Improvement of the machinability of silicon by multiple implantations of different ions for ultra-precision micro-cutting

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Monocrystalline materials are widely used in the semiconductor industry and optical engineering due to their excellent electrical and optical properties. However, due to the hard and brittle nature of these materials, it is difficult to achieve ultra-precise mirrors through the turning process. In this paper, a method of surface modification by multiple ion injection into silicon is proposed, and the machinability of silicon is improved by promoting the transformation from brittleness to ductility. Through simulation software, the distribution and induced displacement of implanted ions on the subsurface of the silicon wafer are visualized. The enhancement of the machinability of silicon is verified by ultra-precision micro-cutting experiments. The improvement of its subsurface was observed by TEM using FIB preparation.

NOMENCLATURE

BDTD = brittle-ductile transition depth
Si-H = Ion implanted monocrystalline silicon

1. Introduction

Monocrystalline silicon is an extremely important optical and semiconductor material. With the development of semiconductor chip industry, the precision machining of monocrystalline silicon has more and more important technical significance and economic value. As the line width of microcircuits in chips becomes thinner, the requirement of surface smoothness of silicon as a semiconductor substrate becomes higher and higher [1]. In the application of optical materials, the surface processing quality of monocrystalline silicon is also extremely important [2]. Therefore, improving the surface processing quality of silicon has been the focus of research in recent years.

Ion implantation is a highly specialized technique in ultra-precision machining, which plays a crucial role in microelectronics, nanotechnology, materials science and semiconductor device manufacturing [3, 4]. This technique uses high-energy ion beams to inject specific elements into the surface of a solid material, thereby altering its chemical composition, physical or electronic properties without significantly increasing the thickness of the material [5,6]. In the manufacture of integrated circuits, ion implantation is used to precisely control the type and concentration of conduction of semiconductor materials, which is a key step in forming basic electronic components such as transistors and diodes. By selectively injecting elements such as boron and phosphorus, P-type or N-type semiconductor regions can be created to achieve the construction of circuits [7,8]. Through the implantation of specific elements, the surface hardness and friction coefficient of the material can be changed, which is very important for the manufacture of high-performance tools, bearings and aerospace components. The application of ion implantation technology to hard and brittle materials such as monocrystalline silicon can effectively improve the machinability of monocrystalline materials, inhibit sub-surface damage, and thus improve the surface quality and service life of products [9,10].

In the past, most studies used only a single type of ion implantation. The modification effect achieved by a single ion is often very limited. The purpose of this study is to investigate the modification effect of multiple ion implantation on the surface of monocrystalline silicon and the influence on the machining process. In this study, three different ions were implanted into monocrystalline silicon in a certain order. Hydrogen and helium ions are used to modify the relatively deep layers, while copper ions are used as heavy ions to modify the shallower layers. This ion implantation strategy can save the implantation energy and the total ion dose.

2. Multiple ion implantations strategy

2.1 Simulation of ion implantation parameters

The depth and distribution of ion implantation were simulated with SRIM (The stop and Range of ions in Matter) software before the ion implantation process began. SRIM is mainly used to simulate and calculate the energy loss, trajectory, and final deposition position of charged particles (such as ions) in different materials. This software is essential for understanding particle-matter interaction processes, designing experiments on radiation effects, as well as in the semiconductor industry, particle accelerator design, radiation protection research and other fields. Through SRIM, the experimental conditions of different ion implantation in monocrystalline silicon can be simulated step by step. After a lot of simulation, the ion implantation parameters are determined under the principle of ensuring sufficient modified thickness and relatively uniform ion distribution. H^+, He^{2+} and Cu^{2+} ions were sequentially implanted into the surface of monocrystalline silicon, the implantation parameters are shown in Table 1.

Types of ions	Ion dose	Implantation energy
H^+	$2x10^{16}$ cm^{-2}	175KeV
He^{2+}	$1x10^{15}$ cm^{-2}	150KeV
Cu^{2+}	$2x10^{14}$ cm^{-2}	140KeV

Table. 1 Ion implantation parameters (implantation sequence from top to bottom)

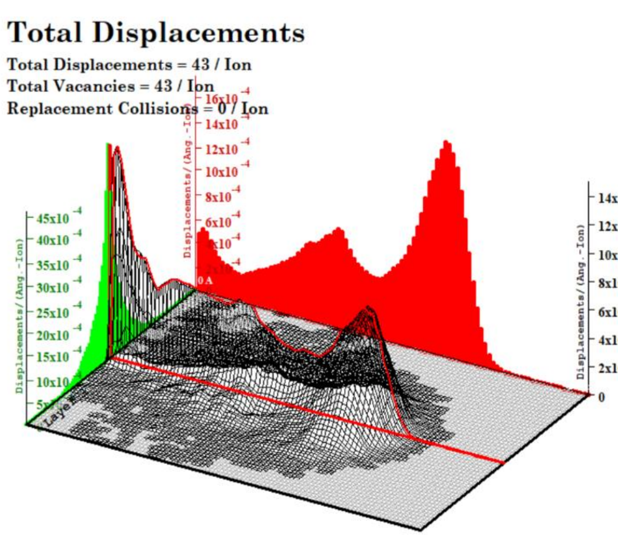

Fig. 1 SRIM simulation results of total displacement caused by three steps ion implantations in silicon

In the process of ion implantation, the incidence Angle of ion beam is deflected by 7° from the normal direction of the surface of monocrystalline silicon, which is to avoid the channel effect. Fig.1 shows the simulation results of the total displacement of ion implantation. It shows that the total displacement is evenly distributed within a depth of 0 ~ 1.6um, forming three main distribution peaks. The overall thickness of the modified layer is sufficient for subsequent micro-cutting experiments. Because the dose of the first implanted hydrogen ion is much larger than that of the other two ions, it also has the largest injection energy. Therefore, the distribution depth of the total displacement peaks at about 1.60um.

2.2 Characterization of ion implantation results

The surface structure of monocrystalline silicon was analyzed by Renishaw micro-Raman spectroscopy system with laser wavelength of 785nm. Fig.2 shows the comparison of Raman spectrum results of monocrystalline silicon before and after ion implantation. After implantation, the characteristic peak of monocrystalline silicon at 521 cm^{-1} is obviously reduced, which means that the single crystal lattice of the silicon is weakened. The peak intensity represents the concentration of c-Si, and for ion-implanted silicon (Si-H), a significant decrease in strength indicates a decrease in the crystallinity of the silicon. The multi-ion implantation strategy can achieve a certain extent of amorphous at a relatively small ion dose, and the results of Raman spectroscopy provide strong evidence for the effectiveness of this strategy.

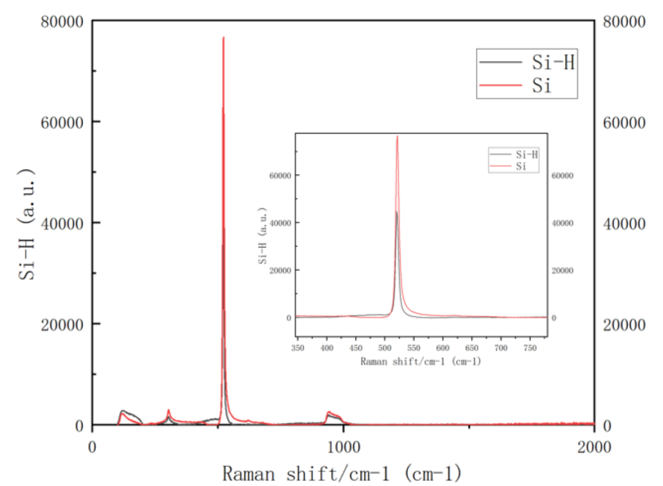

Fig. 2 Raman spectra of monocrystalline silicon (Si) and implanted silicon (Si-H)

3. Machinability verification experiments

3.1 Groove cutting

To compare the different cutting properties of monocrystalline silicon and ion implanted silicon, multiple scratch experiments were carried out on the surface of both samples. As shown in the figure, the silicon wafer is a square sample of 10x10x0.5mm, with the positioning edge of the [110] crystal orientation, so the cutting angle can be adjusted according to the direction of the positioning edge to obtain grooves with different crystal directions. The front Angle of the diamond tool used is -25°, the clearance angle is 15°, and the radius of the tool head is 1.030mm. Moore Nanotech 350FG ultra-precision machine tool was used to scratch the surface of the sample with the linear motion of the main axes Y and Z. The length of each scratch is 3mm and the cutting depth is from 0 to 3um. Scratch experiments were carried out on the surfaces of two samples with different cutting speeds (Y-axis motion speed). The scratch cutting speeds were 10, 100, 500 mm/min respectively, and three scratches were performed for each cutting speed. The scratches on the surface of the sample were preliminary observed by Olympus BX60 optical microscope, the groove sample obtained after the scratch test at a cutting speed of 10mm/min is shown in Fig.3.

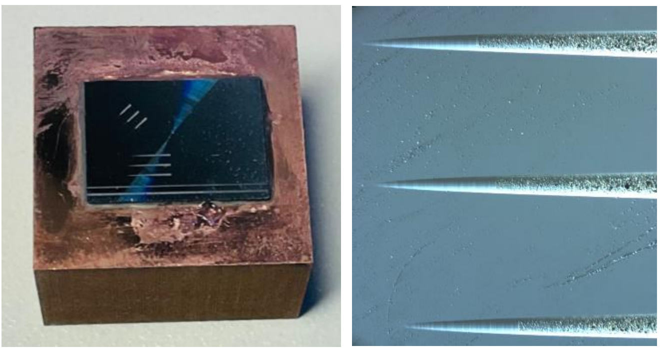

Fig. 3 The sample after the groove scratch test

The grooves were further observed and analyzed by Zygo Nexview white light interferometer. The critical depth of transition from brittle cutting mode to ductile cutting mode at each cutting speed is recorded. Take the grooving surface profile in Fig.4 at a cutting speed of 10mm/min as an example, the crystal orientation of the scratch is [110]. When the linear surface profile of the scratch center from smooth to beginning fluctuates continuously, it indicates a transition from ductile cutting to brittle cutting. The ΔY obtained by intercepting this section is the brittle-ductile transition depth (BDTD) of each scratch. Each cutting speed is measured three times to obtain the calculated average.

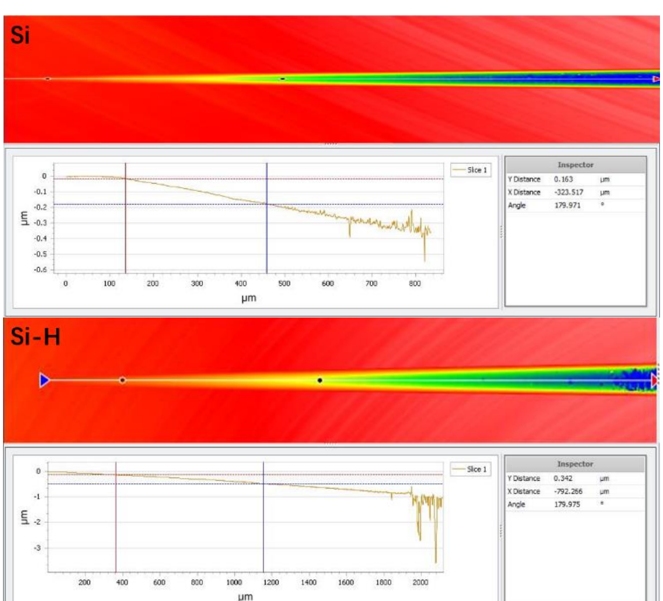

Fig. 4 The white light interference shape of the groove surface and the linear profile of the center position (cutting speed is 10mm/min)

After data processing, at the cutting speed of 10mm/min, the BDTD of the modified monocrystal silicon increases from 159nm before modification to 346nm. At different cutting speeds, the BDTDS of different crystal orientations are increased by about 200nm. This is because the mass and volume of Cu2+ ions are heavy ions relative to silicon atoms, and the final implantation of heavy ions will destroy the single crystal structure of the silicon surface layer, forming a thin amorphous layer. As the anisotropy decreases, the plastic flow of shear stress during cutting becomes easier. Therefore, in the amorphous layer is a ductile cutting mode. When the cutting depth enters the single crystal structure below the amorphous layer, a small part of the ductile cutting will still be maintained before the transition to brittle fracture. Therefore, the BDTD of ion implanted silicon will increase significantly. This proves that the change of the surface structure of monocrystalline silicon due to ion implantation can effectively improve the machinability and machinability of monocrystalline silicon surface.

3.2 Microstructural machinability

To further verify the improvement of the surface machinability of monocrystalline silicon by ion implantation, a 4x5 microlens array was machined on the sample surface by using the same diamond tool servo turning with slow tool speed. The arc radius of each lens is 5626um, and the depth of each lens column increases from left to right. The feed rate is 2um/rev and the spindle speed is 40rpm.

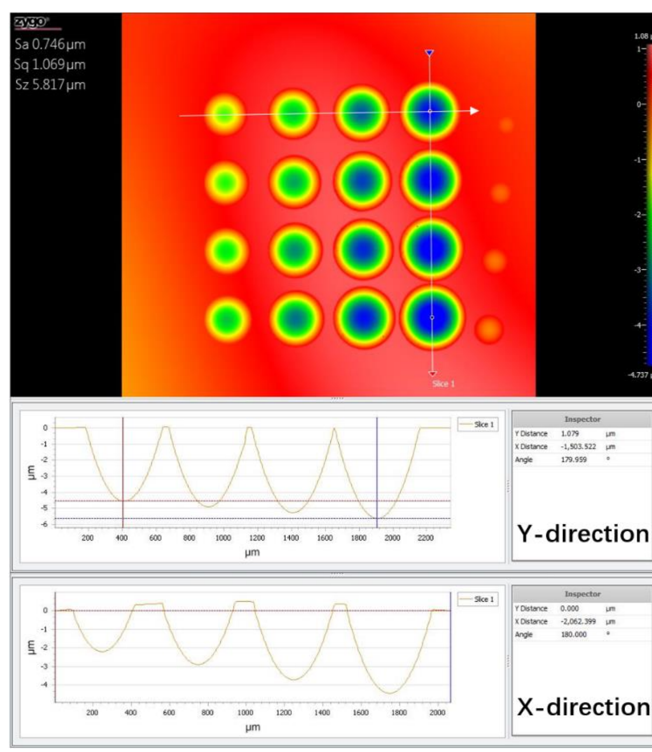

Fig. 5 White light interference topography of microlens array

As shown in Fig.5, the linear morphology of the microlens array was measured laterally and longitude. respectively. The homogeneity of the microlens profile can be seen from the linear morphology of the microlens array in X and Y axes. After removing the surface topography, the average surface roughness of all microlenses was measured, and the average surface roughness of microlenses was Sa = 6nm. In the machining experiment of monocrystal silicon microlens array without ion implantation, the machining parameters must be controlled at a feed rate of 2um/rev and a spindle speed of 20rpm if the average surface roughness of the machined microlens is to reach 6nm. Therefore, the ion implantation modification technology can not only ensure the cutting surface quality, but also improve the surface processing efficiency of monocrystalline silicon.

4. Conclusions

In this study, three different ions were implanted into monocrystalline silicon. Raman spectroscopy and white light interferometer were used to characterize the experimental results to verify the effect of ion implantation on the surface processing ability of monocrystalline silicon. Subsequently, the microlens array was prepared on the silicon surface to further verify the machinability of the microstructures after ion implantation. The results are as follows:

(1) The deepest implantation depth of the three different ions is 1.6μm, and the surface structure tends to be more amorphous after implantation.

(2) After the grooving cutting experiment, the brittle-toughness transition depth of ion implanted monocrystalline silicon is increased by about 200nm at all cutting speeds.

(3) Ion implantation can effectively improve the machinability of the surface of monocrystalline silicon, and successfully prepare crack-free microlens arrays on the modified silicon surface.

Atomic scale observation and analysis of ion implantation results and subsurface damage during cutting by TEM is the focus of further research. In addition, multiple ion implantation strategies form a three-layer modification layer, which greatly saves energy and ion dose costs. How to obtain significant modification effect with less ion dose and lower injection energy is also a problem worth studying in the future, which will have a significant impact on the application of ion implantation strategy in industrial production.

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