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Experimental Study of Electrochemical Micro-milling of Silicon

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Abstract: Electrochemical machining (ECM) is a common method of silicon micromachining, but it is difficult to be directly used for three-dimensional processing. Therefore a new electrochemical micro-milling (ECMM) method is proposed. The method combined electrochemical machining and milling processes technology. Micro-removal of materials can be achieved by electrochemical machining technique, while milling processes enable three-dimensional machining. ECMM utilizes the passivation of silicon in sodium hydroxide solution to reduce electrochemical stray corrosion and improve processing accuracy. Experiments showed that the ECMM technology can limit the electrochemical stray corrosion to less than 10 μm . This method can be used for the machining of tiny three-dimensional structures of silicon materials.

1. Introduction

In micro-electro-mechanical system (MEMS), silicon is a commonly used structural material. Some structural components of MEMS, such as sensing elements, micro actuators, have complex three-dimensional microstructure features ^[1]. These structures have complex three-dimensional shapes with high dimensional accuracy, surface roughness, and surface stress requirements. Therefore, the three-dimensional micro-machining technology of silicon materials has become a research hotspot in the research of MEMS ^[2].

At present, there are three main types of three-dimensional micro fabrication technology for silicon materials: deep etching photo-assisted electrochemical technology, micro-EDM technology, and micro-machining technology ^[3]. Deep etching photo-assisted electrochemical technology is complicated in process, expensive in equipment, and low in processing speed ^[4]. Micro-EDM technology removes materials quickly, but the surface of the material is prone to form heat-affected layers and micro-cracks ^[5]. Micromachining technology removes excess material by cutting. The machine tool accuracy and speed are required to be very high. At the same time, surface mechanical damage and crystal defects are easily generated ^[6].

Electrochemical machining is a common method in silicon micro fabrication, but it is difficult to directly use it for three-dimensional processing, which is caused by electrochemical stray corrosion ^[7]. Allongue et al ^[8] solved the problem of stray corrosion by using ultrashort pulse electrochemical machining technology. This method requires the power pulse width to be in picoseconds and the processing speed is very low. The silicon electrochemical micro-milling technology proposed in this paper has less stray corrosion. Through experiments and theoretical analysis, the removal mechanism of silicon materials and the law of stray corrosion were studied.



2. Experimental details

The experiment was carried out on a micro-three-axis electrochemical machining machine, as shown in Figure 1(a). The experimental device includes a machine tool, a pulse power source, an electrolysis cell, a workpiece, and an electrode. The machine tool uses a precision ball screw drive with a positioning accuracy of 0.1 μm . The pulse power supply uses a FET, and the pulse voltage, current, and pulse width can be adjusted within a certain range. The electrolyte is an aqueous solution of sodium hydroxide. The workpiece is a monocrystalline silicon wafer connected to the anode of the pulse power source and immersed in the electrolyte. The electrode is equivalent to a milling cutter. The machine process uses a cylindrical tungsten electrode which is connected to the Z axis of the machine tool through a precision high-speed rotating fixture, which is connected to the cathode of the pulse power supply.

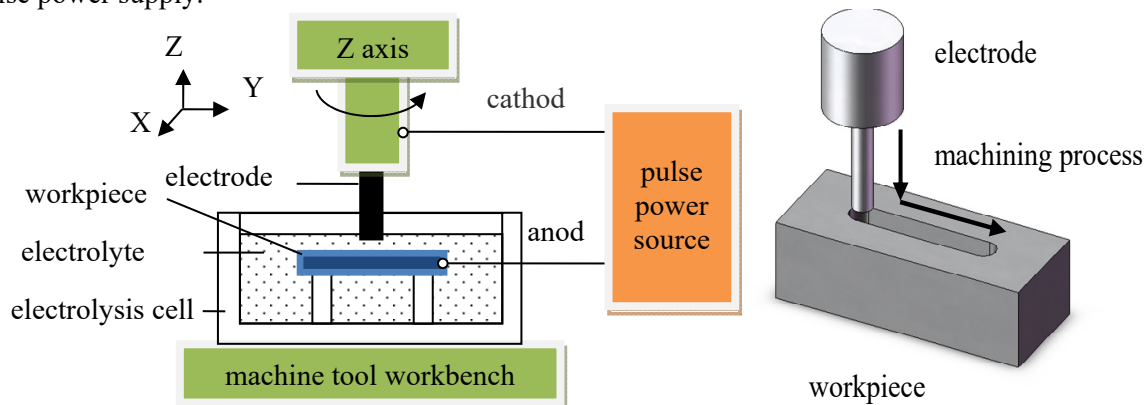


Figure 1. (a) Schematic diagram of the experimental device (b) machining process.

A cylindrical tungsten electrode with a diameter of 100 μm was used in the experiment. The workpiece is N-type single crystal silicon (crystal orientation 100) and the resistivity is 5 $\Omega\cdot\text{cm}$. The electrolyte was 0.5% sodium hydroxide solution, and the remaining experimental parameters are shown in Table 1. The machining process is shown in Figure 1(b). The electrode is fed 50 μm downward from the surface of the workpiece and then moved horizontally by 200 μm .

Table 1. Experimental parameters.

Experimental parameters	value
feed speed/ $\mu\text{m}\cdot\text{min}^{-1}$	6
Pulse width/ms	50
voltage/V	20
Electrode speed / $\text{r}\cdot\text{min}^{-1}$	3000

3. Results, analysis and discussion

The surface of the silicon material is machined into a microgroove, and its scanning electron microscope image is shown in Figure 2. The surface morphology after machining is smoother than that of the original EDM surface, and there are no obvious defects such as hot cracks. The groove width after machining is approximately 120 μm , and the side machining gap between the electrode and the workpiece is 10 μm . No obvious stray corrosion is observed at the edge of the groove. The experimental results show that the electrochemical micro-milling technology of silicon material in alkaline solution is feasible.

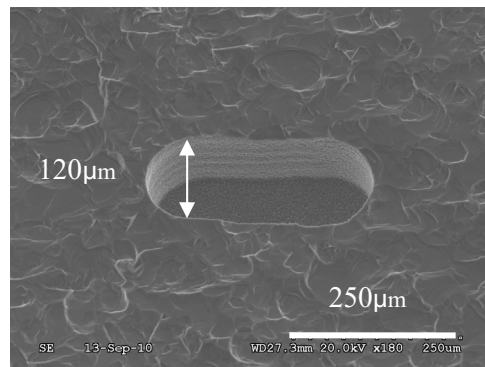


Figure 2. Microgroove milled on silicon Workpieces

When the distance between the electrode and the workpiece is reduced to several microns, there are some small spark discharge between the electrode and the workpiece. The oscilloscope can detect the voltage waveform between the electrode and the workpiece, as shown in Figure 3. It can be found from the figure that frequent discharge voltage waveforms occur in the process of machining. Unlike the discharge waveforms of ordinary metal materials in EDM, the minimum voltage during discharge is not zero, which is about 10 V.

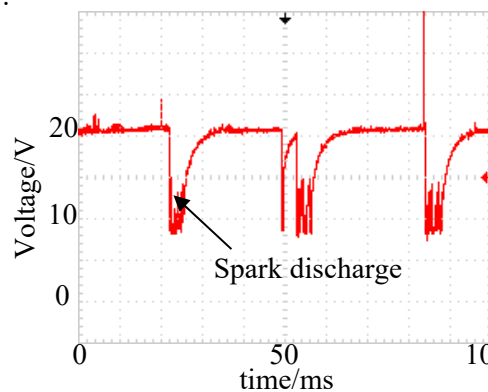


Figure 3. Voltage waveform between the electrode and the workpiece

Through experiments, it can be found that the electrochemical milling process of silicon is different from that of metal materials. There are not only electrochemical machining phenomena, but also EDM phenomena. Therefore, the mechanism of silicon material removal may include not only electrochemical etching, but also EDM. With the change of temperature in the machining gap, In order to study the removal principle of silicon materials, we analyzed the processes of electrochemical etching and EDM respectively.

3.1. Electrochemical etching process

The electrochemical etching rate of silicon material mainly depends on the electrochemical characteristics of silicon material itself, electrolyte, voltage and other factors. The standard potential of silicon (relative to hydrogen standard electrode) is 0.875 V, which is a very active element. However, as solid silicon, it is usually stable in most aqueous solutions, because the passive oxide film composed of silica and silicate is formed on the surface of silicon. This passive oxide film will hinder the electrochemical corrosion of silicon materials and reduce the rate of electrochemical etching. Sodium hydroxide solution can dissolve passivation film and produce soluble sodium silicate. But at room temperature, the electrochemical removal rate of silicon in alkaline solution is very low.

The electrochemical properties of silicon in sodium hydroxide solution were measured by cyclic voltammetry, as shown in Figure 4. The upper limit potential was 10 V, the initial potential was 0 V, the lower limit potential was 0 V, and the scanning rate was 0.4 V/s. A total of five segments were scanned. The results show that silicon passivation occurs during electrochemical processing in sodium hydroxide solution, and the electrochemical etching rate is very slow.

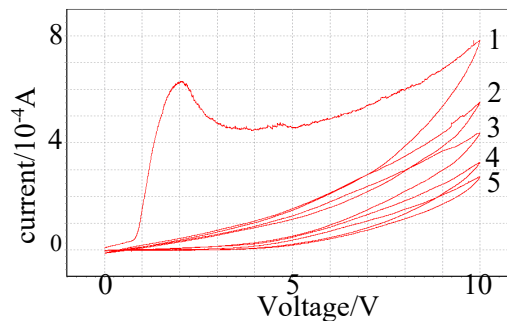


Figure 4. Cyclic voltammetry of silicon in sodium hydroxide solution

3.2. EDM process

In the process of electrochemical milling of silicon, a large amount of hydrogen will be generated on the surface of the electrode. There is a large amount of gas in the gap between the electrode and the workpiece, which forms insulating bubbles in some parts of the gap. Under the action of electric field, discharge occurs first in gas. Spark discharge will break down the passive film on the silicon surface. Under the action of electric spark, the passive film is destroyed. Frequent spark discharge increases the rate of electrochemical etching of silicon. The distance of EDM limits the area of electrochemical etching and improves the localization of electrochemical machining. The gap between the electrode and the workpiece is related to the spark discharge distance, that is, the electrochemical dissolution of silicon occurs only in the region where the spark discharge occurs. Therefore, there is a cut-off gap in electrochemical machining of silicon, that is, the processing area beyond the discharge distance of EDM will not be eroded. According to dielectric breakdown theory, the relationship between breakdown distance and voltage of hydrogen medium is shown in equation (1).

$$d = \frac{U - U_{pol}}{E} \quad (1)$$

Where, U is the machining voltage (V);

U_{pol} - the polarization voltage of silicon (V);

E - breakdown electric field strength of hydrogen (kV/cm).

The breakdown electric field strength of hydrogen is 15.5 kV/cm, the voltage is 20 V, and the polarization voltage of silicon is 6 V. The dielectric breakdown gap of the electrode and the workpiece can be calculated to be 9 μm . The experimental results show that when the voltage is 20V, the machining gap is 10 μm , which is basically consistent with that of gas spark discharge.

4. Conclusion

The electrochemical milling of silicon has the characteristics of small stray corrosion and good localization. When the concentration of sodium hydroxide solution is 0.5% and the pulse voltage is 20 V, the processing gap can be controlled within 10 μm . Therefore, it is feasible to use electrochemical milling technology for three-dimensional micro-processing of silicon. The electrochemical milling of silicon material is a kind of EDM-assisted electrochemical machining process. Among them, the function of EDM is to break down the passive film on the surface of silicon and improve the speed of electrochemical processing.

Acknowledgments

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