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Endless diamond wire saw for monocrystalline silicon cutting

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Abstract

The multi-wire sawing of silicon using diamond coated wire is an important process in the semiconductor and photovoltaic industry. The cut is performed in the industry by pushing the silicon ingot against a wire web that moves in a pilgrim-mode (forwards and backwards). As the cut direction and cutting speed of the wire change several times during the operation, it is not possible to perform a proper investigation of the cutting process. In order to study the multi-wire sawing of monocrystalline silicon (mono-Si), this work has applied a new experimental setup for the purpose. Based on literature research and industry know-how, the main features necessary for the new wafering test rig were defined: i) use of a short wire looped segment; ii) cut with controllable constant wire speed; iii) permit to track specific diamond grains after each cut for wear analysis. Based on that, the conceptual design resulted in a resistance butt-welding device, and a wire saw test rig that uses an endless diamond wire to perform the cut. Although some studies in the literature have applied the endless-wire concept, none of them used wires that are actually employed in the wafering industry. This paper describes the welding and the wire saw concepts with their respective advantages and disadvantages. Outputs of the resistance butt-welding machine are presented, as well as the first results for wear progression of specific diamond grains after sawing monocrystalline. Next planned research steps of the project are described in the end.

Diamond wire, silicon, wafering, endless wire saw, diamond wear

1. Introduction

Silicon wafer is used as main substrate to build the vast majority of semiconductor devices for photovoltaic solar modules. One of the technologies used to cut silicon ingots into wafers is the multi-wire sawing with diamond coated wires.

Although the wire sawing technology has been used in industry for decades, there is a lack of scientific knowledge, and the optimization of the process has been carried out largely based on experience and trial and error [1-2]. The purpose of this work is to establish a substantial experimental methodology for investigations on the diamond wire sawing of mono-Si.

2. Experimental setup

Wafering machines work based on the so-called pilgrim-mode. The wire is set in motion in one direction for several hundred meters, stopped, and then set in motion in the opposite direction for a shorter length. As the cut direction and cutting speed of the wire change during the process (around 100 times in an usual wafering process), the resulting sawn surface that has been cut with constant speed is distributed in very thin lines (1 mm wide in this example). Hence, correlating the non-constant wire speed to the generated wafer surface can be not reliable and difficult to be performed. Moreover, as thousands meters of wire are used in one single cut (around 5 km [3]), investigations on tool wear are done by sampling. Based on that, it was defined that the new wafering experimental setup would work with constant cutting speed. For that, an endless wire saw was designed and built.

The advantage concerning the endless wire setup is the fact that the cutting speed (V_c) and feed rate (f) can be kept constant during the cut. With the looped wire it is even possible to follow the same wire section to analyse the wear progression of a group of abrasives after every cut, which in the case of a spool-to-spool setup would be practically impossible.

Several works about endless wire sawing of silicon have been found in the literature (see Table 1). However, none of them contemplate the machining of mono-Si using endless wire saw with $V_c > 2\ m/s$ and wire diameter $\emptyset < 500\ \mu m$. Moreover, in all reported cases wires were firstly welded in looped-shape without any abrasives, and then coated with diamond grains in a self-made way.

Table 1. List of wire saw test rigs found in literature.

Author	Material Cut	Ø [μm]	V_c [m/s]
Hardin et al. [4]	Wood	300	≤ 20
Meng et al. [5-7]	Granite, Al_2O_3/TiC and mono-Si	500	≤ 20
Gao et al. [8-9]	Granite	800	≤ 20
Subbiah et al. [10]	Mono-Si	140	≈ 2

In order to perform cuts using the endless wire saw test rig, an additional goal has been defined: development of a device to weld abrasive wires with Ø < 500 □□ in looped-shape using actual diamond-coated wires from the industry.

2.1 Resistance butt-welding device

The device was designed and manufactured at the Precision Engineering Laboratory – LMP/UFSC. To perform the welding, wire ends are aligned and fixed by 2 clamps. Electric current flows through the wire ends interface generating heat by Joule effect. The heated material is upset ("forged") by an upsetting force, creating a joint. The alignment obtained using the butt-welding device can be seen in Figure 1 a).

As the wire core is made of ASTM A 228, once the weld is complete, a tempering procedure is done by application of electrical current to the joint so that the resistance heating tempers the material for a less fragile joint. After tempering, welded protruded material is post-processed so that the joint diameter becomes smaller than the rest of the wire. The tension applied to the wire in industrial wafering machines is usually about 35 N, and wires with Ø = 350 µm welded by the developed device supported at least 105 N.

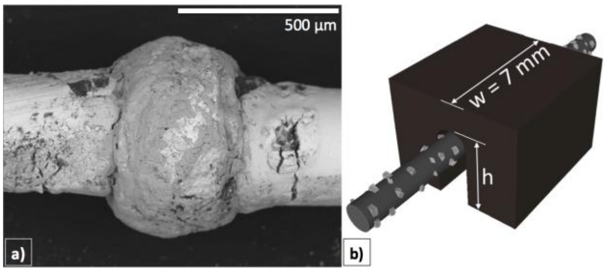

Figure 1. a) Welded joint of looped diamond wire (Ø = 350 µm, electroplated). b) Dimensions of the workpiece cut in the wear analysis.

2.2 Endless wire saw experimental setup

The wire saw was built on an aerostatic bearing test rig developed at LMP/UFSC, so that vibration transmission through moving parts is strongly reduced. As shown in Figure 2, the looped wire (1) is winded around two rotating blockheads (a and a'-axis).

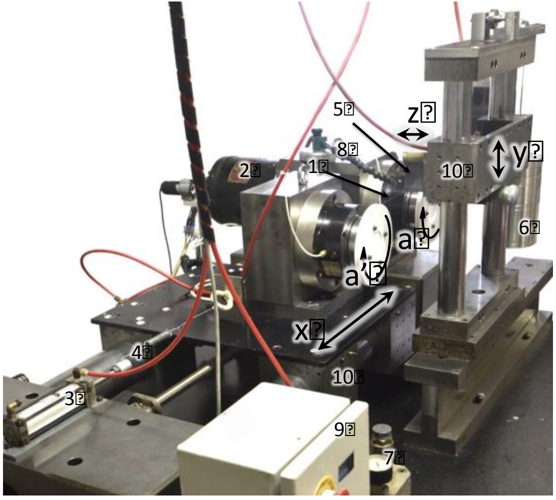

Figure 2. Endless wire saw experimental setup.

The right blockhead is driven by a controlled electric motor (2). The wire is installed by positioning the left blockhead table closer to the right blockhead (x-axis). Tension of the wire is set by a pressure-regulated pneumatic cylinder (3) and controlled by a spring (4) with known elasticity. The silicon workpiece (5) is pushed against the wire with constant normal force controlled by the counter-weight (6), which defines the feed movement (y-axis). The incremental infeed of workpiece is shown as z-axis. Cutting fluid is provided by a Terstegen® minimum quantity cutting fluid system (7) through a nozzle (8). Wire speed is controlled by the control panel (9) and can reach up to 25 m/s.

3. Experimental results

Initial tests have been successfully performed using electroplated diamond wires with Ø = 200 µm, 310 µm and 350 µm. The idea of finding the same diamond grains after each cut was achieved, as it is shown in Figure 3. The same wire section was found after h = 100 mm and h = 250 mm of sawn material (see Figure 1 b), and the wear of specific diamond grains can be analised in detail for tool life investigation.

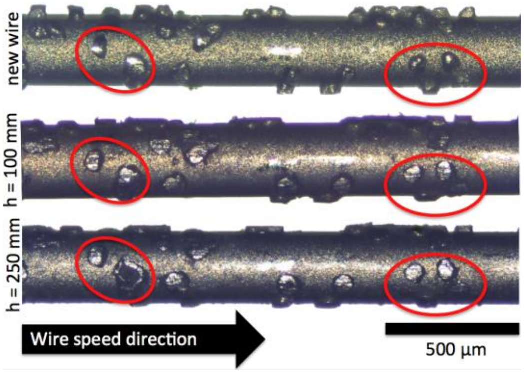

Figure 3. Wear progression of a diamond wire section (Ø = 350 µm, material: mono-Si, $V_c = 12{,}5\ m/s$, $F_N \cong 1\ N$, wire length = 1 m).

4. Summary and outlook

This work applied a new experimental setup to study the sawing of mono-Si. The welded joints of the endless wire showed good alignment and sufficient tensile strength. The proposed idea of tracking same diamond grains for wear analysis was achieved with the experimental setup. The next steps will be to perform cutting experiments using different cutting speeds and feed rates for the wear investigation of diamond coated wires, surface integrity of mono-Si worpieces and process cutting forces.

5. Acknowledgements

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