MICROSCOPIC NEAR INFRARED (NIR) IMAGING FOR INVESTIGATION OF THE SAW-CHANNEL SURFACE DURING WIRE-SAWING OF SILICON

Lars Johnsen, Kay Gastinger
SINTEF ICT Optical measurement systems and data analysis
N-7465 Trondheim, Norway

ABSTRACT: A setup for high resolution video recording of the chipping process during slurry based sawing of silicon is introduced. The setup allows in situ imaging of the chipping process in silicon (Si) by operating in the near infrared region where Si is transparent. Extended resolution is achieved through the use of a silicon lens as sample for the sawing. By sawing in the lens perfect immersion optics are implemented resulting in an imaging system with very high numerical aperture. The sample is illuminated by a halogen lamp through a beam splitter cube. An InGaAs camera with VGA resolution is used for video capturing. The paper presents a work in progress.

Results from experiments with an x,y,z-controlled single indenter as well as indents from silicon carbide (SiC) particles trapped between the saw wire and the Si surface are presented. Image sequences of the dynamic development of the indent process and the consecutive chipping are presented.

Keywords: Experimental Methods, Silicon, Silicon Carbide, Slurry, Sawing, Chipping, In Situ, High Resolution, Video

1 INTRODUCTION

The solar cell industry is today serving a high volume market. Even if there are large scale thin film approaches for solar cell production the PV market is still dominated by Silicon wafer based solar cells. This requires an industrial large scale production of silicon wafers. Sawing in multi wire saws is the preferred technology for cutting of bulk silicon into wafers.

The material removal process is today not fully understood. One theory is described in [1] and claims that the SiC particles creates indents by a plastic deformation. The relaxation of this deformation creates micro cracks that propagate and result in clewing of small Si chips.

In situ observation of the abrasive process is developed to better understand the details of the cutting process. In an industrial wire saw the wire speed is in the range of 10^7μm/s and at the same time the material removal process creates feature sizes well below 1 μm leading to big challenges for detailed investigations.

This paper describes the possibility to observe in situ and with very high spatial resolution the abrasive process related to sawing. The challenge is that for high resolution imaging short wavelengths and high numerical aperture (NA) optics are necessary. As silicon has high absorption for short wavelengths it is necessary to work at longer wavelengths in the near infra read (NIR) range of the spectrum.

Imaging at high resolution can give good quantitative results for in-plane investigations of the chipping process but information on the 3D shape of the chipping is difficult. An approach for 3D investigations of the chipping process is described in [2]. NIR low coherence interferometry is described as a method for 3D shape and deformation measurements of chipping in the sawing process.

2 IMAGING THE ABRASIVE PROCESS

Imaging the dynamics of the abrasive process can reveal important details and can lead to a better understanding of the process. Feature sizes well below 1μm are produced as shown in figure 1.

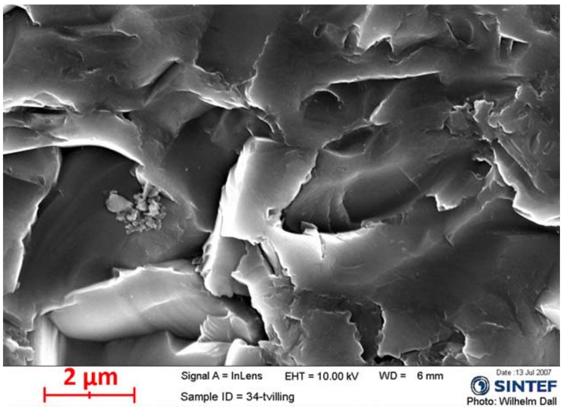

Figure 1: SEM picture of an as sawn surface revealing small structures from the abrasive process.

The challenges of microscopic imaging of processes inside a silicon sample are:

- Strong absorption of wavelengths shorter than the band gap wavelength.
- The refractive index (n) of silicon is high, $n_{si}=3.5$ @ $1.1\mu m < \lambda < 2\mu m$ band.
- The rough surface of the block acts as a very efficient diffuser, due to the high refractive index of silicon.

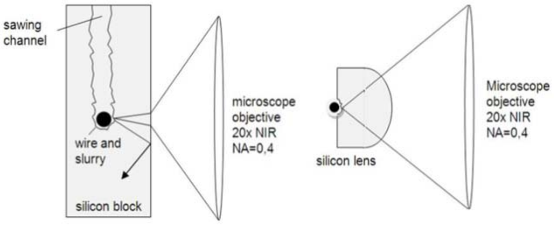

Figure 2: Left: Illustration of refraction of the marginal rays through a flat silicon surface (the effect is exaggerated for illustration). Right: NA transformation through the use of a Si lens as sample.

3 SUB-WAVELENGTH RESOLUTION

Achieving high resolution imaging requires the use of short wavelength for the illumination and high numerical aperture in the optics. Working on Si samples the wavelength region for illumination is limited to λ > 1.24µmn. Using a sample with flat surface limits the availble NA to 1.0.

Different criteria are used to describe the resolution limit for optics. The Rayleigh criterion is often used. It relates to the Airy disk of a circular aperture. Objects are only resolved when their airy disks are separated so that the maximum of the second airy disk falls on the minimum of the first airy disk pattern. When *x* is the separation of the objects, *f* is the focal length of the lens, *D* is the diameter of the aperture and *λ* is the wavelength the Rayleigh criterion is given by equation (1).

$$(1)\quad x = 1.22\frac{f}{D}\lambda$$

The numerical aperture NA is given by equation (2) where the approximation is valid within 10% for NA<0.5.

$$(2)\quad NA = \sin(\tan^{-1}\frac{D}{2f}) \approx \frac{D}{2f}$$

Substituting *D* in (1) the resolution criterion is given by equation (3) showing that sub wavelength resolution can be achieved with high NA optics.

$$(3)\quad x \approx 0{,}601\frac{\lambda}{NA}$$

In the above equations operation in air (refractive index *n=1*) is assumed. Operating in a different medium the effect of the refractive index must be taken into account. The numerical aperture inside a medium with refractive index n_{med} is given by equation (4).

$$(4)\quad NA_{med} = n_{med}\sin\left(\tan^{-1}\frac{D}{2f}\right) = n_{med}\,NA$$

Silicon has a high refractive index and when observing inside a sample with flat surface refraction will occur. This refraction will reduce the diameter of the optical aperture as shown in the left sketch in figure 2. Achieving sub wavelength resolution with this configuration requires optics with very high numerical aperture, NA>0.6. At high numerical apertures the refraction at the flat surface will introduce aberrations for the rays close to the marginal rays. This aberration reduces the resolution and limits the useful range of NA.

The use of immersion optics with liquids is a well known method for reaching sub wavelength resolution. With immersion optics the refractive index differences are reduced in the optical path from the inspected area (the sample) to the first lens element in the optics. Ideally the index of refraction should be matched.

Silicon has a very high refractive index, n_{si}=3.5 (@ 1.1µm< λ <2µm). No liquids exist with this high refractive index. Index matching with lower index liquids will give insufficient results.

As an alternative to liquid immersion we substitute the immersion liquid with solid silicon obtaining “solid state” immersion (right sketch in figure 2). We use a tailor made lens of single crystal silicon as sample. Thus a perfect index match is achieved in the optical path from the inspected area to the first lens element in the optics.

According to equation (4) this increases the numerical aperture with a factor of the refractive index of silicon, n_{Si}=3.5. From equation (3) the same improvement of the resolution is predicted. Using a microscope objective with NA=0.4 a theoretical resolution of x≈0.56µm @1300nm can be obtained. In practice it is difficult to reach this number due to aberrations.

Finally, the surface of the silicon needs to be perfectly polished. Considering the high refractive index of silicon already small surface variations would reduce the spatial resolution.

4 EXPERIMENTAL

The optical setup is designed to obtain maximum spatial resolution, see figure 3. The imaging system consists of a Mitutoyo 20x NIR microscopic objective (NA=0,4) and a Xenics Xeva-1.7-640 InGaAs camera. The light source is coupled in through a beam splitter between camera and objective realizing a Köhler illumination. As test object a tailor made, plano convex Si lens with centre thickness equal to the radius of curvature (r= 8mm) and a diameter of 12.5mm has been manufactured. The optical system obtains thus a 66x magnification. The object plane of the imaging system is positioned directly on the plane back surface of the lens.

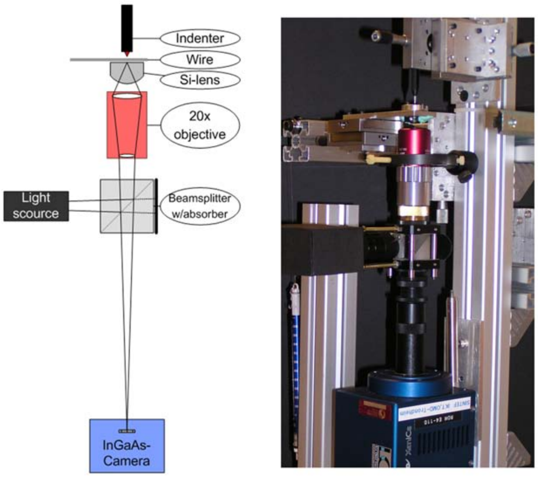

Figure 3: Experimental setup, left: sketch, right: photo

On top of the lens backside a simple, single wire sawing setup was prepared. A wire is stretched with a spring weight along the centre of the lens. A motor drives an eccentric metal rolling guide forcing the wire to a stroke of about 1mm back and forth. In Addition a indentation tool can be mounted at the centre of the lens using a x,y,z- translation stage.

The indentation events can thus be observed in the centre of the plane surface of the Si lens. Using this configuration all light beams reflected from the sawing area meet the convex Si surface almost perpendicular. The spatial resolution of the system can thus be increased significantly.

5 RESULTS

First results from experiments are presented. Further experiments and refining of the setup are planned.

The magnification of the setup has been verified using a crossed scale reticle (NT62-235 from Edmund Optics) with 0.1mm increments. The reticle was placed flat on the plan surface of the Si lens with backside illumination. From figure 4 a scale of 0.305µm/pixel was calculated giving a magnification of 65.6 for the system setup.

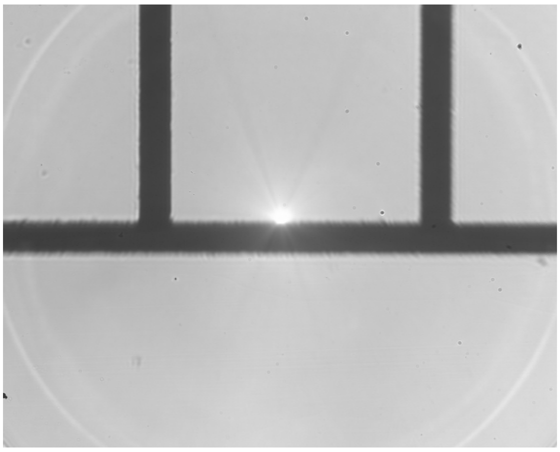

Figure 4. A scaled reticle (NT62-235 from Edmund Optics) with 100µm increments is placed on the flat surface of the Si lens. The image scale is 0.305µm/pixel giving a field of view of 195µmx156µm.

The setup produces clear images of SiC particles in the slury on the lense surface. An image of poly ethylen glycol with a small amount of F600 SiC on the lense surface can be seen in figure 5.

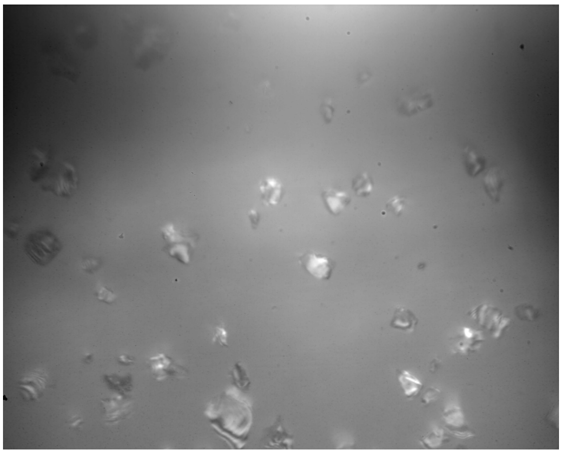

Figure 5: PEG with a small concentration of F600 SiC on the lens surface. Newton fringes from white light interference in the gap between the lens surface and the SiC particles can be seen at some particles. The field of view and scale is the same as in figure 4.

The position controlled indenter can introduce micro indents in the lens surface. With the introduced system in situ video images can be captured of the indent process as seen from inside of the silicon. A snapshoot series from an indent is shown in figure 5. The sequence starts before the first contact and shows the different steps through the indentation process. The indent increases and introduses mechanical stress. When the indentation force is reduced the mechanical stress is released by chipping.

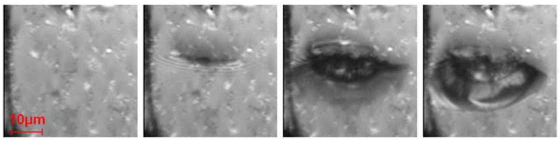

Figure 6: Dynamic development of single indent. From left side: No contact, starting indent, increasing indent, indent relaxed – chipping. Surface contamination by small debris from nearby indents can be seen in the image

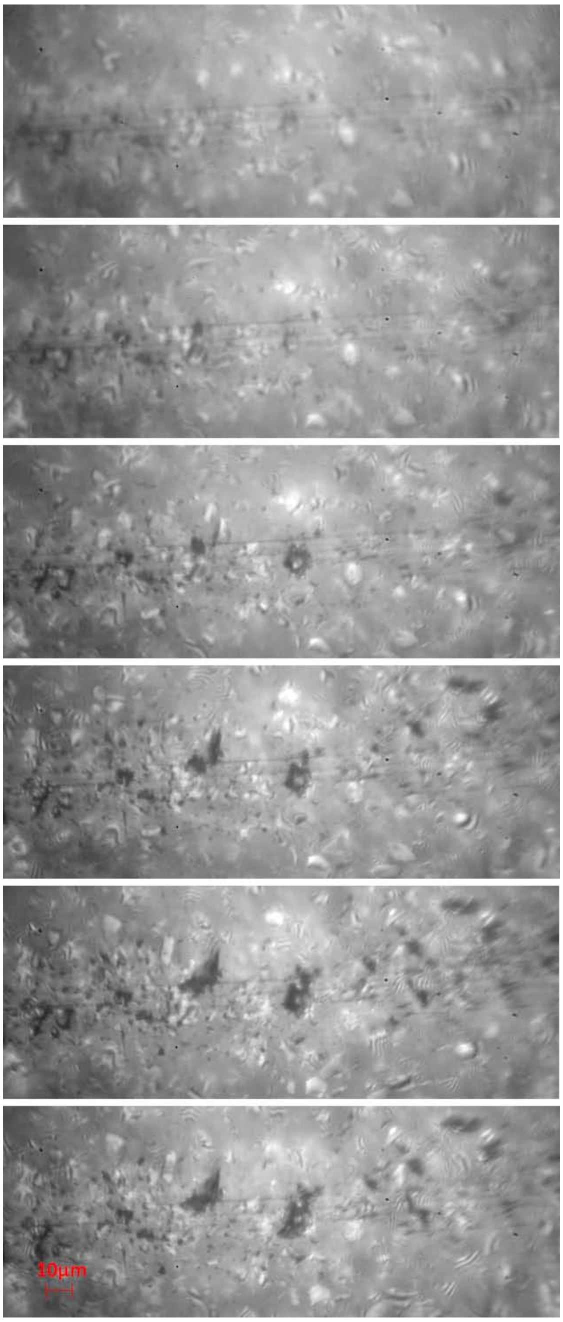

Figure 6: Video sequence showing development of indents from SiC particles trapped between the lens surface and the wire. Pressure is applied to the wire by a small roller pressed down on top of the wire and rolled across the image.

The second test is a static wire based indentation process. By introducing slurry in the lab sawing setup the indentation processes introduced in a wire/slurry configuration can be investigated.

SiC particles are trapped between the stretched wire and the lens surface . Pressure is applied to the wire by a small roller pressed down on top of the wire. The roller is rolled along the wire and SiC particles indent in the Si surface. A snapshot series from this static wire indenation process can be seen in figure 7.

6 CONCLUSIONS

A setup allowing in situ investigations of the abrasive processes in wire sawing has been built. The setup is characterized by:

- Imaging and illumination in the NIR wavelength region where silicon is transparent.
- High resolution imaging can be obtained in spite the long wavelengths used. This is achieved through the use of a silicon lens as sample realising perfect immersion optics with high numerical aperture.
- Video capturing allows in situ investigation of the dynamics of the indentation process.
- High resolution video capturing of the process dynamics is demonstrated for:
    - Single indent process with chipping.
    - Indent from SiC particles trapped between the wire and the Si surface.

7 FURTHER WORK

Further progress of the work is planned:

- Investigation of the real resolution obtained in the setup.
- Using the simple sawing setup for investigation of abrasion during sawing.
- Implementation of a standard geometry indenter with force sensor for controlled indents.
- increasing the frame rate of the setup to be able to investigate sawing close to the real conditions.

8 REFERENCES

[1] Möller, H.J., *Wafering of silicon crystals*. 2006, WILEY-VCH Verlag. p. 659-669.

[2] Gastinger, K. and Johnsen L. Near infrared low coherence speckle interferometry (NIR-LCSI) as a tool for the investigation of silicon in the solar cell production, Speckle 2010, Florianopolis, Brasil, SPIE proc. 2010 (in print)

9 ACKNOWLEDGEMENTS

The authors want to thank Karl Henrik Haugholt for the optical modelling using Zemax and Wilhelm Dall for the SEM measurement.

The work is partly financed by the Norwegian Research Council through the user-driven innovation project “TyWatt” in cooperation with REC Wafer, SiC Processing and Washington Mills as industrial partners.