Precision Engineering 33 (2009) 378–386

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Fundamental investigation of subsurface damage in single crystalline silicon caused by diamond machining

Jiwang Yan[a,*], Tooru Asami[a], Hirofumi Harada[b], Tsunemoto Kuriyagawa[a]

[a] Department of Nanomechanics, School of Engineering, Tohoku University, Aramaki Aoba 6-6-01, Aoba-ku, Sendai 980-8579, Japan
[b] Siltronic Japan Corporation, 3434 Shimata, Hikari, Yamaguchi 743-0063, Japan

ARTICLE INFO

Article history:
Received 30 January 2008
Received in revised form 18 October 2008
Accepted 22 October 2008
Available online 24 November 2008

Keywords:
Single crystal silicon
Nano precision cutting
Ductile machining
Phase transformation
Dislocation
Subsurface damage
High pressure

ABSTRACT

Single crystalline silicon was plunge-cut using diamond tools at a low speed. Cross-sectional transmission electron microscopy and laser micro-Raman spectroscopy were used to examine the subsurface structure of the machined sample. The results showed that the thickness of the machining-induced amorphous layer strongly depends on the tool rake angle and depth of cut, and fluctuates synchronously with surface waviness. Dislocation activity was observed below the amorphous layers in all instances, where the dislocation density depended on the cutting conditions. The machining pressure was estimated from the micro-cutting forces, and a subsurface damage model was proposed by considering the phase transformation and dislocation behavior of silicon under high-pressure conditions.

1. Introduction

Precision machining of single-crystal silicon has become tremendously important both technologically and economically in microelectronic, micromechanical and optical element manufacturing. As the line widths of the integrated circuits become finer and finer, approaching several tens of nanometers, extremely flat and smooth silicon substrates are required. Therefore, the improvement of the "surface integrity" of silicon has been a focused research topic during the past decade. The topic of "subsurface integrity" has recently gained importance as well. Since all mechanical machining processes involving tool-workpiece contacts inevitably cause subsurface damage, the depth and structure of the near-surface layer will influence the mechanical, optical and electronic performance of silicon products. However, to date, the subsurface damage mechanism of silicon has remained unclear and many aspects related to this issue are still controversial. The lack of literature in this area is primarily due to technological difficulties in precise characterization of the subsurface damage, which is invisible from the surface.

A number of researchers have used cross-sectional transmission electron microscopy (TEM) to observe the subsurface structure of machined silicon wafers. For example, TEM studies on diamond-turned silicon surfaces by Shibata et al. revealed that machining led to the formation of a 150-nm-thick amorphous layer above a 2–3 μm deep crystalline region with dislocation loops [1]. Jeynes et al. showed that a 110-nm-thick amorphous layer was formed above a ~260-nm-deep dislocated crystalline region during diamond turning [2]. Puttick et al. demonstrated that the total depth of the subsurface damage, including amorphous layers and dislocations, was in the 100–400 nm range for both diamond turned and ground silicon [3]. Zarudi and Zhang investigated the grinding-induced damage to silicon using TEM and energy dispersive spectroscopy (EDS) [4]. A few other studies on machining damage in silicon via X-ray diffraction [5], Raman scattering [6], micro laser Raman [7,8], and a combination of laser Raman and chemical etching [9] have also been reported. However, to date, no systematic study on the relationship between subsurface damage and machining conditions can be found in the literature. For manufacturing engineers, finding the optimum machining conditions that produce minimum subsurface damage in silicon wafers remains a difficult issue.

The objective of the present study is to investigate the subsurface damage mechanism in silicon and to establish its relationship to machining conditions. We used two different methods to characterize subsurface damage: laser micro-Raman spectroscopy and cross-sectional TEM. Laser micro-Raman spectroscopy is a powerful method for materials characterizations. In a previous paper [10], we proposed a method to quantitatively measure the depth of the machining-induced amorphous layer by analyzing the Raman

* Corresponding author. Tel.: +81 22 7956946; fax: +81 22 7957027.
E-mail address: yanjw@pm.mech.tohoku.ac.jp (J. Yan).

0141-6359/$ – see front matter
doi:10.1016/j.precisioneng.2008.10.008

intensity data. We found that there was a close correlation between the Raman intensity ratio and the depth of the amorphous layer, which can be used to measure the subsurface damage depth of silicon quickly and in a nondestructive manner.

To prepare the experimental samples, we used the plunge-cutting method. In plunge-cutting, individual cuts are made on pristine single crystalline silicon without preexisting defects. It is different from diamond turning, where due to the cross feeds of the tool, all cuts except the first are made on a subsurface-damaged material and not on the starting crystalline material [8,11]. Also, in plunge cuts, micromachining forces can be measured precisely without the influence of dynamical disturbances. Moreover, thermal effects can be neglected when the cutting speed is low. Furthermore, the tool geometry used for plunge-cutting is well-defined, and a continuous change in depth of cut can be easily achieved in a single cut. The results obtained from plunge-cutting can be used to understand the subsurface damage mechanism in abrasive machining processes, such as grinding, lapping and polishing, where the definition of cutting edge geometry and depth of cut is difficult.

2. Experimental

As shown in Fig. 1, a diamond-cutting tool is subjected to a transverse feed in the x direction while the depth of cut changes continuously in the z direction. In this way, a microgroove with varying depth (schematized in Fig. 2) can be obtained during a single cut. Machining tests were conducted with an ultraprecision lathe (Toyoda AHN-05, JTEKT Corporation, Japan), whose tables have the capability to move under four-axis (XYZB) numerical control at a stepping resolution of 1 nm. Fig. 3 is a photograph of the main section of the machine. A piezoelectric dynamometer (Kistler 9256A) was mounted below the workpiece to measure micro-cutting forces during the cutting tests.

The cutting tool is made of single-crystal diamond and has a nose radius (R_n) of 10 mm. The edge radius R_e was estimated to be around 50 nm by the diamond tool manufacturer using a special scanning electron microscope (SEM) having two electron detectors [12]. The tool rake angle γ was changed from -15° to -60° by adjusting the B-axis rotary table on which the diamond tool was fixed. The relief angle was changed accordingly (from 21° to 66°). Depth of cut d was changed from 0 to 500 nm at a constant cutting speed of 500 mm/min (0.0083 m/s), far lower than that of fly cutting (15–18 m/s) [13] and diamond turning processes. At such a low cutting speed, the effects of cutting heat generation will be insignificant. As lubricant and coolant, the cutting oil Bluebe #LB10 was used in the form of mist jet.

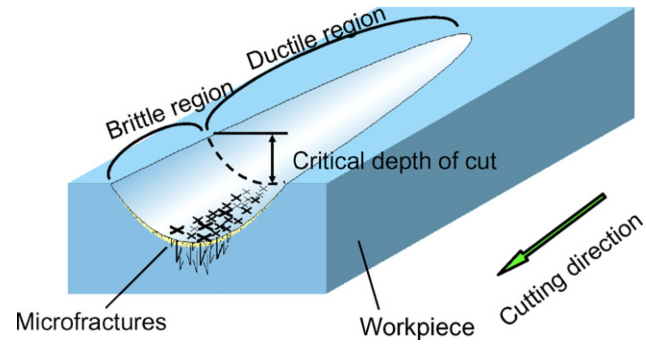

Fig. 2. Schematic model of a microgroove plunge-cut with a round-nosed tool.

As workpiece, an electric-device-grade n-type single-crystal silicon (1 0 0) wafer was machined. The wafer was 150 mm in diameter, 550 μm in thickness and obtained with a chemomechanical polish finish. In this paper, we report results for cutting tests performed along the [1 1 0] direction, which is perpendicular to the orientation flat of the wafer. The effect of crystallographic orientation on the subsurface damage mechanism is another complex issue, which will be reported in detail in a future paper.

The machined samples were first observed by a Nomarski microscope, and then their three-dimensional surface topographies were measured using a white-light interferometer (NewView-5000, Zygo Corporation, USA). A laser micro-Raman spectrometer (NRS-3100, JASCO Corporation, Japan) was used to characterize the material structural changes. The laser wavelength was 532 nm and the output laser power was 10 mW. A 100× objective lens with a numerical aperture (NA) of 0.95 was used so that the focused laser spot size was 1 μm, which enables the laser spot to be directed to any location within the machined microgrooves. To minimize experimental error, all measurements were performed under the same strictly controlled conditions at room temperature.

In order to examine the subsurface structure of machined samples in detail, we also performed cross-sectional TEM (H-9000NAR, Hitachi Ltd., Japan). The TEM samples were cut out from the center of the microgroove bottom and thinned to about 100 nm by the focused ion beam (FIB) technique to enable electron transmission. The acceleration voltage used was 300 kV. To protect from possible damage from the FIB, carbon (C) and tungsten (W) coatings were deposited on the samples.

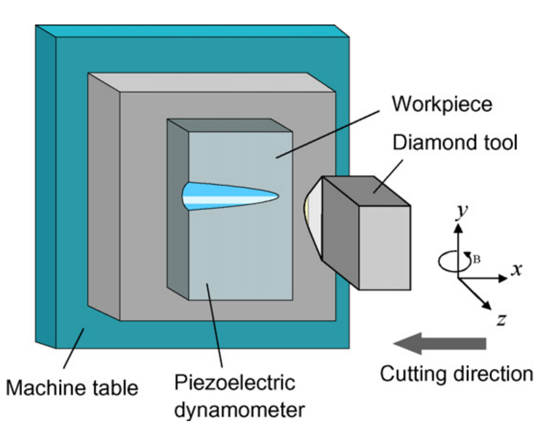

Fig. 1. Schematic of plunge-cutting experiment.

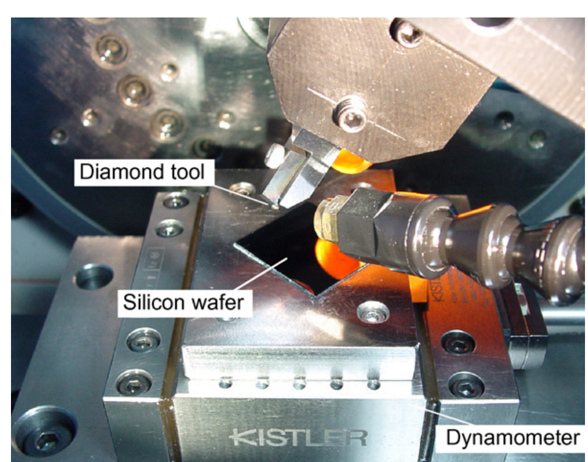

Fig. 3. Photograph of the main section of the experimental setup.