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Short Communication

Enhancement of the machinability of silicon by hydrogen ion implantation for ultra-precision micro-cutting

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ABSTRACT

This paper presents the implementation method of surface modification by hydrogen ion implantation in silicon on the enhancement of machinability of silicon by facilitating the brittle-to-ductile transition. The distribution of the implanted hydrogen ions and induced displacements in the sub-surface of silicon wafer is visualised through modelling. The micro-cutting experiments are conducted on ultra-precision raster milling to verify the enhancement effect on the machinability of silicon.

1. Introduction

Silicon is one of the most important semiconductor and infrared optics materials. For the fabrication of high quality products, a series of processing methods in industry have been developed to cope with its brittle nature, including slicing, grinding, lapping, chemical-mechanical polishing, etc. [1]. To replace the costly process of low efficiency, the techniques and theories of ductile-regime cutting have been widely studied at the sub-micrometric to nano-metric scales. A considerable amount of research work has been devoted to determining the critical undeformed chip thickness for ductile-regime cutting of brittle materials through experimental approaches. In the early research work, Blake et al. [2] attempted to measure the location of ductile-to-brittle transition on the "shoulder region" left by interrupted cutting. Blackley et al. [3] introduced a damage depth parameter and developed the phenomenological model devised by Blake et al. [2]. They further designed experiments with various machining parameters to quantify the critical undeformed chip thickness and damage depth for germanium single crystals. Hung et al. [4] investigated the material anisotropic effect on ductile regime machining of single crystal silicon and concluded that the same cutting conditions yielded different surface qualities with regard to crystallographic orientations. Yan et al. [5] focused their research on the critical undeformed chip thickness for CaF_2 in facing along different crystal orientations and with a systematic design of experiments with different machining conditions. Liu et al. [6] studied the influence of diamond tool edge radius on the critical undeformed chip thickness in cutting of silicon wafers at various feed rates. Yu et al. [7] proposed a damaged region analysis method to determine the subsurface damage depth in the machined micro-structured surface. Compared with turning experiments, the cutting experiments with variable depth of cut for determining critical undeformed chip thickness have been implemented by means of plunge cutting and fly cutting, such as inclined plunge cutting on silicon by Fang et al. [8–11] and Yan et al. [12], plunge cutting on tungsten carbides by Liu et al. [13], fly cutting on silicon by O'Connor et al. [14], etc. Nevertheless, these proliferated experimental methods had not proposed a perfect solution to solve the problem of cutting of brittle materials like silicon. Therefore, Fang et al. [15] introduced in their recent work the fluorine ion implantation technique to modify the surface of silicon for nanometric cutting. In their work, the high implantation energy of 10.0 MeV was employed to improve the machinability of silicon with certain enhancement on machining efficiency and reduced tool wear rate.

In the other field of research, ion implantation technique has been well developed for many different applications in semiconductor industry and materials science. One of these typical applications is to introduce hydrogen of high concentration at

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the depth in the range of 1 μm and through bonding and annealing exfoliate the top silicon layer and transfer it onto another wafer, forming silicon on insulator wafer [16]. The key factor for the exfoliation is hydrogen. After exfoliation, the surface layer is in fact damaged (by ion implantation) and this layer has to be removed. Being damaged, this layer may offer a better machinability, opening another opportunity to apply diamond cutting on silicon. It is reported that crystalline lattice of silicon can be damaged and even amorphised [17,18] by hydrogen ion implantation with the dose of $1\times10^{16}\,cm^{-2}$ up to $1\times10^{17}\,cm^{-2}$. Since the implantation is a costly process, it is of practical interest to seek for the lowest hydrogen ion dose that can cause visible lattice displacements. It has been identified by transmission electron microscope (TEM) that for the dose of $3\times10^{16}\,cm^{-2}$ the implanted layer is about 100 nm thick [19]. Therefore, in this present work hydrogen ion replaces the toxic fluorine ion in literature [15] and is implanted into the silicon wafer with energy from 125 keV to 175 keV, which results in a modified layer at the depth over 1 μm from the silicon wafer surface. The enhancement effect of hydrogen ion implantation method on the machinability of silicon wafer is confirmed through comparison with micro-cutting experiments.

2. Experiments

2.1. Hydrogen ion implantation

P-type (100) silicon wafer (4″) with resistivity of 4–6 Ω-cm was implanted with H^+. To obtain a broad hydrogen implantation profile, hydrogen ion was implanted with three consecutive steps with energies of 175, 150 and 125 keV and the corresponding doses of 2×10^{16}, 2×10^{16} and $3\times10^{16}\,cm^{-2}$, respectively. Implantation was done at low current density in order to avoid wafer heating. To predict the results a priori, the simulation was performed by SRIM software (free) for two doses and three energies (125, 150 and 175 keV). In Fig. 1, distributions of implanted hydrogen ion and displacement count are shown respectively, where the energy is given in real terms. The implanted ion concentration and the created implantation layer have relative meaning because the simulation is stopped once the distribution profile has reached a "constant" shape. With the selected implantation energies, relatively continuous distribution of hydrogen ions is achieved from ~1.1 μm to 1.85 μm. According to Fig. 1(b), the main damage of silicon is located approximately in the same region. The thickness of the implantation layer is enough for the succeeding micro-cutting experiments.

2.2. Micro-cutting experiments

To reveal the enhancement effect on the machinability of silicon by hydrogen ion implantation, a series of micro-cutting experiments were conducted on ultra-precision raster milling machine, Precitech Freeform 705G. Three different work-piece materials were employed, including bare silicon wafer (Si), hydrogen ion implanted wafer (H–Si) and aluminium alloy 7075 (Al7075), to examine the brittle/ductile cutting characteristics in separate-groove cutting tests, respectively. An APEX diamond tool (KC1.5mLEI-MA) with zero rake angle, 15° clearance angle and 1.537 mm nose radius was used. The swing radius of the diamond tool mounted on spindle was 27 mm. Separate grooves were cut along the [110] direction on the work-piece surface of (100) crystallographic plane at the cutting speed of 0.08 m/s by setting the spindle at 30 rpm and feed rate at zero. In the groove cutting process, the depth of cut ranged from zero to its maximum of 3 μm. The main cutting force (Ch1), lateral force (Ch2) and thrust force (Ch3) were recorded by Kistler force sensor 9256C1 and data acquisition (DAQ) software Dynoware on a workstation. The sample rate was set at 100 kHz. Power spectrum density analysis was further performed on the measured forces using MATLAB to extract the micro-cutting characteristics. The machined grooves were examined in optical microscope Olympus BX60 and scanning electron microscope (SEM) Hitachi TM3000.

3. Results and discussion

The machined separate grooves on the bare silicon wafer (Si) and hydrogen ion implanted wafer (H–Si) are examined under

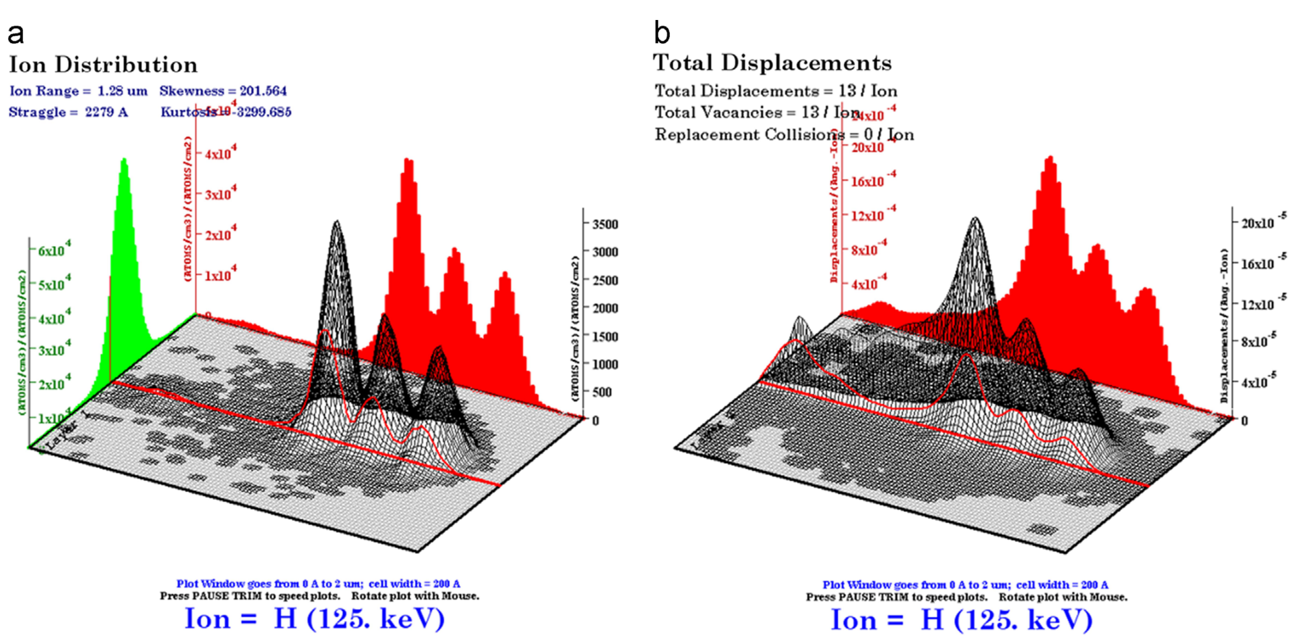

Fig. 1. 3D presentation of (a) hydrogen distribution and (b) defects distribution in silicon: E = 175, 150 and 125 keV; respective doses = 10,000, 10,000 and 15,000 counts; the surface of silicon is on the left hand side of the graph (Note: in this figure 125 keV is indication of the last implant).