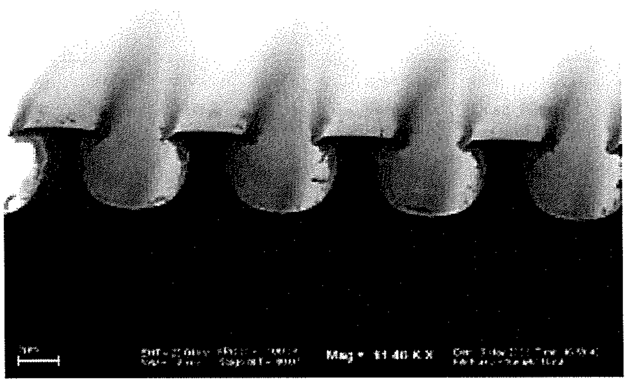

Fig. 15. Micrograph of run #1 anisotropic etch for 3μm array lines

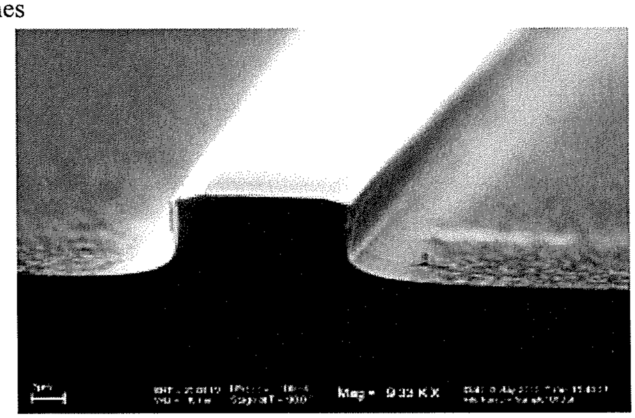

Fig. 16. Micrograph of run #7: completely anisotropic etch for 10μm isolated line

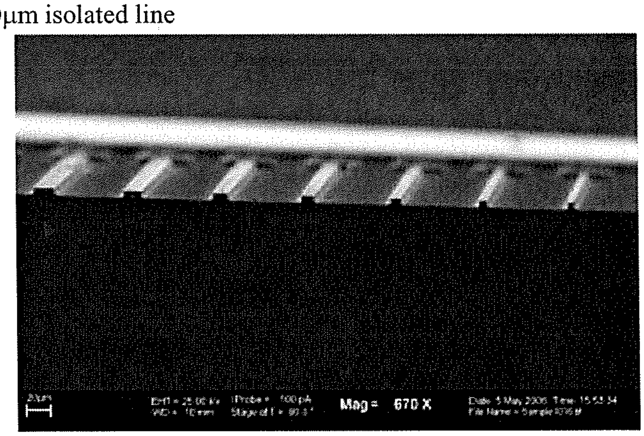

Fig. 17. Micrograph of run #7 showing highly anisotropic etched isolated lines

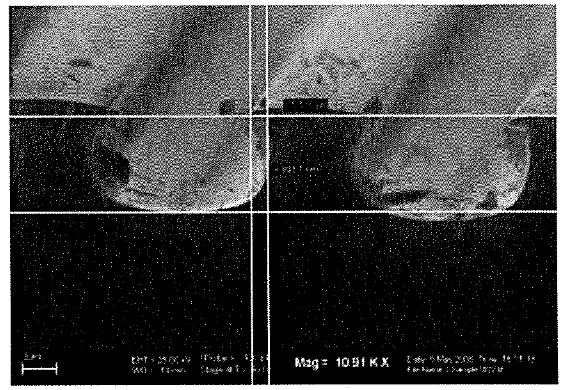

Fig. 18. Micrograph of run #7: highly anisotropic etch for array lines

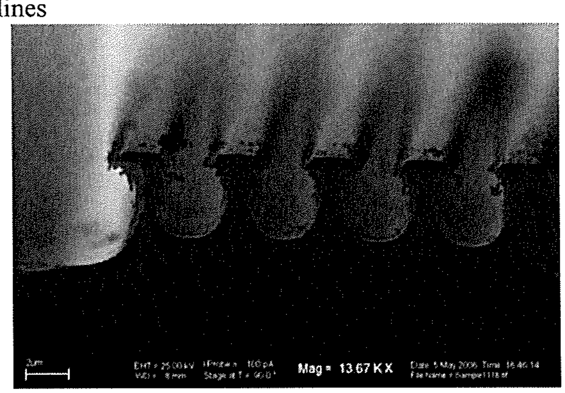

Fig. 19. Micrograph of run #5: 2μm array lines also showing the undesired ARDE effect

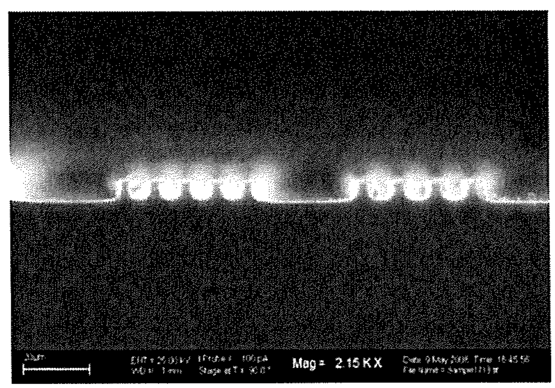

Fig. 20. Micrograph of run #2 showing the minimization of the ARDE effect

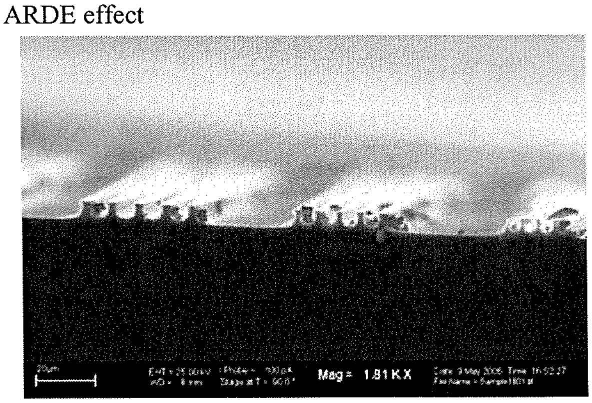

Fig. 21. Micrograph of run #9 showing that a power of 32(watts is to high for etching 1μm array lines

VI. Conclusion

A baseline process for anisotropic trenches in silicon was established. This investigation demonstrated highly anisotropic trenches etched in silicon. However, isolated lines exhibited a more anisotropic etch profile than array lines. This is a well-known phenomenon which occurs due to reactant depletion and can be minimized by decreasing the etch rate of silicon, therefore using a lower power, or by increasing the gas flow rates. The experimental design performed gave a better understanding of the newly developed process. When etching isolated lines a high power (320 watts), low pressure (40mtorr), and high argon gas flow (90sccm) must be used for an anisotropic etch profile. When etching an array of lines use low power (280 watts), low pressure (40mtorr) and high argon gas flow (90 sccm). In order to minimize the ARDE effect use low power (280 watts), low pressure (40mtorr) and low argon gas flow (60 sccm). The selectivity between silicon and silicon dioxide was about 7 to 1. The deepest trench obtained in this investigation had a depth of 6.8μm. For future investigation a better etch mask such as aluminum or nickel can be used for deeper trenches. Techniques such as wafer bonding can be investigated to create micro channels for micro fluidic MEMS applications using the Drytek Quad reactive ion etching system tool.

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