Study on Electrochemical and electrical discharge compound Micro-machining for Silicon

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Abstract: Silicon material is a widely used substrate in micro-electromechanical systems, and its micro-fabrication technology has always been a research hotspot. The main microfabrication methods of silicon material are chemical etching, electrochemical machining (ECM) and electrical discharge machining (EDM). The electrochemical and electrical discharge compound machining technology is a kind of machining method for non-conductive materials. In this paper, the compound machining technology was studied and applied to the microfabrication of silicon material. The machining principle of silicon material in hydrochloric acid solution was studied, and the influence of silicon material type and voltage on the machining was analyzed. It is found that n-type silicon can be machined, while p-type silicon can hardly be machined. With this technology, micro three-dimensional structures can be fabricated on silicon material.

1. Introduction

Because silicon materials are widely used in micro-electromechanical systems, the micro-fabrication technology of silicon materials has become a hot spot in the field of micro-fabrication. At present, the commonly used micro-fabrication methods of silicon materials include chemical etching [1], electrochemical machining and electrical discharge machining [2, 3]. However, the machining speed of these methods is generally slow, and the equipment and process is complex. For chemical and electrochemical machining, stray corrosion control has always been a difficult problem, which has a great impact on the machining accuracy. Therefore, these methods are difficult to machine three-dimensional structures.

Generally, electrochemical machining and electrical discharge machining can not machining non-conductive materials, but the combination of the two makes the machining of non-conductive materials possible [4,5]. W.Y. Peng and other scholars studied the electrochemical discharge machining technology and applied it to the machining of non-conductive brittle materials. They adopted the method of auxiliary electrode to produce a large number of bubbles between the electrode and the workpiece, and spark discharge occurred to achieve the purpose of removing the workpiece materials [6]. Xuan Doan Cao and other scholars studied the method of electrochemical discharge machining of glass material. Using high frequency pulse power supply, they can machine tiny three-dimensional structures on glass [7]. Professor Wang Wei of Nanjing University of Aeronautics and Astronautics used high conductivity compound working fluid to machine silicon material by EDM and ECM.
compound cutting \cite{8}. The results showed that the surface cracks were obviously reduced and the machining speed was obviously increased, which provided a new method for the machining of silicon material.

The ECM and EDM compound technology is mainly used in the machining of brittle non-conductive materials. It achieves the purpose of material removal through the principle of EDM \cite{9}. Therefore, the workpiece surface will produce heat-affected layer, or even thermal cracks. Through the study of these machining methods, a new EDM and ECM compound method for silicon material is adopted. It uses acidic electrolyte, removes materials by the principle of electrochemical machining, and EDM plays an auxiliary role in machining. With this machining technology, the surface of silicon material machined will not produce heat-affected layer, and will not produce electrochemical stray corrosion. The machining accuracy is high.

2. Experimental design

The experiment was carried out on a three-axis micro-EDM machine tool, as shown in figure 1. The pulse power supply was RC pulse power supply. The electrode was connected with the negative pole of the power supply. The workpiece was connected with the positive pole of the power supply and was immersed in the electrolyte. The machining process is shown in Figure 1. The experiment was divided into two steps. The first step is to fabricate the electrode. The tungsten electrode with a diameter of 0.5mm was used as the electrode, and then the required diameter was machined by EDM. In the second step, the EDM oil was replaced by electrolyte, and the silicon material was machined by ECM and EDM compound machining method. During the machining, the electrode rotated at high speed and moved along a certain path. The silicon material near the electrode was removed due to the electrochemical anodic oxidation reaction.

![Figure 1. Experimental equipment schematic diagram](image)

The machining parameters selected in the experiment are shown in the table 1. Pure silicon material is not suitable for electrochemical machining because of its extremely low conductivity. So we chose two different types of doped silicon materials, whose properties are shown in Table 2. The workpiece was cut into silicon wafers by electrical discharge wire cutting.

| Table 1. Experimental parameters |
|----------------------------------|
| Experimental parameters | value |
| Electrode diameter (μm) | 200 |
| feed speed (μm·min⁻¹) | 6-24 |
| Pulse on time (ms) | 20 |
| Pulse off time (ms) | 20 |
3. Results, analysis and discussion

Firstly, the machining experiment of N-type silicon was carried out. The decomposition voltage of silicon is about 6.686V. So the minimum machining voltage was set to 8V, and then gradually increased the voltage. It was found that when the voltage was between 8V and 18V, the bubbles in the machining area increased gradually, but there was no obvious erosion trace on the silicon surface, and no wear of the electrode was found. When the voltage is 18V, the machined trace on the surface of n-type silicon is shown in figure 2. There was only a very shallow trace in the machining area, which was the result of friction between the electrode and the workpiece surface. At the same time, some granular substances appeared near the machining area. These substances were oxides of silicon, which can be inferred from the principle of electrochemical reaction of silicon. The product of anodic electrochemical dissolution of silicon in hydrochloric acid solution is silicic acid, as shown in formula 1. The silicic acid is unstable and becomes silica after dehydration, as shown in the formula 2. So the tiny particles we found on the surface of the workpiece were silicon dioxide. The electrochemical cathodic reduction reaction took place on the surface of the electrode. The product was hydrogen, as shown in the formula 3. At this time, a large number of bubbles can be observed on the surface of the electrode.

\[
\begin{align*}
Si + 2OH^- &\rightarrow H_2SiO_3 \downarrow + 2e \quad (1) \\
H_2SiO_3 &\rightarrow SiO_2 \downarrow + H_2O \quad (2) \\
2H^+ + 2e &\rightarrow H_2 \uparrow 
\end{align*}
\]

![Figure 2. Silicon surface machined at 18 Voltage](image)

When the voltage exceeded 18V, the electrochemical reaction was intense. A large number of bubbles appeared in the machining area, and a small number of bubbles appeared on the surface of the workpiece. The bubbles in the machining area were mainly hydrogen, while the bubbles on the surface of the workpiece were oxygen produced by the oxidation of hydroxide ions in aqueous solution. At the same time, when the voltage was greater than 18V, sparks can be observed in the machining area.
When the machining voltage was less than 18V, a short circuit will occur even at the minimum feed speed. This was because the electrochemical dissolution rate of silicon was very slow at low voltage. In addition, due to the influence of passive film on silicon surface, low voltage cannot destroy the passive film, which made the electrochemical dissolution rate of silicon slow. When the voltage was 18V, the machining speed can only reach 6um/min, and the short circuit was frequent. When the voltage reached 20V, the spark between the electrode and the workpiece was more obvious, the discharge frequency increased, and there was basically no short circuit phenomenon. When the machining voltage reached 35V, the electrolysis reaction of water was intense, and a large number of bubbles were produced in the machining area. At the same time, the polarization potential of silicon increased, and hydroxide ions in the electrolyte were oxidized to produce oxygen. At this time, it can be found that there were many small bubbles on the surface of silicon. With the increase of voltage, the frequency and energy of EDM in the machining area were increasing.

We fabricated some through holes on 0.2mm silicon wafer by electrochemical discharge machining. Figure 3 is a SEM photograph of the holes fabricated under different voltages. It was found that there were some wears at the bottom and side of the electrode due to EDM discharge. The side wear of the electrode was larger, while the wear on the bottom was very small, only 2 to 3 microns. As shown in figure 4 and 5.

![Figure 3. SEM image of holes machined on silicon wafers](image)

![Figure 4. Electrode wear after machining](image)
In the machining of p-type silicon materials, we found that the process had been in a short-circuit state. When the voltage was increased from 8V to 35V, there was no obvious machining trace on the surface of p-type silicon, which indicates that p-type silicon was difficult to be processed in hydrochloric acid solution. This was because the surface of p-type silicon was easily passivated during electrochemical machining, which increases its polarization potential. At this time, the electrochemical anodization reaction on the silicon surface was the hydroxide ion in the solution, as shown in the formula 4.

\[ 4OH^- \rightarrow O_2 \uparrow + 2H_2O + 4e \]  

Finally, a micro-cavity structure was fabricated by using n-type silicon, as shown in figure 6a, which is a SEM image of the fabricated structure. The structure was divided into two layers, the outer side length was 0.8 mm quadrilateral, the depth was 400 microns, and the middle groove depth was 200 microns. The machining voltage was 20V, and the feed speed of the electrode was 6um/min. The width of the groove after machining was 220 microns, that was, the side clearance was 10 microns. The bottom clearance was measured to be 2 micron. The bottom of the machined cavity is shown in Fig. 6b. Layered exfoliation occurred on the silicon surface.

Through experiments and analysis, it was found that the removal process of silicon material was as follows. First, since the surface of the silicon material had a dense oxide film, the silicon material was passivated, and electrochemical anodization was difficult to occur. Therefore, under the action of electrochemistry, the electrolyte was electrolyzed to generate hydrogen and oxygen, and a mixture of bubbles and working fluid was formed between the electrode and the silicon material. The bubbles formed a "bridge" in the machining gap. Then, as the distance between the electrode and the workpiece decreased, and the electric field strength in the machining gap reached the electrical breakdown strength of the gas, the gas was ionically broken down to form an electric spark discharge.
The spark discharge would break down and destroy the oxide film on the silicon surface. Finally, the silicon material exposed to the working fluid underwent an electrochemical reaction to dissolve and regenerated an oxide film on the surface of the silicon material.

4. Conclusion
From the experimental results and analysis, the following conclusions can be drawn:

1. In hydrochloric acid solution, electrochemical and electrical discharge compound technology can machine p-type silicon, while p-type silicon can not be machined.
2. The gap between electrodes and workpieces was affected by voltage. If the voltage was larger, the gap was larger. In order to ensure a certain machining speed and accuracy, the voltage should be between 18V and 35V.
3. Using this method, micro three-dimensional structures can be machined on silicon materials. The side machining gap can reach 10 microns, and the bottom machining gap can reach 2 microns. However, layered exfoliation was easy to appear on the machined surface, which needed further study.

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