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Effect of crystal defects on mechanical properties relevant to cutting of multicrystalline solar silicon

Hao Wu, Shreyes N. Melkote *

The George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA

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ABSTRACT

The effect of crystalline defects such as dislocations and grain boundary on the cutting behavior of multicrystalline solar silicon is investigated. Diamond scribing experiments reveal significant intra-granular variations in the critical depth of cut for ductile-to-brittle transition in the material. This is explained by characterizing the local dislocation density variations in (100) and (311) grains of a cast multicrystalline silicon wafer and measuring the corresponding elastic modulus, nanoindentation hardness, and fracture toughness. Measured elastic moduli are shown to be higher than theoretical values for defect-free single crystal silicon of the same crystallographic plane. For a given grain orientation, a higher dislocation density is shown to be correlated with higher fracture toughness and a larger critical depth of cut.

1. Introduction

Crystalline silicon (c-Si) photovoltaic (PV) or solar wafers are cut from a silicon ingot or brick by a wire sawing process, which accounts for 10–15% of the overall cost of a solar cell [1]. While loose abrasive slurry wire sawing is still the dominant process for producing solar silicon wafers [2–4], fixed abrasive diamond wire sawing is rapidly gaining attention due to its potential for higher productivity [5–8]. Industrial diamond wire sawing experience suggests that while single crystal Si (sc-Si) can be cut successfully, significant challenges remain to be overcome before this process is economical for multicrystalline Si (mc-Si) material. Unlike single crystal silicon, mc-Si has a higher density of defects and impurities [9,10]. As a major type of crystal defect, dislocation clusters are widely known to act as electrical recombination centers that negatively impact solar cell efficiency [11,12]. While the detrimental effect of dislocations on the electrical properties of silicon is well understood, their influence on the mechanical properties and the resultant cutting performance of mc-Si during wafer production are still unclear.

Although silicon is brittle at room temperature, it exhibits ductile behavior when cut at low feed rates [13]. A number of studies on ductile mode cutting of crystalline silicon have been reported [14–18]. It is known that the mode of cutting (ductile vs. brittle) in wire sawing plays a significant role in determining sawing productivity and the wafer mechanical strength [5,8]. This study aims to shed light on the influence of dislocation clusters in silicon on the ductile-to-brittle mode transition during cutting. Diamond scribing experiments are carried out in regions of varying dislocation density inside (100) and (311) grains of a cast multicrystalline silicon wafer. The critical depth of cut for ductile-to-brittle transition is measured and the observed differences are explained in terms of the differences in the localized mechanical properties including the elastic modulus, nano-indentation hardness and fracture toughness. Effect of grain boundary on the cutting force generated during scribing is also analyzed.

2. Experimental method

Six adjacent wafers of ~750 μm thickness each were obtained from a directionally solidified mono-like cast

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* Corresponding author. Tel.: +1 404 894 8499; fax: +1 404 894 9342.
E-mail address: shreyes.melkote@me.gatech.edu (S.N. Melkote).

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(also known as quasi-mono) silicon ingot and used in the experiments reported here. Mono-like cast silicon wafers are a recent development in crystalline silicon PV and are known to yield higher efficiency cells than standard cast mc-Si wafers [6]. One side of the wafers was mirror polished by removing 25–50 μm of material in order to eliminate the influence of wire saw-induced damage. The diamond scribing experiments and mechanical property measurements were made on the polished side of the wafers.

2.1. Dislocation etching

The presence of dislocation clusters in the wafers was identified through a Yang chemical etch [19], which reveals etch pits at the dislocation sites. An etching time of 12 min was applied in all dislocation etching. The top and bottom wafers in the six adjacent wafers were etched to confirm that the dislocation etch pit distribution in all six wafers was identical. The scribing experiments and mechanical property measurements were then carried out in the same locations but on the four remaining sister wafers. A large (100) grain covering almost half the wafer surface and a neighboring (311) grain were selected for scribing and evaluation of mechanical properties. The crystallographic orientations of the grains were identified using X-ray diffraction (Philips Pan Analytical XRD). In the (100) grain, regions of low, medium and high dislocation etch pit density were selected for evaluation and labeled as Region I, Region II, and Region III, respectively (see Fig. 1). Note that in Region III dislocations cluster at the dark lines which appear to be grain boundaries. However, it has been shown that those so-called sub-grains appear in a small area of the seed grain and only have small angular difference (less than 3°) with the seed grain ((100) in this case) [20]. Therefore, they are considered as high dislocation density region in the (100) grain.

As seen in Fig. 2, the dislocation etch pit density in the (311) grain located adjacent to the (100) grain is found to be much higher than in the (100) grain area, which is close to the grain boundary. The high dislocation density region close to the grain boundary in the (311) grain is labeled Region V whereas the area with lower dislocation etch pit density in the (311) grain is labeled Region IV. The dislocation etch pit densities in these two regions are shown in Fig. 3.

2.2. Diamond scribing tests: critical depth of cut

Diamond scribing experiments were carried out in the same orientation in Regions I through V of the silicon wafer using a conical diamond scriber with 90° included angle and an effective cutting tip radius of ~5 μm. The scribing setup can be found in [8]. The scribing experiment is depth controlled where the depth was increased from 0 to 2 μm along a 5 mm long track. Due to the possible influence of material property anisotropy along different crystallographic orientations [18], all scribing tests were carried out in the same direction. Further, the scribing tests were conducted under ambient conditions without any cutting fluid. Fig. 4 shows the typical cutting mode transition in the (100) grain with increasing cutting depth.

It can be seen that as the scribing depth increases, the cutting mode transitions from purely ductile cutting, which yields a smooth crack-free surface, to a mixture of ductile cutting and brittle fracture, as shown in Fig. 4. As the depth of scribing increases further, more brittle fracture is observed. The critical depth of cut for ductile-to-brittle transition, defined as the depth of the cut at the location of the first observed crack produced during

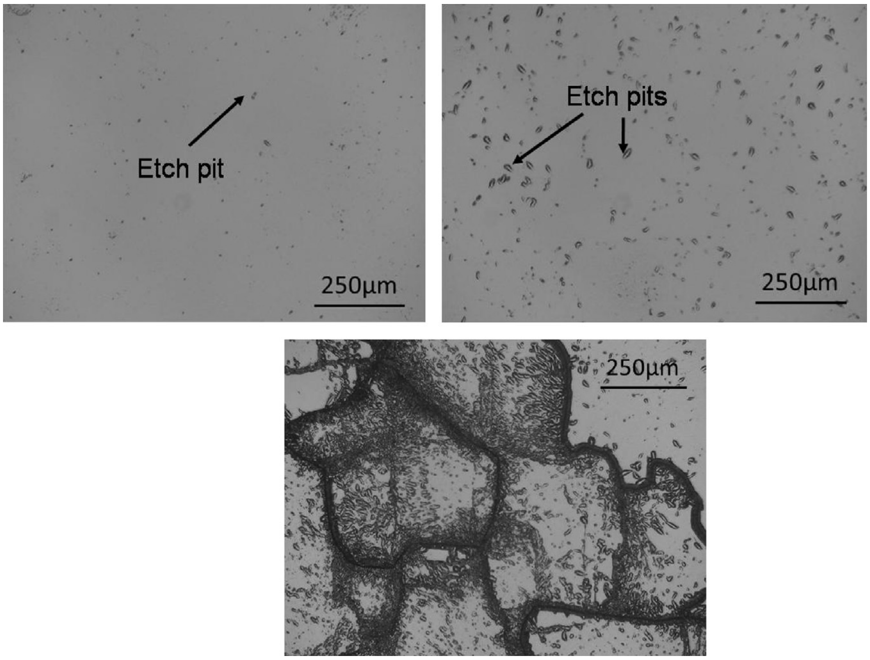

Fig. 1. Regions of varying dislocation etch pit density: low (Region I, top left), medium (Region II, top right), and high (Region III, bottom).