Materials Science in Semiconductor Processing 86 (2018) 23–35

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

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

Experimental study of rectangular groove texture in the surface of photovoltaic silicon with diamond coated micro-milling tools

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ARTICLE INFO

Keywords:
Single crystal silicon
Micro-end milling
Diamond coated tool
Reflectance

ABSTRACT

Microstructure in the surface of photovoltaic silicon can decrease the reflectance of light and improve absorption efficiency of silicon solar cell, and mechanical texturization is a kind of clean method to fabricate light trap microstructure in the surface of silicon. This paper is an experimental study to verify reflectance simulation of rectangular groove texture in the surface of photovoltaic silicon. In this paper, two types of micro-end diamond coated cemented carbide tools in different diameters were used to carry out mechanical texturization in single crystal silicon along < 111 > and < 100 > crystal orientation. Firstly, formulas aiming to achieve ductile mode milling are derived and offering guidelines for subsequent parameters set of rectangular light trap machining, and then cutting parameters such as axial depth of cut, feed rate and uncut width (width of wall between adjacent rectangular grooves) were studied for diamond different coated tools. The finish and integrity of structures obtained by machining along < 111 > and < 100 > crystal orientations were compared and analyzed, and machining along < 100 > crystal orientation showed a better surface finish and integrity of light trap than along < 111 > under the same conditions. Finally, the appearance of worn tools were observed and the reflectance of fabricated light trap microstructure was analyzed, and a satisfying reflectance below 15% for 0.4–1.1 μm wavelength lights can be achieved in the texture obtained when the principle angle of light incidence > 20°.

1. Introduction

The performance of silicon solar cells is determined by its photoelectric characteristics. Since the deterioration of performance originates in two issues, optical losses in reflected light arising from the texture and electricity losses in solar cell, preparing light trapping texture has been a common way to promote absorption efficiency of solar cells. To form a low reflectance texture in the surface of silicon solar cells, various feasible alternatives has been developed and evaluated experimentally.

Alkaline solution such as potassium hydroxide (KOH), sodium hydroxide and sodium hypochlorite aqueous solutions (NaClO) combined with isopropanol have been widely used to texture monocrystalline silicon cells. Based on the anisotropy of monocrystalline silicon, a homogeneous pyramid texture with top angle appropriately 70° is inherent due to different corrosion speeds along different crystal orientations [1], which limits the study of low reflectance in monocrystalline silicon. Polycrystalline silicon is developing as an alternative of monocrystalline silicon, however, light trap texture in the surface of polycrystalline silicon can't be prepared by alkaline solutions due to its isotropy, besides, the absorption efficiency of polycrystalline silicon solar cells is not comparable to monocrystalline silicon under the same conditions. Currently, MAEE(Metal-Assisted Electro-less Etching) method is utilized to form arbitrarily distributed SiNWs (Si Nanowires) in the surface of polycrystalline silicon, with dimension ranging from tens of microns to hundreds microns, which appear to completely absorb lights of all wavelengths in wide range of incidence. However, a high surface-volume ratio of SiNW arrays could initiate higher surface recombination velocity, which decays the PCE (Power Conversion Efficiency) of silicon solar cells. Mews et al. used HF(50%), H_2O_2 (30%) solution and water with ratio 1:5:10 respectively,catalyzed by Au, prepared a black-silicon structure with a reflectance appropriately 5% and PCE about 17.2%, and proved the black-silicon is the reason the lifetime of current carriers deteriorates [2].

On the other hand, the need to prepare miniature components with complicated structures and high accuracy with features or dimensions ranging from several microns to several millimeters has driven the researches on micro manufacture process [3,4], especially for silicon, which play a significant role in necessary area of applications such as MEMS and optoelectronics as semiconductor material. However, those

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https://doi.org/10.1016/j.mssp.2018.06.018
Received 30 March 2018; Received in revised form 14 June 2018; Accepted 15 June 2018
Available online 22 June 2018
1369-8001/

Table 1
Silicon's parameters of different fracture plane from literatures.

Fracture planes	{100}	{110}	{111}
Fracture toughness(Mpa $m^{1/2}$) [12]	0.89	0.73	0.68
Hardness(GPa) [18]	10	–	12
Young's modulus(GPa) [19]	130	169	188

traditional approaches of fabrication of semiconductor components such as chemical etching and lithography are not economic for HMLV (High Mix Low Volume) production, due to high cost for prototyping, as well as limitations in the matter of quality of surface finish, achievable dimensions and maximum achievable thickness. Lee et al. studied femtosecond laser milling of silicon wafers, which could also form black-silicon texture in silicon surface, while the power consumed in texture preparation process is too much on a large production scale [5]. As a kind of new and clean method compared to chemical txturization, Huo et al. claimed that mechanical texturization is emerging as a potential mask-less alternative able to achieve new type of 3D complicate shape micro-components with high precision and satisfactory surface finish [6]. Despite that micro-milling using high hardness tools e.g. CVD diamond end mills shows potential in micro machining of ductile materials such as some metals and polymers, generation of surface and subsurface fractures remain a challenge in micro-milling of brittle materials e.g. silicon, many theoretical and experimental researches have been conducted in this field. Presently, suitable machining conditions with a low feed rate and depth of cut have successfully achieved partial ductile or ductile mode machining of silicon. Fang et al. claimed that by decreasing uncut chip thickness or/and tool rake angle, a necessary hydrostatic stress would occur, which would enable plastic deformation in the cutting zone [7], micro-milling is a feasible method to break through the limitations of crystal orientation(e.g. in alkaline etching) though the ductile machining shows crystallographic orientation and behavior of different cutting tools. A good surface integrity is believed to ensure longer operational lifetime and better strength of element of MEMS components, Yang et al. carried out an experiment study to verify the reflectance calculated by a mathematical algorithm [8], found that some cracks or defects distribution in the surface of silicon are advantageous for anti-reflectance effect when integrity of shape of pyramids is ensured, and ensuring integrity of low reflectance structure is more important.

The experiment in this paper is a verification of reflectance of rectangular groove texture in the surface of photovoltaic silicon proposed by our previous work, two types of diamond coated micro-end milling tools with different diameters are used. First, ductile mode machining theory of brittle materials was reviewed and formulas enable to achieve ductile mode micro-milling of silicon were derived to guide the subsequent experiment, then the suitable uncut width, axial depth of cut and feed rate are studied in different crystal orientations of silicon with two types of tools, found that multi-pass milling in the same groove is comparably not an effective way to achieve the correspondent low reflectance structure proposed in our previous simulation work, while a satisfying reflectance below 15% for 0.4–1.1 μm wavelength lights can be achieved in the texture obtained when the principle angle of light incidence > 20°.

2. Ductile micro-milling theory of silicon

Though the feasibility of machining brittle materials e.g. silicon in ductile mode has been proved in single-point diamond turning (SPDT)

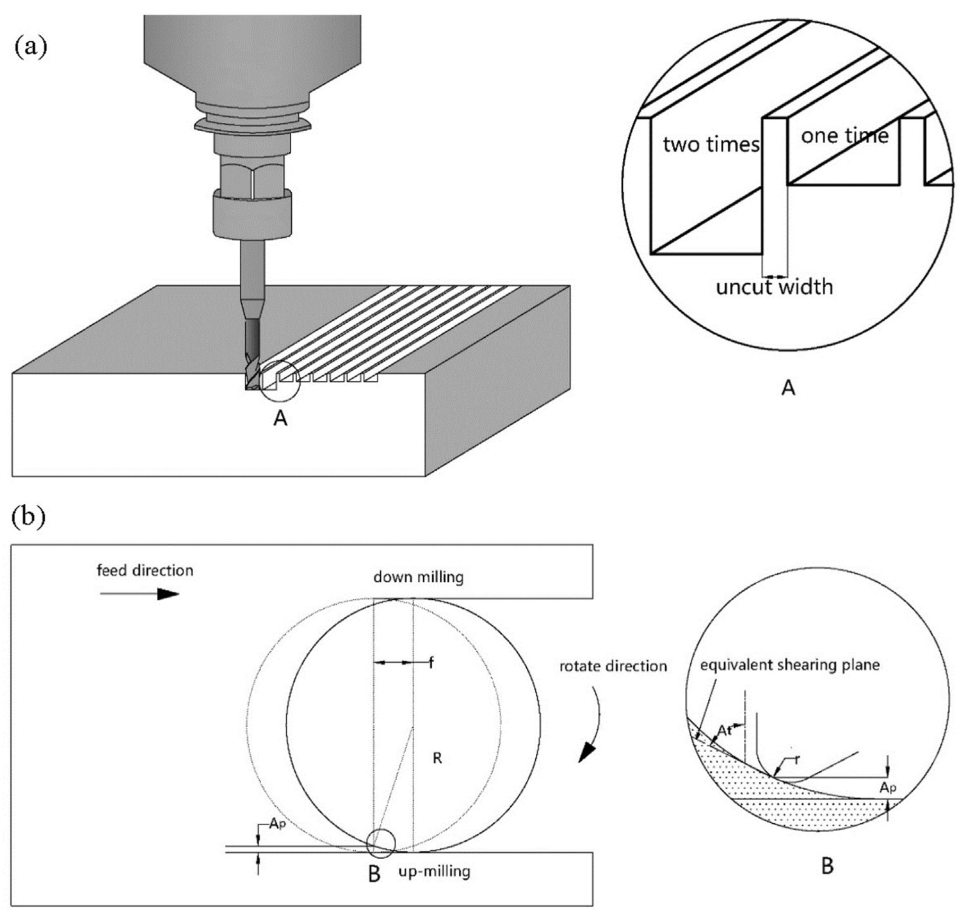

Fig. 1. (a)Micro-milling model and (b) schematic of geometrical modal of micro-milling.