Linear Motion Microsystem Fabricated on a Silicon Wafer

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1. Introduction

Anisotropic etching can produce regular shapes that consist of specific crystal planes. The shape-generating principle is different from the conventional copying rule of machine tools, in which the accuracy of relative motion between the tool and the workpiece is copied to the workpiece geometry. Thus, the accuracy by anisotropic etching is expected to be higher than that of the conventional machining processes. However, this etching has been used mainly for micromachining technique for MEMS[1,2)] and its geometrical accuracy have not been extensively discussed.

This paper introduces the development of a precise linear motion microsystem fabricated on a silicon wafer that is produced by anisotropic etching to utilize the crystal regularity. Position control by applying vertical and horizontal vibrations simultaneously to the guide is also undertaken.

2. Linear Motion Microsystem

2.1 Fabrication process[3)]

Figure 1 shows an example of regular shapes that consist of {111} crystal planes of silicon. When the (100) substrate with rectangular mask oriented to [110] direction is etched, V-grooves can be obtained. Its opening angle is determined as 70.5 degrees by crystallography, because the etching rate of {111} plane is much slower than that of the others and these planes form the groove face. As a result, high geometrical accuracy such as parallelism of grooves as well as good repeatability is expected.

In this study, silicon substrates with oxide layer of 1 μm thickness, which serves as an etch-mask, were used. An electron-beam pattern generator produced the mask pattern. The etchant was KOH solution (35 wt%, 333 K).

Figure 2 shows the process to fabricate the linear motion system. Two rectangular patterns produce two V-grooves. This groove is used as the guide. Also, three rectangular patterns produce two V shapes and this part is used as the slider. After etching, the necessary part is cut by a dicer. Assembling these V's completes the linear motion system. Table 1 shows typical dimension range. The longest dimension 3.7 mm is limited by the capacity of the electron-beam pattern generator

Once an accurate mask pattern is exposed aligning with the crystal orientation, precise process control is not necessary. Since etching rate is as slow as 0.3 μm/min against the (100) plane, the control of etching time is not critical.

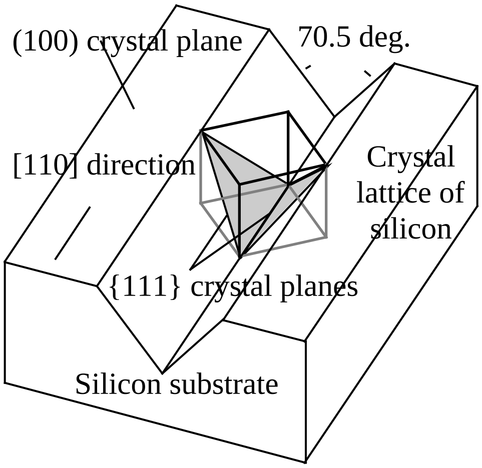

Fig.1 V-groove that consists of {111} crystal planes

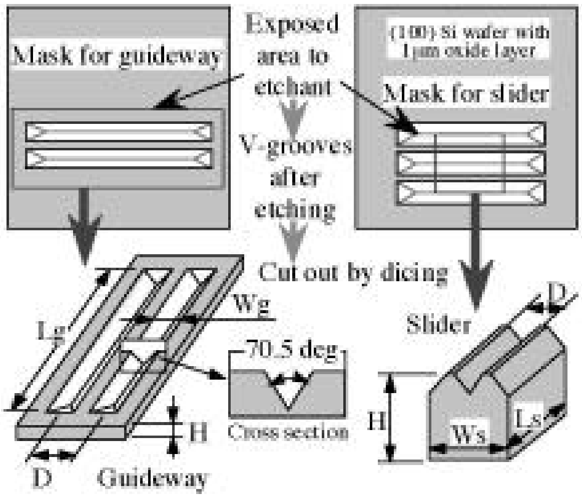

Fig.2 Process for linear motion system

2.2 Evaluation of accuracy

Figure 3 shows the results of SEM observation of the developed system. Figure 3(left) shows a close-up of the sliding face. As can be seen, V-shapes are accurately machined though the slider's width is small as 327 μm. Figure 3(right) shows the assembled view. The V-shapes of the slider fit well with the V-guide, because both faces are made of {111} planes and the opening angle is same.

In the conventional slideway system design, a double-V configuration is preferred to achieve good motion accuracy. However, the machining accuracy is crucial and the desired accuracy is difficult to obtain. Therefore, other configurations such as V-flat, are often adopted. By making use of crystal regularity described above, the geometrical error of the V's can be minimized.

Figure 4 shows the edge profile of the grooves measured by a profilometer. It can be seen that the groove width is constant over the full length and the parallelism between grooves is good. However, the grooves are not straight but curved. The maximum deviation from the ideal straight line is about 4 μm over 3.7 mm length. The reason is considered as intrinsic error of the pattern generator during the lithography.

The groove width and depth are evaluated using a confocal-type laser microscope. The nominal resolution in vertical direction is 1 nm. Table 2 shows the results. The groove width and depth are measured at five points per one groove, and the opening angle was calculated, which coincide with the theoretical one, 70.5 degrees.

3. Drive and Control

3.1 Effect of adhesion force at the interface

The sliding motion of such a microscopic object is affected by the adhesion force F_a between the slider and the guide much more than by the inertial force. This effect was indirectly measured as shown in Fig.5. The motion system was set on an inclined stage and only vertical vibration with various amplitudes and frequencies was applied. The critical acceleration when the slider begins to slide down was measured.

Figure 6 shows the results. The lines in the figure show the calculated results assuming arbitrary adhesion force F_a. Fitting the experimental results, the F_a is estimated as large as 16 μN, though its own weight is just 4 μN.

Table 1 Range of dimensions of the system

Element	Items	Minimum Size (μm)	Maximum Size (μm)
Guideway	Length Lg	3700	3700
	Width Wg	90	280
	Thickness H	450	450
	V-groove depth	64	198
Slider	Length Ls	187	360
	Width Ws	250	420
	Pitch of V's D	30	80

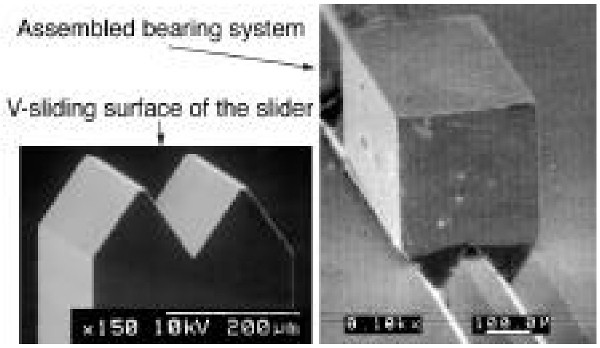

Fig.3 SEM photos of the microslider

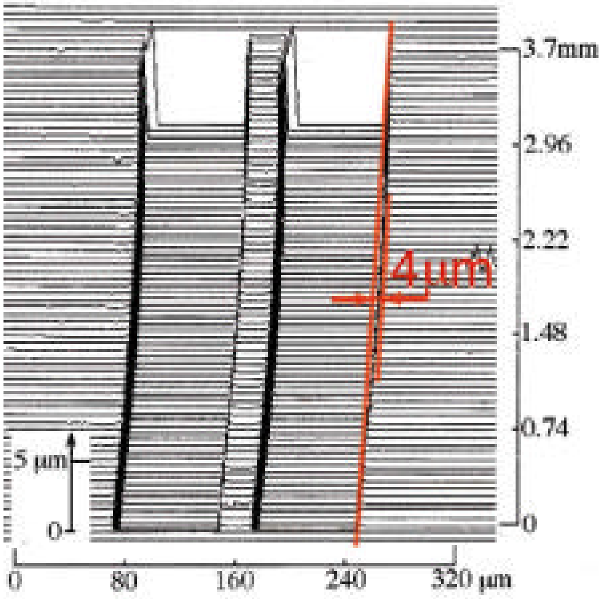

Fig.4 Profile of groove edge

Table 2 Evaluation of geometrical accuracy
(Average of five points measurement)

Item	Groove width [μm]	Groove depth [μm]	Opening angle [deg]
Left groove(Fig.4)	77.43	54.52	70.7
Right groove(Fig.4)	76.80	54.45	70.5

3.2 Drive method

Vibrations in two directions, vertical and horizontal, are applied simultaneously to the guide to drive the microslider as shown in Fig.7. If the downward acceleration is sufficiently high, the slider jumps slightly due to inertia and moves intermittently along the guide. By adjusting the amplitude ratio and phase difference between the two vibrations, the motion speed and direction can be controlled.

Figure 7 also shows the experimental setup. Two voice coil motors apply vibrations in two directions, and a two-channel function generator, which is interfaced with a PC, controls their signals. In the following experiments, the generated signals are 1.4 kHz sinusoidal waves, and the burst mode is adopted due to the limitations of the equipment. A laser micrometer with a resolution of 0.02 μm monitors the feed. This signal is used for feedback control.

3.3 Driving properties and position control

It was found from other experiments that the feed rate of the slider is almost proportional to the amplitude of the horizontal vibration. On the other hand, the relationship between the number of burst pulses and the feed per burst shows a nonlinear property. The feed rate is almost proportional to the pulse number when the burst number is larger than four, at which a constant and stable feed rate, in other word good controllability, is expected. However, when the number is less than four, the feed rate becomes larger and has greater scatter. This may result from the elastic deformation of the structural members. In the following experiments, the number of burst was kept at four.

Figure 8 shows the block diagram for closed-loop position control. The current slider position is measured using a laser micrometer and used for feedback. The vibration amplitude in the horizontal direction is changed according to the position error magnitude. On the other hand, the vertical amplitude is kept constant at 1μm. This amplitude is critical to achieve smooth motion, while overcoming large adhesion force at the interface. It was determined from the experience in this study. The phase shift between these two is set to zero or 180 degrees, depending on the positioning error sign, that is, the control of feed direction.

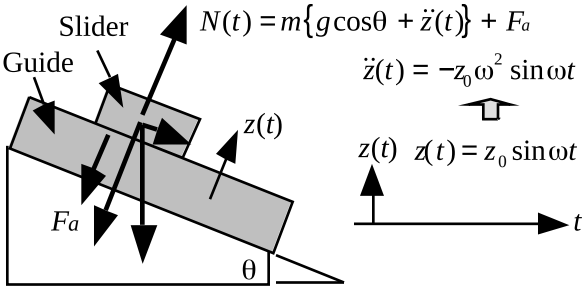

Fig.5 Measurement of adhesion force

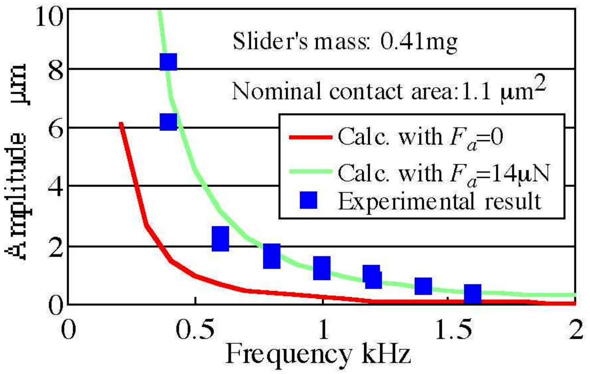

Fig.6 Effect of adhesion force at the interface

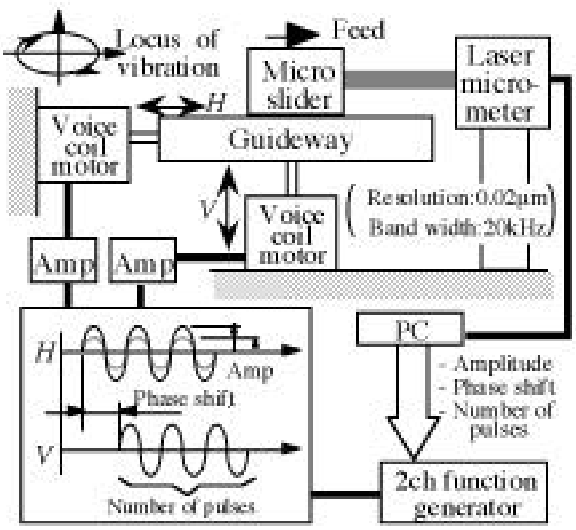

Fig.7 Experimental setup for vibration drive

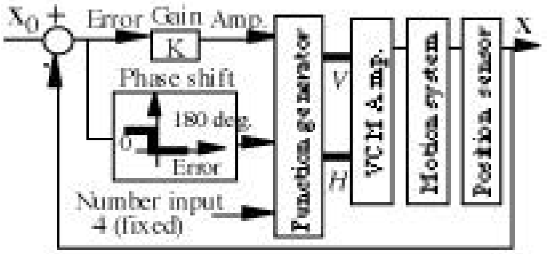

Fig.8 Position control system

The slider dimension is 330 μm in width, 625 μm in length, and 350 μm in height. The experiments were done in a clean room (class 10000) with the temperature control of 293±1 K.

Figure 9 shows the time history of the positioning process. The vertical axis shows the position of feed, where the starting point is zero and the destination is 160 μm, respectively. The slider position converged after repeating several stepwise motion cycles. The residual position error was 2 μm, where the slider position was no longer controlled, although the control was kept on. The adhesion force and friction at the interface may govern this limitation. The cycle time of control loop was long as 0.3 seconds due to the slow transmission rate of the interface between PC and function generator. By refining the apparatus, the response, as well as the positioning accuracy, will be improved.

4. Further development

Utilizing the characteristic of cubic crystal system of silicon, an accurate XY table system can be achieved as shown in Fig.10. V-grooves that cross in right angles can be made on opposite side of a wafer by anisotropic etching from both sides. By mating V-ridge structures with these grooves, XY motion guide mechanism is completed.

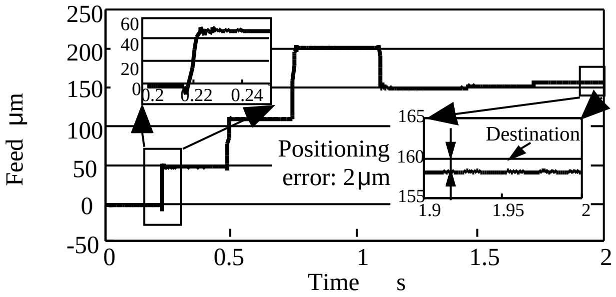

Fig.9 Result of feedback position control

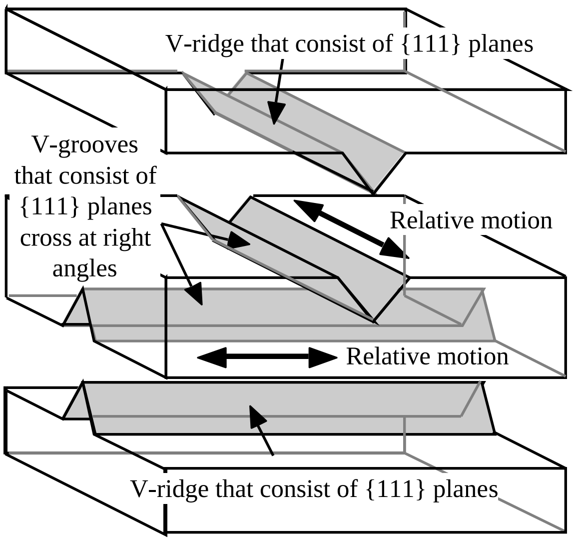

Fig.10 XY-stage utilizing crystal regularity

The squareness of X- and Y-axis is determined crystallography again, because all of the groove faces are {111} crystal planes and high squareness is expected. However, the experimental result shows the error of 0.5 degrees in the squareness between the grooves. The reason of this error is considered as the off-angle of the substrate. That is, the top surfaces of ordinary (100) substrates are not exactly the (100) plane and often have certain angular error. It should be less than ±0.5 degrees, according to the specifications of the vendors. This error should cause a geometrical error, though this does not cause any problems in the semiconductor industries.

5. Conclusions

An application of an accurate anisotropic etching due to the use of crystal regularity has been demonstrated. The results are summarized as follows.

- A linear motion microsystem was developed, in which both the slider and the guide are produced by the anisotropic etching of silicon. The geometrical accuracy was examined.
- The developed system was driven and positioned with an accuracy of 2 μm by applying vibrations in horizontal and vertical directions.

References

(1) K. E. Peterson: Silicon as a Mechanical Material, Trans IEEE, 70, (1982), pp.420-457.
(2) M. Madou: Fundamentals of Microfabrication, CRC Press, (1997), p.449.
(3) N. Moronuki and Y. Furukawa: Microlinear Motion Bearing Produced by Anisotropic Etching of Silicon, Annals of CIRP, 46, 1, (1997), pp.151-154.