Solar Energy 161 (2018) 109–124

Contents lists available at ScienceDirect

Solar Energy

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

A comprehensive study on slicing processes optimization of silicon ingot for photovoltaic applications

Savas Ozturk[a,b,*], Levent Aydin[c], Erdal Celik[d]

[a] Faculty of Engineering and Architecture, Department of Material Science and Engineering, Izmir Katip Celebi University, 35620 Izmir, Turkey
[b] The Graduate School of Natural and Applied Sciences, Dokuz Eylul University, 35370 Izmir, Turkey
[c] Faculty of Engineering and Architecture, Department of Mechanical Engineering, Izmir Katip Celebi University, 35620 Izmir, Turkey
[d] Faculty of Engineering, Department of Metallurgical and Materials Engineering, Dokuz Eylul University, 35370 Izmir, Turkey

ARTICLE INFO

Keywords:
Silicon wafer
Cutting parameters
Regression models
Minimize the surface roughness

ABSTRACT

Systematic cutting process design and optimization problems are studied for surface roughness minimization by stochastic algorithms. As the experimental background of the study, n-type single crystalline silicon (Si) ingot are cut into Si wafer with a thickness of 375 µm using a wire saw machine. In order to optimize the cutting parameters successfully, a two-step study has been organized as (i) a detailed study on multiple nonlinear regression analysis of the process parameters for predicting the feed rate and wire speed effects, (ii) design and optimization steps. Regression models include linear, quadratic, trigonometric, logarithmic and their rational forms for the same surface roughness problem. In design and optimization section, four distinct stochastic optimization algorithms (Differential Evaluation, Nelder-Mead, Random Search and Simulated Annealing) have been performed systematically to avoid inherent scattering of the stochastic processes. To investigate the advantages and disadvantages of the introduced mathematical processes for the similar cutting process problems, a review list are also given for the optimization on volumetric metal removal rate (VMRR), wear ratio (WR), material removal rate (MRR) and surface roughness (SR) by distinguishing the modeling methodology, model types, and optimization algorithms. It is also shown that different rational regression models can be utilized with the collaboration of stochastic optimization methods successfully to minimize the surface roughness of Si wafers.

1. Introduction

Approximately 90% of solar panels used in the world are produced using crystalline silicon (Si) (Pei et al., 2003). However, the high-cost of the silicon material is a major obstacle for solar panel applications. Based on the sawing technology, the most important strategy for solar panels is to reduce the production cost and the time of Si wafering. Additionally, the known fact "cutting process represents 30% of total wafer production cost" is taken into account: (Yu et al., 2012).

There are two main types of equipment utilized in cutting of silicon ingots, namely conventional inner diameter (ID) saws and wire saws. The wire saws have some advantageous compared to ID saws, because of that they contain higher cutting diameter, higher production capability, low surface damage and low kerf loss (Zhu and Kao, 2005; Dongre et al., 2012). The wire saw is one of the abrasive machining processes commonly used to cut of hard and brittle materials. Since the 1990s, wire saws have been used to produce thin disk shape wafers from Si ingots and nowadays, they are also widely used in Si wafering process (Bhagavat and Kao, 2006; Chung and Nhat, 2014; Gao et al., 2016). In commercial multiple Si wafering processes, slurry-sawn method is not preferred to avoid three-body abrasion of cutting webs, which include the wire, SiC grit and silicon (Kumar et al., 2016a). However, it should be noted that the diamond wire saws have the advantages in terms of higher feed rate, low surface roughness and clear operating environment over the slurry wire saw in Si wafering (Yu et al., 2012; Bidiville et al., 2009).

In the literature, the researches on the cutting process of Si using wire saws are growing rapidly. The recent studies (Yu et al., 2012; Chung and Nhat, 2014; Gao et al., 2016; Kumar et al., 2016a; Sopori et al., 2013; Anspach et al., 2014; Wu et al., 2014, 2017; Bidiville et al., 2015; Dongre et al., 2015; Mai et al., 2015; Würzner et al., 2015; Choi et al., 2016; Yao et al., 2016; Zhang et al., 2017) on Si wafering including ingot types, experimental equipment, variables, and targets are listed in Table 1. It can be concluded from the studies that the main purpose of wafer production is to achieve low surface roughness value. It is also seen that experimental process variables $\boldsymbol{t}$ wire speed and $\boldsymbol{k}$ feed rate can be distinguished from the others.

It should be noted that, unlike the studies in the literature given

* Corresponding author at: Faculty of Engineering and Architecture, Department of Material Science and Engineering, Izmir Katip Celebi University, 35620 Izmir, Turkey.
E-mail addresses: ozturkksavas@gmail.com (S. Ozturk), leventaydinn@gmail.com (L. Aydin), erdal.celik@deu.edu.tr (E. Celik).

https://doi.org/10.1016/j.solener.2017.12.040
Received 29 April 2017; Received in revised form 16 December 2017; Accepted 20 December 2017
0038-092X/

Table 1
Recent studies on Si wafering.

Study	Ingot Type	Exp. Equipment	Process Variable	Experimental Target
Gao et al. (2016)	mc-Si	MWSS	Wire speed, feed speed	Wafer surface roughness (SR), subsurface micro-crack damage and depth, total thickness variation (TTV) and warp
Kumar et al. (2016a)	mc-Si	MDWS	New and used wire sections	The effect of wire wear on the surface morphology, surface roughness, subsurface damage of Si wafers
Yao et al. (2016)	pc-Si	DWS	Wire speed	Comparison of cutting performance of single and double layer UV-curing resin diamond wire saw with surface roughness and surface damage analysis of Si wafer
Wu et al. (2017)	pc-Si	DWS	Feeding force, wire speed	Comparison between experimental and finite element modeling results of the deformation for crack generation in silicon with maximum cutting depth
Zhang et al. (2017)	Optical glass and Si	DWS	Magnetic field intensity	Investigation of the magnetic field intensity effect and distribution on the wire sawing performance
Choi et al. (2016)	mc-Si	MWSS	Constant variable	Investigation of Cu contamination mechanism and its solution of cutting Si wafer
Bidiville et al. (2015)	mc-Si	MWSS	Abrasive volume fraction, wire tension and feed rate	Wafer bending strength, the surface roughness and the wafer thickness, a microscopic model of the sawing process is also developed
Dongre et al. (2015)	Not specified	SWS	Wire diameter, work piece height, duty cycle and current	Kerf loss minimization
Würzner et al. (2015)	mc-Si	DWS	Wire speed	Analyzing the impact of different wire velocities on the surface damage of mc-Si wafers. Surface roughness measurement and micro crack depths analysis
Mai et al. (2015)	pc-Si	DWS	Wire speed, discharge current, discharge duration, feed rate, pulse-off time	Increasing the load capacity of discharge current under high wire tension condition using by a new wire shape, called flat wire
Chung and Nhat (2014)	Not specified	DWS	Wire speed, feed rate, size and distribution of diamond grits	Surface roughness minimization
Wu et al. (2014)	mc-Si	MWSS	Forward and backward distance variations of cutting wire	Analyzing the effects of reciprocating wire sawing on the surface quality and fracture strength of Si wafers
Anspach et al. (2014)	mc-Si	DWS	Si block length	Single wire sawing experiments using structured wire
Sopori et al. (2013)	Amorphous Si	DWS and MWSS	–	Surface roughness and surface damage
Yu et al. (2012)	P-type mc Si	DWS and MWSS	–	Surface roughness, surface damage and the fracture strengths

MWSS: Multi-Wire Slurry Saw, MDWS: Multi Diamond Wire Saw, DWS: Diamond Wire Saw, SWS: Slurry Wire Saw.