Precision Bulk Micromachining Based on KOH Anisotropic Etching Using Ultrasonic Agitation

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Abstract: Ultrasonic agitation is introduced to reduce the surface roughness and improve the etching uniformity in the process of most commonly used KOH anisotropic etching. Etching characteristics of (100) Si are studied and compared with that without agitation source. Smooth pyramid-free surfaces are obtained with the uniform etching depth within the resolution of 1μm on the same wafer being achieved at the same time. The results reveal that the ultrasonic agitation is a very efficient approach for high precision bulk micromachining.

Key words: MEMS; anisotropic etching; ultrasonic agitation; KOH; surface roughness; uniformity; etching rate
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1 Introduction

Anisotropic silicon etching is one of the most important process steps in the fabrication of MEMS devices[1]. It can be used to form diaphragms on one side of a wafer or to make a variety of trenches, holes and other structures. For most micromachining and active circuit processing, (100) orientation material is used, for which hydroxide etchants produce pyramidal pits with 54.74° (111) sidewall angles relative to the (100) surface. Of all the anisotropic etchants, aqueous KOH solution is most commonly used.

For the best result, the etching process should produce smooth, defect-free silicon surface with high dimensional uniformity on the whole wafer. The quality of vertical roughness produced has been investigated by several groups[2~4]. Such studies suggested the masking of hydrogen bubbles or silicate etching products is the principle origin of surface roughness. In general, KOH etching produces smooth surfaces at low and high molarities, with the maximum roughness occurred at 5~6M (28wt%~34wt%), decreased with stirring and increased temperature[1]. It is shown that the formation of pyramidal hillocks during etching can be suppressed by addition of oxidizers to consume the hydrogen as it is generated, or by etching under anodic bias[4].

There is also an increasing requirement for dimensional control of miniature structures such as diaphragms, beams and suspended masses, which can be achieved by P^{++} doping or electrochemical etch-stop[5]. Unfortunately, these two methods have some restrictions and can not be employed in

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many applications. In this case, time control is taken instead. Our previous efforts to form uniform diaphragms of 15μm thickness by etching from one side of a wafer is failed, a 15μm difference in etching depth exist within the etched wafer. It is estimated that the KOH in unagitated solution tends to stratify, and the temperature distribution in the vessel is not uniform, resulting in etch rate variation of the solution. Williams *et al*. have declared to solve the problem by use of a recirculation pump[6]. Ohwada *et al*. noted that the use of ultrasonic waves can obtain uniform depth in (110) Si anisotropic etching[7], but they did not mention about the (100) case.

In the present work, the anisotropic etching of (100) Si with ultrasonic agitation has been studied for KOH solutions. A special ultrasonic washer with heater and temperate controller has been designed and manufactured for this purpose. Etching characteristics of (100) Si have been explored and compared with that without agitation. The results have shown that the ultrasonic agitation is an effective way to achieve smooth, "mirror-like" surface as well as ideal uniformity of groove depth on the whole wafer.

2 Experimental technology

The etching experiments were carried out with P-type, 30Ω·cm(100) Si wafers with a diameter of 50mm and a thickness of 350μm. Masking layer of thermal oxide (500nm) and LPCVD silicon nitride (200nm) was patterned.

The etching apparatus is shown in Fig. 1. Etching was performed in 50wt% KOH solutions. The washer can generate 40kHz single frequency ultrasonic waves continuously, the output power and the temperature of the bath are adjustable. Silicon wafer were supported vertically in a quartz holder and were etched at 60℃ and 80℃ respectively.

The etched surfaces were inspected with a JSM-6301F scanning electron microscope, and the

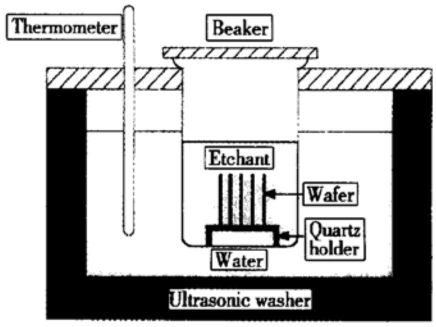

Fig. 1 Experimental setup for anisotropic etching

surface roughness was measured with a Tencor Alphastepper 200 step profiler. The groove depth was measured with a micrometer fixed on an optical microscope.

3 Results

Sample A was etched in typical 33wt% and 50wt% KOH solutions at 80℃ with no agitation. The 50wt% solution results in a drop of etching rate and slightly improvement of surface roughness, compared with that achieved by the 33wt% solution. However, no difference was found between their SEM surface profiles. Samples B and C were etched in 50wt% KOH solution with ultrasonic agitation, at 60℃ and 80℃ respectively.

Figure 2 shows the intersection of surface (111) and (100), while (111) is on the left and (100) is on the right. Figure 3 shows the (100) surface finish. As it can be seen, the (100) surface of sample A is very rough, but those finished with ultrasonic agitation is very smooth. With the increase of etching temperature, pyramid-free surfaces were obtained although a few pits were still presented in some grooves, which have been observed with an optical microscope.

Five step heights on the finished (100) plate distributed around the wafer were measured with a profiler. The average step-height difference was used to determine the surface roughness, as listed in Table 1, which confirmed the conclusion further.

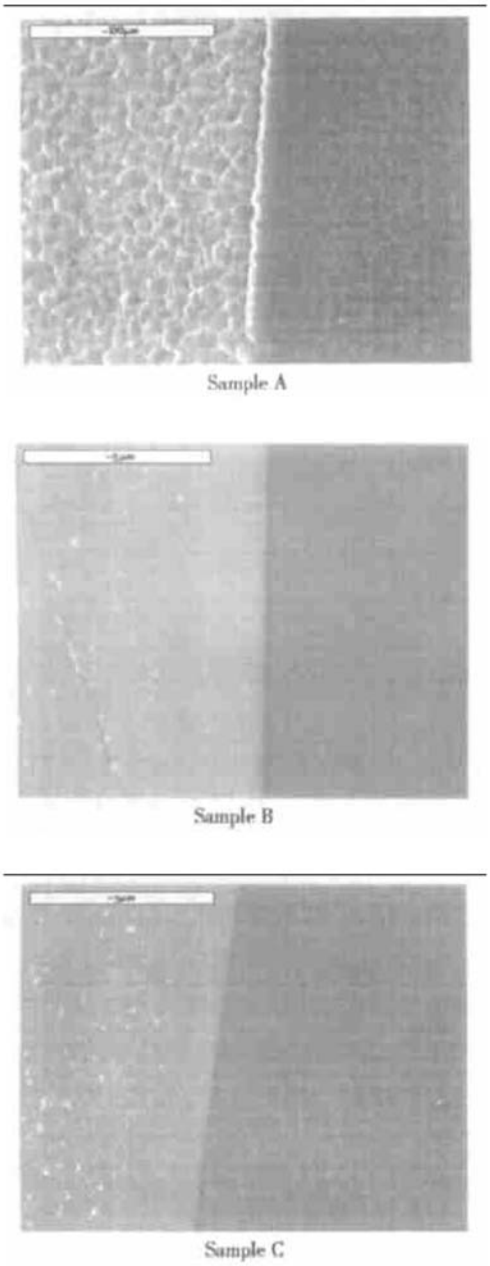

Fig. 2 SEM profiles of the boundary of the (111) plate and (100) plate

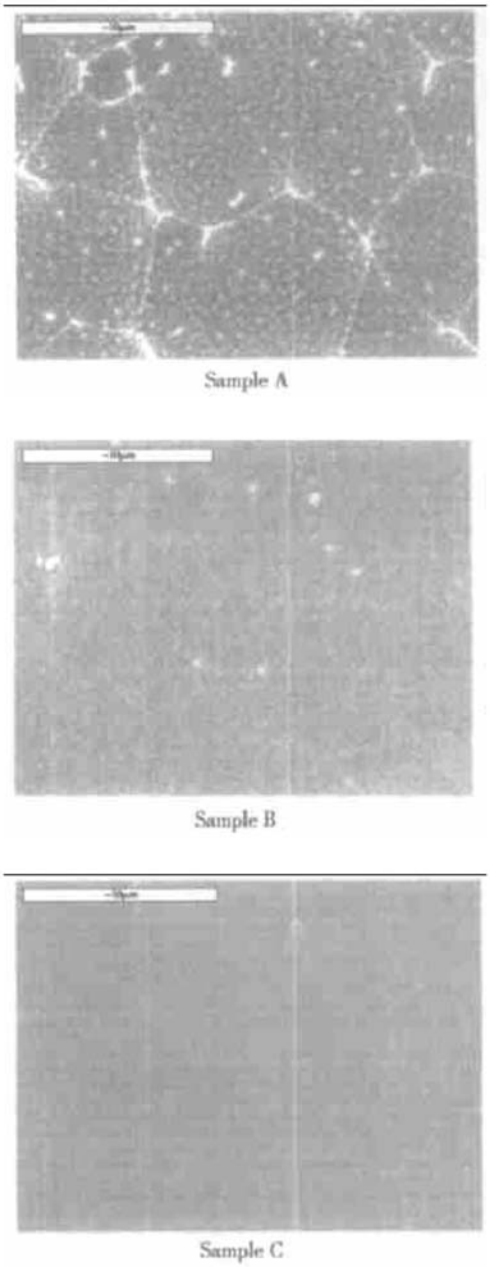

Fig. 3 SEM profiles of the (100) surface finished

Table 1 Surface roughness and etching rate of the sample wafers

	Sample A		Sample B	Sample C
KOH concentration/wt%	33	50	50	50
Surface roughness/nm	1216	1158	166.5	66
Etching rate/($\mu m \cdot min^{-1}$)	1	0.8	0.45	1

It can be observed from Fig. 2 that the surface quality of (111) surface is also improved greatly with ultrasonic agitation.

Sample wafers with the groove depth of 50, 110, 200 and 310μm were chosen to verify the etching uniformity. Ten locations on eaching wafer have been measured after etching. All the samples show a considerable etching uniformity that is within 1μm. Taking the $\pm 0.5\mu m$ accuracy of the optical apparatus into consideration, the deviation should be even smaller.

4 Discussion

During silicon anisotropic etching, bubbles are generated on the silicon surface. When a bubble remains on the etched surface, the etching reaction does not proceed at that point, resulting in a hillock on the etched surface. In order to get perfect silicon surface with high dimensional uniformity, the bubbles must be detached smoothly and the return current of the etching solution must be promoted. By applying ultrasonic waves during etching, the bubble detachment and return current can be evenly promoted owing to the generation of currents in the solution by the cavitation effect of ultrasonic oscillation[7]. In addition, with ultrasonic stirring, the stratification of KOH solution is eliminated and the temperature distribution tends to be more uniform. Consequently, uniform etching can be achieved with improved surface finish.

It is interesting that etching rate of the 50wt% KOH solution with ultrasonic agitation is no less than that of the 33wt% KOH solution without agitation at the same temperature. Kovacs *et al*. have pointed out that if sufficiently high hillock density forms on the surface of the silicon, the (100) etching rate can drop greatly[1]. This may explain the dropping of etching rate in the 33wt% KOH solution without agitation.

It is proposed that the surface quality can be further improved by addition of isopropyl alcohol (IPA) and the oxidizers to the KOH solution[3], which can also be performed in our etching apparatus. This experiment will be carried out before long.

5 Conclusion

The anisotropic etching of (100) Si with ultrasonic agitation has been studied for KOH solutions. Etching characteristics of (100) Si have been explored and compared with that without outside agitation source. Smooth pyramid-free surfaces were obtained as well as the uniform etching depth within the resolution of 1μm on the same wafer being achieved. The ultrasonic agitation has been proved to be a very effective and promising way to achieve smooth, defect-free silicon surface with high dimensional uniformity within the wafer.

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使用超声搅拌实现精密 KOH 各向异性体硅腐蚀

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摘要: 对使用超声搅拌和不加搅拌时(100)单晶硅的腐蚀特性进行了研究和对比. 使用超声搅拌, 可以得到光滑的、无小丘的腐蚀表面, 整个硅片腐蚀深度的误差不超过 1μm. 实验结果表明, 该方法可以有效地实现精密 KOH 各向异性体硅腐蚀.

关键词: MEMS; 各向异性腐蚀; 超声搅拌; KOH; 表面粗糙度; 均匀性; 腐蚀速率

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