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Ductile mode behavior of silicon during scribing by spherical abrasive particles

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Abstract

Reducing surface and subsurface damage in cutting brittle materials using fixed abrasive processes like wire sawing is an important challenge. This paper investigates the effect of size and shape of abrasives on ductile mode cutting of single crystal silicon. Diamond and tungsten carbide abrasives of different shapes (irregular and spherical) deposited on a steel surface are used to scribe silicon and the material removal mode is analyzed. Experiments show that spherical abrasives enhance ductile mode cutting when compared to irregular shapes, yielding a smoother surface and significantly fewer micro-cracks.

Keywords: Surface integrity; Silicon; Tungsten carbide

1. Introduction

The surface integrity of silicon wafers is an important factor in solar cell and microelectronic device processing. The manufacturing process to fabricate a silicon wafer consists of first producing an ingot from polysilicon feedstock. Next, the ingot is cut into bricks and then sliced into wafers using a wire saw. The mechanical integrity of the cut surface is determined by the surface and subsurface damage generated by the wire sawing process. The surface of as-cut silicon is characterized by micro-cracks, grooves, pits, and spalling. This as-cut surface is chemically etched to remove sawing damage during solar cell manufacturing. These damage removal processes are expensive, labor-intensive, and often environmentally unfriendly. To improve the surface of as-cut silicon and potentially reduce the time and cost associated with saw damage removal, ductile mode cutting of brittle materials is an option. Ductile mode cutting of semiconductor materials was studied by Blake et al. [1] and recently reviewed by Kovalchenko [2]. Numerous theoretical and experimental studies on the subject have been reported [1, 2]. The phenomenon of ductile cutting occurs when the local pressure at the cutting edge of the tool reaches the pressure of phase transformation. Crystalline silicon first transforms under pressure into a metallic β -Sn phase and subsequently into an amorphous phase, which allows for material removal without micro-cracks, spalling, and pitting. The pressure required for phase transition of silicon is about 12 GPa [3]. If the pressure at the cutting edge does not reach the phase transformation pressure, only elastic deformation of the material occurs without any material removal. However, if the pressure at the cutting edge exceeds the phase transformation pressure (more than 16 GPa), brittle fracture occurs. Thus, ductile mode cutting of silicon occurs only in a narrow range of loading. The critical parameters for cutting silicon in ductile mode are: 1) the pressure/stress level created by the depth of cut, and 2) the radius of the tool cutting edge. As previously

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demonstrated [2], the undeformed chip thickness must be smaller than the tool cutting edge radius for ductile mode cutting to be realized. In addition, the rake angle should be negative, in contrast to cutting metals in ductile mode, which requires a positive rake angle [4]. For tools with multiple cutting edges, such as grinding wheels, cutting saws, or fixed abrasive wires, the ideal design consists of controlling the loading condition at each cutting grain to achieve ductile mode cutting over the entire surface. The shape of the abrasive affects the loading condition. For typical abrasive materials like diamond, silicon carbide, or aluminum oxide, typical cutting grains are never uniform; they differ in size and are irregular in shape. To ensure ductile mode cutting, abrasive grains in multi-point tools should nominally have the same size and be similar in shape. This paper utilizes low-speed scribing experiments to investigate ductile mode cutting produced by uniformly sized and shaped abrasive grains.

Numerous researchers have employed scribing experiments using single point indenters to understand ductile mode cutting of silicon [5-11]. These studies report an initial elastic/ductile deformation in the beginning of the scribe with ductile material removal, followed by ductile-to-brittle transition depending on the load and indentation depth. In prior work [8, 11] the influence of indenter type on the transition from ductile material removal to brittle fracture was investigated. Spherical indenters were found to cause surface crack initiation leading to partial cone cracks, while sharp indenters initiated deep lateral and median cracks [12]. Thus, the shape of the indenter or scribing tool affects the material removal characteristics. However, prior work on abrasives with controlled/engineered shapes is limited, which provides the motivation for this paper.

1. Experimental procedure

We performed scribing experiments of gradually increasing scribing depth using abrasives deposited on a hardened steel ball made of bearing steel (AISI 52100, HRC 60). The substrate material was mirror-polished microelectronic grade silicon wafer of (100) crystallographic orientation and the scribing was performed in the [110] crystallographic direction [13] with increasing depth of scribe (see Figure 1). The mirror-polished surface condition helped in determining the material removal mode after scribing. A constant speed of 100 mm/min was used for all scribing experiments (Note: silicon is not known to be strain rate sensitive). The length of the scribe was 5 mm for all experiments and the final programmed maximum depths of scribe were 2 µm, 5 µm, and 10 µm over the 5 mm length. This allowed investigation of the effect of rate of increase in scribe depth. The silicon sample was fixed to a moving stage, which allowed movement in the horizontal plane along with controlled vertical displacement during scribing.

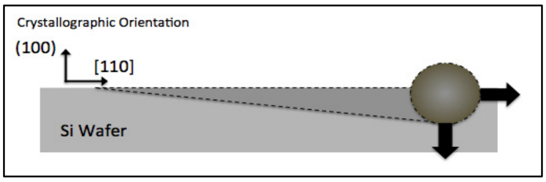

Figure 1. Schematic showing the steel ball with abrasive grits moving in the [110] direction with the (100) crystallographic direction normal to the silicon surface.

The three types of abrasives used in the study are as follows:

(1) Diamond particles ranging in size from 28 µm to 40 µm.

(2) Crushed tungsten carbide (WC) particles, whose size ranged from 20 µm to 40 µm.

(3) Round tungsten carbide (WC) particles, whose size ranged from 30 µm to 90 µm. The round WC particles were divided into six groups and the mean size of particles in each group were differentiated in 10 µm intervals (30-40 µm, 40-50 µm, and so on till 80-90 µm).

Figure 2 shows representative images of the crushed and round tungsten carbide particles. Tungsten carbide (WC) was chosen as the material for abrasive particles due to its high hardness (Mohs hardness of 9–9.5) compared to silicon (Mohs hardness of 6-7). Moreover, spherical shaped WC abrasives are more readily producible than spherical diamond abrasives. Note that WC is softer than diamond (Mohs hardness of diamond is 10). Spherical tungsten carbide particles were produced by the method used for thermal centrifugal spraying of cast tungsten carbide ingots [14].

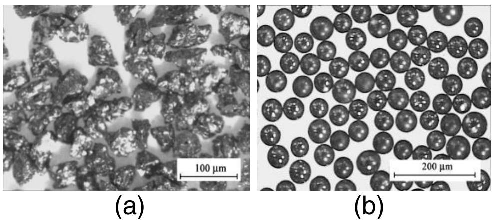

Figure 2. Optical images of (a) crushed and (b) spherical tungsten carbide abrasive particles [14].

The abrasive particles of each type, diamond, crushed WC, and spherical WC were deposited on steel balls 4 mm in diameter. The abrasive particles were attached to the surface of the steel ball using a polymer bonding material typically used in diamond tool manufacturing. Figure 3 shows a representative image of the surface of the steel ball covered with spherical WC particles. The balls were rigidly held in a modified holder, which was attached to the collet located above the displacement-controlled stage in the scribing setup.

After scribing, the resulting surface morphology was analyzed using scanning electron microscopy (SEM). The phase of silicon in the scribed grooves was determined using micro-Raman spectroscopy. The wavelength of Raman laser was 488 nm, with surface penetration of approximately 0.6 µm and spatial resolution of 1 µm, which is less than the scribed groove width.