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Effect of Width Ratio on the Etching Behavior of Joint Channel Structure*

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Abstract: Effect of width ratio on the etching behaviour of joint channel structure is studied. By theory and experiments, the etching behaviors of joint channel with different width ratios are compared. The results show that the effect of width ratio on the etching behavior is much different for the narrow-wide joint channel and the wide-narrow structure. For the narrow-wide joint channel, the etching process depends not only on the width ratio but also on the width of the channel. The etching rate and concentration of etching front at each stage are very close with the same width ratio. The etching time required at each stage increases with the channel width, but the final total etching time is very close if the length of the wide channel is much longer. For the wide-narrow joint channel, the etching process depends only on the width ratio. For wide-narrow joint channel, the etching process, including the required etching time, is absolutely the same with the same width ratio. The etching rate and concentration of etching front at each stage increases with the rise of the width ratio, while the total etching time decreases with the increase of width ratio.

Key words: joint channel; width ratio; etching rate
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1　Introduction

Sacrificial layer etching is widely used in the fabrication process of micro-electro-mechanical-systems (MEMS)[1]. The combination of HF and silicon dioxide or phosphosilicate glass (PSG) is more popular in sacrificial layer etching. Up to now, the combined first-and-second order release-etching model presented by Monk[2] and Liu *et al*.[3] seems to predict the etching process well. However, in this model, only the channel structure with etching window at one end is considered. Eaton [4~6] extends their work, making the etching model fit for simple structure (such as channel structure and bubble structure) and complex structure (such as joint-channel structure) by applying different boundary conditions. Jin [7] points out that Eaton's model cannot predict the extended etching process accurately, especially when the temperature is not room temperature. He also proposes a modified model by considering the diffusion coefficient of HF as a function of temperature and concentration of the solution. Wu *et al*.[8] apply the Jin's modified model to the joint channel structure. He finds that the mathematic model proposed by Eaton for joint channel structure works well when the etching starts from a wide channel, but it may be wrong when the etching starts from a narrow channel. Then he proposes a new mathematic model for the etching front profile, in which the etching process can be divided into four stages. The model fits the experiments well. This work is an extension work done by Wu[8]. The effects of width ratio on the etching behavior for both narrow-wide and wide-narrow channels are studied.

In this paper, the modified etching model of joint channel proposed by Wu *et al*.[8] will be first reviewed. Then the etching behaviors of joint channel with different width ratios are compared. The results show that for the narrow-wide structure, if the width ratio is the same, the etching rate and concentration of etching front at each stage are also very close. But the etching time required at each stage increases with rise of the channel width. Interestingly, if the length of the fourth stage is much longer, the final total etching time is again very close. For different width ratios, the etching rate and concentration of etching front at each stage decreases with the increase of the width ratio.

For the wide-narrow structure, if the width ratio is the same, the etching process is absolutely the same. The etching rate and concentration of etching front at each stage increases with the width ratio. The total etching time decreases as the width ratio increases.

2　Etching model of the joint channel structure

For a joint channel structure, when the etching

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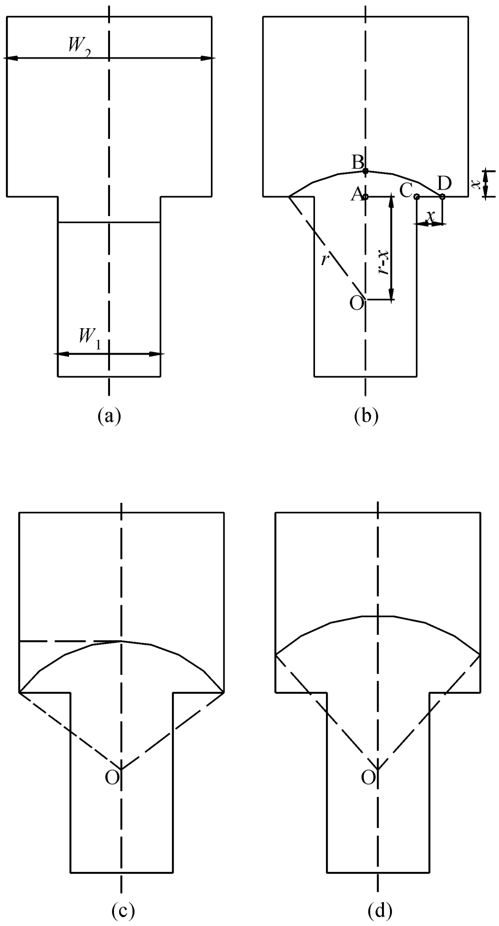

Fig. 1　Schematic of a narrow-wide channel's etching process
(a) Etching front moves in the first narrow channel; (b) Etching front enters the second wide channel; (c) Etching front reaches the corners; (d) Etching front passes the corners

front moves into the second channel, the diffusion flux of the second channel can be calculated by applying a total mass flux boundary condition [4].

$$J_1 S_1 = J_2 S_2 \tag{1}$$

where J_1 and J_2 are the diffusion fluxes of the first and second channels with unit of mol/(cm^2 · s), and S_1 and S_2 are the cross section areas of the first and second channels with unit of μm^2.

Wu *et al*.[8] point out that if the etching starts from a wide channel, when the etching front proceeds into the narrow channel, S_2 is the cross section area of the narrow channel. But if the etching starts from a narrow channel, when the etching proceeds into the wide channel, the area of etching front is no longer a plane.

Figure 1 shows the etching process in the joint channels, which starts from the narrow channel. The etching front keeps a straight line when moving in the narrow channel, as shown in Fig. 1(a). When the etching front reaches the wide channel, the etching front profile becomes a curve. At the very beginning of the second channel, the etching front consists of a quarter circle, a straight line and a quarter circle as viewed from the top. However, as the etching front moves ahead, the straight line becomes shorter and shorter quickly. So the etching front becomes approximately as an arc as shown in Fig. 1(b). As the arc moves ahead, the arc's center also moves ahead till the etching front reaches the corner of the second channel as shown in Fig. 1(c). After that, the arc center seems not to move any more even though the arc front still moves ahead and the radius still increases as shown in Fig. 1(d).

The radius of the arc can be obtained by

$$\begin{cases} r = x + \dfrac{W_1}{2} + \dfrac{W_1^2}{8x}, & x \leqslant \dfrac{W_2 - W_1}{2} \\ r = x + \dfrac{W_1}{2} + \dfrac{W_1^2}{4(W_2 - W_1)}, & x > \dfrac{W_2 - W_1}{2} \end{cases} \tag{2}$$

where x is the etched length of the wide channel, and W_1 and W_2 are the widths of the narrow channel and wide channel, respectively. The depth of the two channels is usually equal and can be marked as 'H'.

From Eq.(2), the length of the arc can be expressed as

$$\begin{cases} l_2 = \dfrac{r\pi}{90}\sin^{-1}\left(\dfrac{x + W_1/2}{r}\right), & x \leqslant \dfrac{W_2 - W_1}{2} \\ l_2 = \dfrac{r\pi}{90}\sin^{-1}\left(\dfrac{W_2}{2r}\right), & x > \dfrac{W_2 - W_1}{2} \end{cases} \tag{3}$$

Then the area of the etching front, namely S_2, can be obtained expressed as

$$\begin{cases} S_2 = \dfrac{r\pi H}{90}\sin^{-1}\left(\dfrac{x + W_1/2}{r}\right), & x \leqslant \dfrac{W_2 - W_1}{2} \\ S_2 = \dfrac{r\pi H}{90}\sin^{-1}\left(\dfrac{W_2}{2r}\right), & x > \dfrac{W_2 - W_1}{2} \end{cases} \tag{4}$$

When $x = (W_2 - W_1)/2$, the area of etching front reaches the maximum. At that time, assuming the width ratio, namely the ratio of W_2 to W_1, is n, the radius of the arc can be written as

$$r = \frac{2n^2 - 2n + 1}{2n - 2} W_1 \tag{5}$$

So the expression of the maximal area is:

$$S_{2\max} = \frac{(2n^2 - 2n + 1) W_1 \pi H}{360(n - 1)} \sin^{-1}\left(\frac{2n^2 - 2n}{2n^2 - 2n + 1}\right) \tag{6}$$

It can be seen clearly from Eq.(6) that the maximal area depends not only on the width of the narrow channel or wide channel but also on the width ratio.

For a wide-narrow joint channel, the etching front keeps a line from the top view when the etching proceeds into the narrow channel. Then the area of etching front can be written as

$$S_2 = W_2 H \tag{7}$$

The area of etching front depends only on the width of the narrow channel as shown in Eq.(7).

3 Experiment

The process to fabricate the samples began with a 100mm silicon wafer. First, a PSG layer with 0.6μm in depth was deposited on silicon by low-pressure chemical vapour deposition (LPCVD). The device used is ASM LB45 LPCVD furnace. The process condition of PSG, is at 420℃, the flow rate of O_2 is 100sccm, SiH_4 is 24sccm, 50% PH_3 in SiH_4 is 8sccm, and the pressure is 27Pa. The deposition rate is 60 ~ 70A/min. The phosphorous concentration of the PSG is about 8%. The PSG layer was patterned to form the etching structures and the rulers to indicate the etching length. A low-stress poly-silicon layer was deposited by LVCVD. The etching windows were opened by plasma on the poly-Si layer.

A digital camera takes photos of the sample through a microscope during the process. There is a ruler beside each micro-channel to indicate the etched length. The time is recorded as the etching process beginning and the time when taking photos is recorded automatically by the camera itself. In this way, the etching length and time can be read out at the photo taken by the camera. For narrow-wide structure, when measuring the etching length, a tangent line is drawn. With the tangent line and the ruler, it is easy to obtain the etching length. For wide-narrow structure, it is much easier to measure the etching length as the profile of the etching front is a line.

The microphotographs of the samples with joint channel are illustrated in Fig. 2. Two types of samples are used in this paper. For the first type, the etching process starts from the narrow channel, as shown in Fig. 2(a). For the second type, the etching process starts from the wide channel, as shown in Fig. 2(b). Four groups of narrow-wide structure and four groups of wide-narrow structure are studied in the work. They are 25~100, 100~400, 10~80, 20~160μm and 100~25, 400~100, 80~10, 160~20μm, respectively.

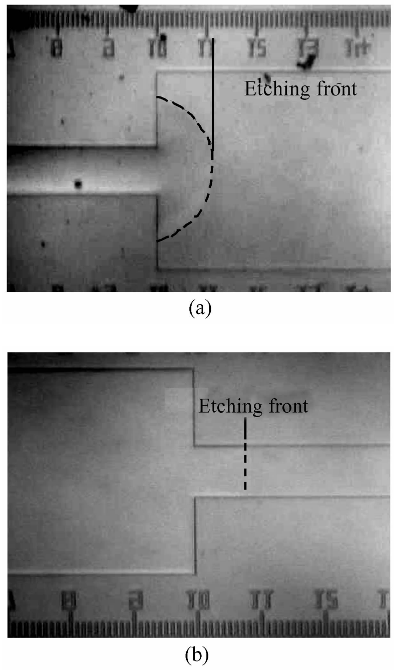

Fig. 2 Samples with different structures (a) Narrow-wide channel; (b) Wide-narrow channel There are rulers to indicate the etching length in the samples. The major unit of the ruler is 100μm. Though the etching front is clear in color photographs, it is blurry in monochrome photograph. To indicate the etching front clearly, the etching front is marked with dashed lines.

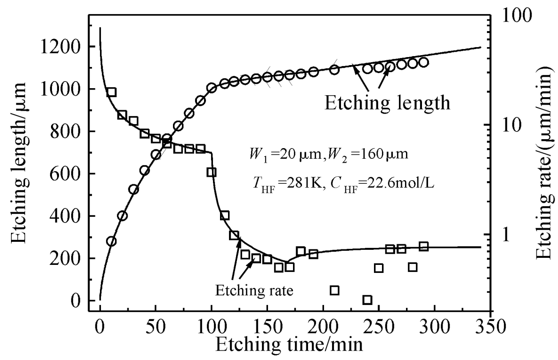

Fig. 3 Etching length and etching rate as functions of etching time Widths of the narrow and wide channels are 20 and 160μm, respectively.

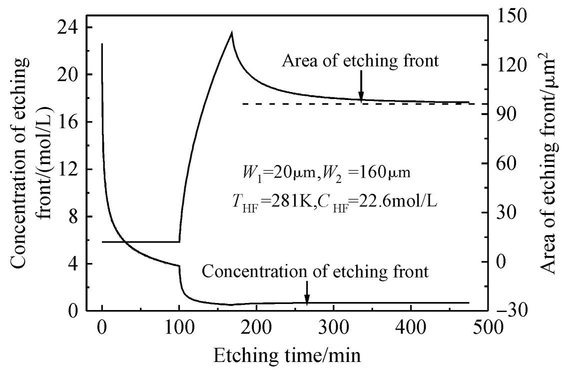

Fig. 4 HF concentration and area at the etching front as functions of etching time Widths of the narrow and wide channels are 20 and 160μm, respectively.

4 Results and discussion

The etching length and rate as functions of etching time for the narrow-wide channel is shown in Fig. 3. HF concentration and area at the etching front as a function of the etching time is shown in Fig. 4. The etching process begins from a narrow channel with width of 20μm to a wide channel with width of 160μm. The lengths of the narrow and wide channels are 1000 and 500μm, respectively. The curves are the results calculated by the model proposed by Wu[8]. The symbols are the experiment results.

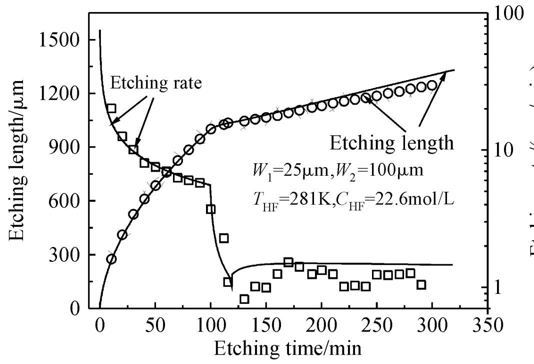

Fig. 5　Etching length and rate as functions of etching time　Widths of the narrow and wide channel are 25 and 100μm, respectively.

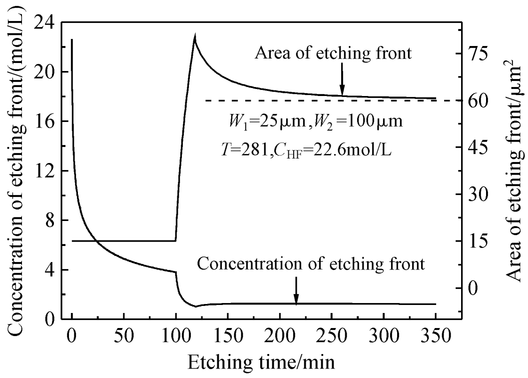

Fig. 6　HF concentration and area of etching front as functions of etching time　Widths of the narrow and wide channels are 25 and 100μm, respectively.

Etching length and etching rate as functions of etching time for the narrow-wide structure with the width ratio of 4 are illustrated in Fig. 5. The other conditions such as experimental temperature and HF concentration are the same as shown Fig. 3 in which the width ratio is 8. HF concentration at the etching front and area of the etching front as functions of etching time are shown in Fig. 6. Comparing Fig. 3 with Fig. 5, Fig. 4 with Fig. 6, one can see that the trends of the curves are similar. But the extrema of the etching rate, concentration of etching front, area of etching front and the etching time to achieve the extrema are different. In order to analyze the effect of width ratio on the etching behavior in detail, four kinds of joint channel structures, namely 25～100, 100～400, 10～80, and 20～160μm, are studied. As described by Wu[8], the etching process can be separated into 4 stages. At the end of the each stage, the variables are calculated, as shown in Table 1.

For the first stage, it takes 100.1min to etch 1000μm for all the four structures. At that point, the etching rate is 4.89μm/min and the concentration of etching front is 3.81mol/L. The etching rate is independent of the channel's width. The same phenomenon is also observed by Liu [3].

From the second stage, for the structure with the same width ratio, the variables are very close. For example, at the end of the second stage, if the width ratio is 4, the etching rate and concentration are 1.01μm/min and 1.02mol/L respectively for 25～100μm joint channel. While for 100～400μm joint channel, the two variables are 1.04μm/min and 1.00mol/L, respectively. The relative errors are less than 3%. If the width ratio is 8, the two variables are 0.58μm/min and 0.51mol/L respectively for 10～80μm joint channel, 0.57μm/min and 0.51mol/L respectively for 20～160μm joint channel. The relative errors are also less than 3%.

For the other two stages, the situations are the same as the second stage. So it is concluded that for narrow-wide structure, if the etching proceeds in the wide channel, the etching rate and concentration of etching front are only dependent of width ratio and independent of the width of the channel.

Table 1　Variables at each stage with two different width ratios

T = 281K, C_{HF} = 22.6mol/L

No.	Width ratio is 4 (25～100μm)					Width ratio is 8 (10～80μm)				
	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²
1	100.1	1000	4.89	3.81	15.0	100.1	1000	4.89	3.81	6.0
2	119.0	1038	1.01	1.02	80.4	133.9	1035	0.58	0.51	69.6
3	189.7	1140	1.49	1.27	63.2	298.7	1160	0.78	0.70	48.5
4	437.8	1500	1.40	1.20	60.1	738.9	1500	0.76	0.68	48.0
No.	Width ratio is 4 (100～400μm)					Width ratio is 8 (20～160μm)				
	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²
1	100.1	1000	4.89	3.81	60.0	100.1	1000	4.89	3.81	12.0
2	176.8	1150	1.04	1.00	321.6	168.0	1070	0.57	0.51	139.2
3	325.8	1350	1.39	1.19	250.7	415.5	1254	0.77	0.69	97.5
4	434.0	1500	1.38	1.18	245.3	737.0	1500	0.76	0.68	96.3

But the maximal area of etching front and the etching time required at that stage are different though the width ratio is the same. For example, for 25～100μm joint channel and 100～400μm, the maximal areas of etching front are 80.4 and 321.6μm^2, respectively. The etching time required at this stage is 18.9 and 76.7min, respectively.

Besides, the ratio of maximal area for the two structures (321.6μm^2/80.4μm^2 = 4) is just equal to the ratio of the two narrow channels (100μm/25μm = 4) or wide channels (400μm/100μm = 4). It can be seen clearly from Eq. (5) that the maximal area is proportional to the width of the narrow channel or wide channel when the width ratio is a constant.

At the end of each stage except the first one, the etching rate and concentration of etching front decreases with the increasing of width ratio. This is because the larger the width ratio, the more obvious diffusion limitation is.

Interestingly, as shown in Table 1, for two kinds of joint channel with the same width ratio, though the etching time is different at the end of the second and third stage, the total etching time at the end of the fourth stage is very close. For example, for 25～100μm joint channel, the etching time at the end of the third stage and the total etching time are 119.0, 189.7 and 437.8min, respectively. While for 100～400μm joint channel, the three etching time are 176.8, 325.8 and 434.0min, respectively. The relative error of total etching time is less than 1%. When the width ratio is 8, the total etching time is 738.9 and 737.0min, respectively. The relative error is also less than 1%. This is because at the fourth stage, the etching front tends to become a straight line and the etching rate is very small due to the diffusion limitation. So the etching time for the second stage and the third stage is much shorter when compared with the fourth stage. For example, for 25～100μm joint channel, the total etching time for the second stage and the third stage is 89.6min, while the etching time for the fourth stage is 248.1μm. So if the length of the fourth stage is much longer, the final total etching time only depends on width ratio. While if the length of the fourth stage is much shorter, the final total etching time depends not only on the width ratio but also on the width of the channel.

Etching length and rate as functions of etching time with wide-narrow channel are shown in Fig. 7 and Fig. 9. In Fig. 7, the widths of the wide channel and narrow one are 160 and 20μm, respectively. In Fig. 6, they are 100 and 25μm, respectively. HF concentration and area of etching front as functions of etching time are shown in Fig. 8 and Fig. 10.

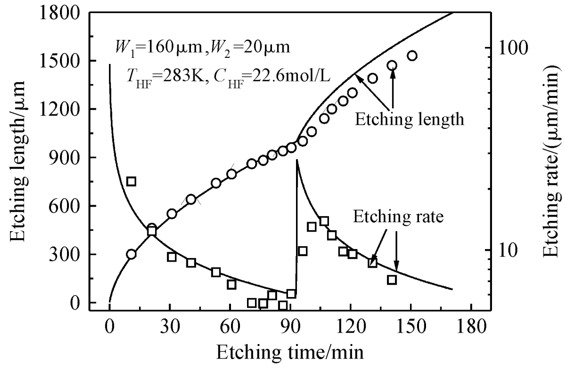

Fig.7 Etching length and rate as functions of etching time Widths of the first and second channel are 160 and 20μm, respectively.

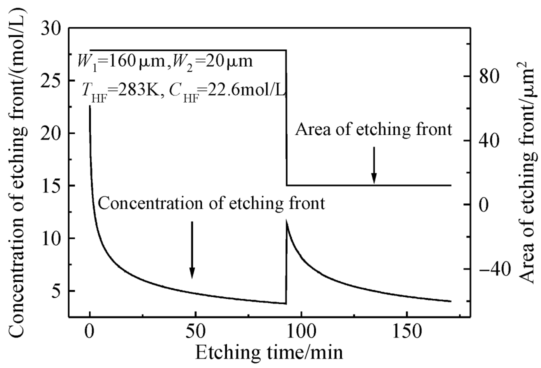

Fig.8 HF concentration and area of etching front as functions of etching time Widths of the first and second channels are 160 and 20μm, respectively.

Similar to narrow-wide joint channel, for wide-narrow joint channel, the trends of curves are the same whatever the width ratio is. But the etching process of wide-narrow channel can only be divided into 3 stages as shown in Fig. 7 to Fig. 10. In the first stage, the etching runs in the wide channel. In the second stage, the etching runs from the wide channel to the narrow channel abruptly. In the third stage, the etching runs in the narrow channel.

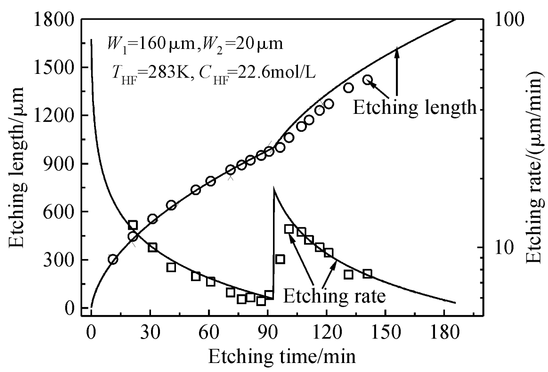

Fig.9 Etching length and rate as functions of etching time Widths of the first and second channel are 100 and 25μm, respectively.

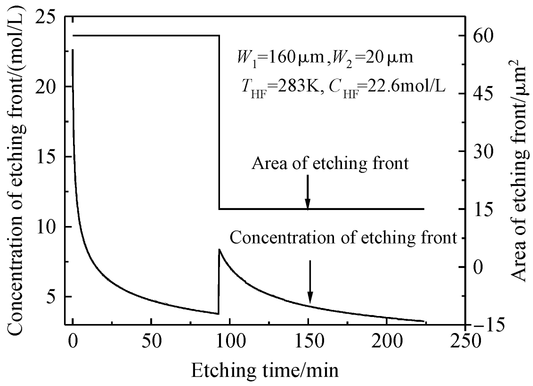

Fig. 10　HF concentration and area of etching front as functions of etching time　Widths of the first and second channels are 100 and 25μm, respectively.

Taking 160～20μm joint channel as an example, in the first stage, the etching rate decreases with the etching time. It decreases from 83.0 to 7.35μm/min in 92.9min. The quick drop of the etching rate is due to the diffusion limitation. As shown in Fig. 8, the concentration decreases from 22.6 to 3.79mol/L. In the second stage, the etching rate increases suddenly in a very short time, namely 0.3min, as shown clearly in Fig. 7. The etching rate increases because the etching front area jumps down from 96 to 12μm² suddenly. So the reactive flux available is sufficient, which causes the accumulating of HF concentration at the joint, as shown in Fig. 8. When the etching runs in the third stage, the etching rate decreases again due to the diffusion-limited effect.

Also four kinds of joint channel structures, namely 100～25, 400～100, 80～10, and 160～20μm, are studied to reveal the effect of width ratio to the etching process. For convenient description, the width ratio in wide-narrow channel is defined as the ratio of W_1 to W_2.

The variables at the end of the each stage are calculated as shown in Table 2.

As shown in Table 2, in the first stage, the etching processes for four different structures are the same. The etching time, etching rate, concentration of etching front are 92.9min, 7.35μm/min, and 3.79mol/L, respectively.

In the second stage, the etching process lies on the width ratio. If the width ratio is the same, then the etching process is the same. For example, if the width ratio is 4, namely the joint channel is 100～25 or 400～100μm, the etching rate increases to 17.8μm/min, which is about 2.42 times the value of 7.35μm/min. The concentration of etching front increases from 3.79 to 8.43mol/L. When the width ratio is 8, namely the joint channel is 160～20 or 80～10μm, the result is similar. But the etching rate and the concentration of etching front are different from the joint channel when the width ratio is 4. The etching rate increases from 7.35 to 28.1μm/min. The concentration of etching front increases from 3.79 to 11.4mol/L. As mentioned in previous section, the reason for the etching rate increases suddenly at the joint is because HF concentration accumulates suddenly at the joint. Then the larger the width ratio, the larger the accumulation is.

The end etching rate of the second stage is just the initial etching rate of the third stage. So the etching rate increases with the width ratio in the third stage. To etch 500μm, for the width ratio of 4, the etching time is 47.2min. But for the width ratio of 8, the etching time is only 37.6min.

From the analysis above, one can obtain that for wide-narrow channel, if the width ratio is the same, the etching process is absolutely the same. The etching rate and concentration of etching front increase with the width ratio when the etching front proceeding into the narrow channel.

5　Summary

In this paper, the effect of width ratio on the

Table 2　Variables at each stage with two different width ratios

T = 283K, C_{HF} = 22.6mol/L										
No.	Width ratio is 4 (100～25μm)					Width ratio is 8 (80～10μm)				
	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²
1	92.9	998	7.35	3.79	60	92.9	998	7.35	3.79	48
2	93.2	1000	17.8	8.43	60	93.2	1000	28.1	11.4	48
3	140.4	1500	7.60	4.59	15	130.8	1500	8.84	5.14	6
No.	Width ratio is 4 (400～100μm)					Width ratio is 8 (160～20μm)				
	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²	Time /min	Length /μm	Rate /(μm/min)	Con. /(mol/L)	Area /μm²
1	92.9	998	7.35	3.79	240	92.9	998	7.35	3.79	96
2	93.2	1000	17.8	8.43	240	93.2	1000	28.1	11.4	96
3	140.4	1500	7.60	4.59	60	130.8	1500	8.84	5.14	12

etching behavior of joint channel is studied in detail. The etching process of four groups of narrow-wide joint channels and four groups of wide-narrow joint channels are compared. The results show that for narrow-wide joint channel, the etching process depends not only on the width ratio but also on the width of the channel. But for wide-narrow joint channel, the etching process depends only on the width ratio.

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宽度比对组合沟道结构牺牲层腐蚀特性的影响*

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摘要: 对宽度比对组合沟道结构的牺牲层腐蚀特性的影响进行了研究. 从理论和实验两个方面,对不同宽度比的腐蚀特性进行了比较. 结果表明,宽度比对窄-宽组合结构和宽-窄组合结构的影响不同. 对于窄-宽组合结构,腐蚀过程不仅与宽度比有关,而且与沟道宽度有关. 对于宽度比相同的结构,每个阶段的腐蚀速率和腐蚀前端浓度非常接近,每个阶段的腐蚀时间却随沟道宽度的增加而增长. 但是,如果宽沟道的长度比较长,总的腐蚀时间非常接近. 对于宽-窄组合沟道结构,如果宽度比相同,则包括所需腐蚀时间在内的所有过程完全相同. 每个阶段结束时的腐蚀速率和腐蚀前端的浓度随着宽度比的增大而增大,但是总的腐蚀时间随宽度比的增大而下降.

关键词: 组合沟道; 宽度比; 腐蚀速率
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