Transflection, a new illumination technique for in line crack detection in crystalline silicon wafers

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ABSTRACT: Crack detection is mandatory for high yield production of crystalline silicon solar cells. Instrumentation for in-line crack detection is a part of today's standard production lines. However the commercial equipment available today has some serious weaknesses allowing some parts with cracks to pass the inspection. In this paper some of these weaknesses are described and a new illumination technique is presented to eliminate these weaknesses. The illumination technique introduced is known form other fields of optical metrology under the name of transflection or interactance. With transflection an area of wafer surface is illuminated, the light is coupled into the wafer and interacts with any defect in the light path and is emitted from the wafer surface at a different position. A crack will obstruct light and so create a clear signature in the emitted intensity. The technique suppresses the grain pattern from multi crystalline silicon wafers and also allows detection of cracks independent of crack orientation.

Keywords: Manufacturing and Processing, Fabrication, Defects, Silicon Solar Cell, Wafer, Inspection, In-line, Crack, Non visible cracks, NVC, Transflection.

1 INTRODUCTION

Today the photovoltaic solar energy market is dominated by Si-wafer-based solar cells. Bulk silicon is cut into wafers in multi wire saws. As silicon is a brittle material the thin wafers, typically 150-200µm thick, are very fragile. In the production process handling and other processes will introduce mechanical stress in the wafer. Small cracks present in the wafers acts as initiation centres for crack growth. When the wafer is exposed to mechanical stress the crack growth will often cause wafer breakage. It is therefore mandatory to remove cracked wafers from the production line is in high yield cSi solar cell manufacturing.

Crack detection instruments for in-line inspection are standard equipment in today’s wafer lines and are commercially available from a number of suppliers. Different crack detection methods are used. Optical based crack detection is dominating the market. The present industry standard method uses on back illumination of the wafer with Near Infrared (NIR) light. The transmission image is captured with a silicon CCD/CMOS camera. Image processing are used to identify cracks which normally appear as intensity drops in the captured image, figure 1.

2 CHALLENGES IN CRACK DETECTION

Automatic crack detection on crystalline silicon wafers, especially on mc-Si wafers, is a challenging task. Some of these challenges are:

- Detection of small cracks (< 1mm length)
- Image intensity variations due to varying crystal grain orientation and wafer thickness
- Non visible cracks (undetected large cracks), figure 2.
- Inspection speed matching the wafer line cycle time

Crack detection instrument suppliers are using different approaches to tackle the challenges of crack detection

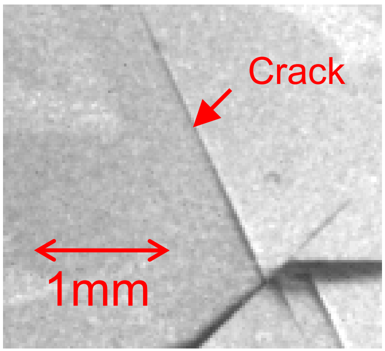

Figure 1: A transmission image of a crack using NIR back illumination. The image resolution is approximately 20µm/pixel (8000pixels/157mm). The image is captured with an InGaAs NIR camera using broadband illumination (1 < λ < 1.7µm).

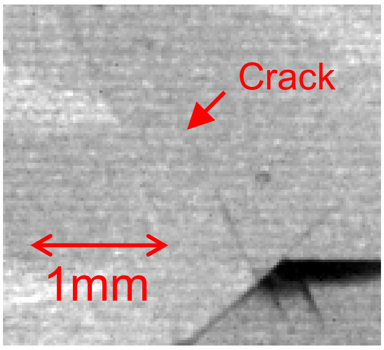

Figure 2: A transmission image of a cracked area using NIR back illumination. A large part of the crack (position indicated by the arrow) is invisible due to the geometry of the illumination system. The same area is shown in figure 1 displaying high crack visibility using different illumination geometry. The image resolution is approximately 20µm/pixel (8000pixels/157mm). The image is captured with an InGaAs NIR camera using broadband illumination (1 < λ < 1.7µm).

3 TRANSFLECTION

Transflection describes the optical phenomenon occurring when light entering a transparent or partly transparent object is scattered and exits from the object at a position different from the point of entrance. The light travels some distance inside the object before exiting through the surface as shown in figure 3. The light scattering can be caused by the object surface or the bulk material of the object.

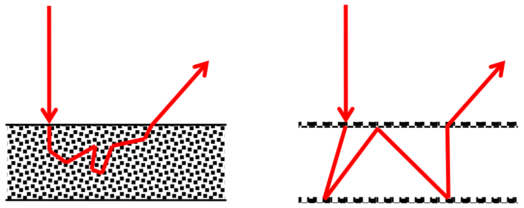

Figure 3: Transflection. Due to scattering light exits the object surface at a position different from the point of entrance. The light travels a distance inside the object before exiting.
Left: Transflection due to bulk scattering.
Right Transflection due to surface scattering.

4 THE TRANSFLECTION METHODE

The transflection method addresses some important challenges in automatic crack detection through an innovative illumination technique. The main features of the transflection method are:

- The wafer is illuminated through the wafer surface.
- Due to the rough surface light is scattered into the wafer plane and travels inside the wafer.
- Light leaks out through the rough surface-
- Light is reflected (blocked) by cracks in the wafer
- The imaged wafer area is separated from the illuminated area by some distance.

4.1 Crack detection with the transflection method

The principle of crack detection with the transflection method is shown in figure 4. The rough wafer surface is illuminated and light is scattered into the wafer. As the light travels inside the wafer the rough surface will cause light to leak out creating luminous surface. A crack in the wafer will cause reflection and block the light transport. Beyond the crack the light intensity inside the wafer will be considerably reduced and thus the surface luminance of the wafer will be strongly reduced.

If no crack is obstruction the light path inside the wafer the imaged area will have a high luminance. If a crack occurs between the illumination area and the imaged area the imaged area will have a low luminance. The crack will be casting a shadow creating a crack signature that is much larger than the crack, the crack signature is enlarged.

4.2 Illumination in the transflection method

Illumination is applied through the wafer surface. Due to the rough wafer surfaces light is scattered into the wafer plane and is transmitted inside the wafer. Because the light must travel some distance inside the wafer from the illumination area to the detection area it is important that the optical absorption in the wafer is low. The absorption in silicon is strong for wavelengths shorter than $\lambda=1,24\mu m$ due to the silicon band gap. Thus for silicon wafers the illumination wavelength must be chosen in the near infrared (NIR) region $\lambda>1,24\mu m$.

The transflection effect in silicon wafers having rough surfaces causes strong despeckling of laser illumination. An example of the inherent laser despeckling of the transflection method compared to the speckled image with laser back illumination (1450nm semiconductor laser) is shown in figure 7. Having inherent despeckling the transflection method allows the use of highly efficient and high intensity laser illumination without speckle noise in the images.

With high illumination intensity the integration time in image acquisition can be low allowing high camera line rates. Also using for example semiconductor lasers the illumination can be pulsed at high speed. Together with a high line rate camera this allows capture of images with different illumination geometries to be captured in a single pass.

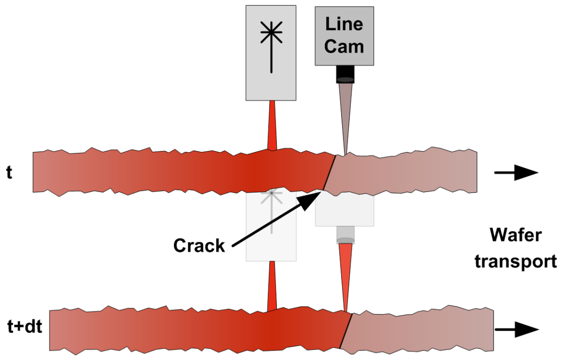

Figure 4: Crack detection with the transflection method using a line scan camera. Top: At the time t crack is occurring between the illumination area and the imaged area of the wafer. The light path is blocked by the crack and the imaged area has low luminance. Bottom: At time t+dt the conveyer movement has transported the crack out of the light path between the illuminated and imaged area and the imaged area has high luminance.

5 EXPERIMENTAL SETUP

A laboratory setup was built for transflection crack detection experiments. In the experiments a configuration with illumination and imaging from opposite sides of the wafer was chosen. A sketch showing the setup is shown in figure 5. The wafer is placed on an open sample holder controlled in the x-direction by a step motor controlled linear translation stage (Thorlabs NRT150). For illumination a NIR semiconductor laser is used (Roithner L145T600, 1450nm 600mW). Beam shaping optics is used to control the illuminated area and the illumination geometry. Different illumination geometries can be selected manually. For image capture an InGaAs, Xenics Xeva FPA-1,7-640 camera is used. This is an area camera and a line scan function is implemented by single line selection from the captured image. In the laboratory setup both the camera and the illumination optical axes is perpendicular to the wafer surface.

5.1 Test wafer with cracks

For the experiments artificially made cracks was produced in a mc-Si wafer. The cracks were created by impact with a metal tool. The impact energy was not measured but was varied in an attempt to create different sized cracks. The impacts resulted in x-shaped cracks typical of surface impact generated cracks, figure 6

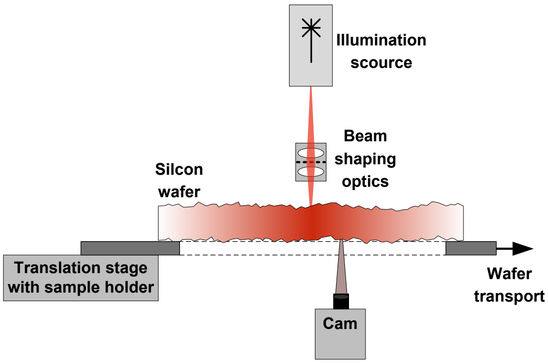

Figure 5: A sketch of the laboratory setup for the transflection crack detection experiments. The imaged area is separated from the illumination area by some distance. The beam shaping optics allows different illumination geometries to be applied and images captured while the wafer is stationary.

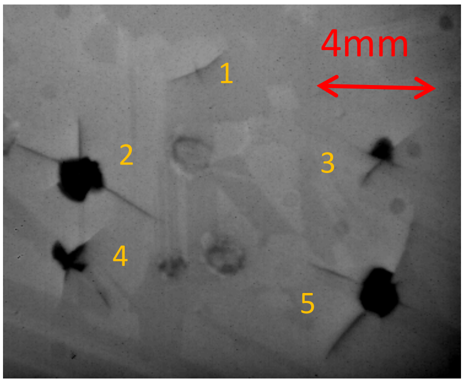

Figure 6: High resolution image of the artificially made cracks created for transflection experiments. The image is captured in back illuminated transmission mode. The image resolution is approximately 8700pixels/157mm. Some shadows from felt pen marks identifying crack positions can also be seen in the image.

6 RESULTS

Results obtained with the transflection setup shown in figure 5 are presented. The experiments are performed on mc-Si wafers with a thickness of approximately 180µm.

6.1 Image capture of cracks

The wafer area containing the artificially made cracks was investigated using the transflection method. In figure 8 images from three different illumination geometries are presented. The results show that different illumination geometries results in different crack signatures. The crack labeled "1" can barely be identified on figure 8 upper and lower images. In the figure 8 center image it can be more clearly identified.

6.2 Despeckling of laser illumination

The inherent laser despeckling property of the transflection method is investigated. Image are captured both with the transflection method and the standard back illuminated transmission mode method. The beam is shaped to a single point for the transflection experiment. For the back illuminated transmission mode experiment the laser beam is shaped for wide area illumination. The images are presented in figure 7. As can be seen from the images the speckle noise is strongly reduced with the transflection method.

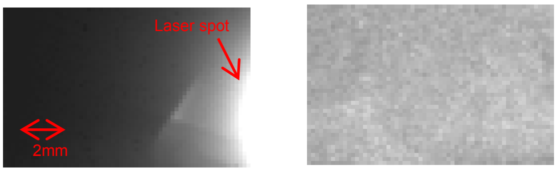

Figure 7: Left: Inherent laser despeckling of the transflection method demonstrated. Right: Speckles from back illumination with 1450nm laser. The two images are from different parts of the same wafer. Image resolution: 1000pixels/157mm.

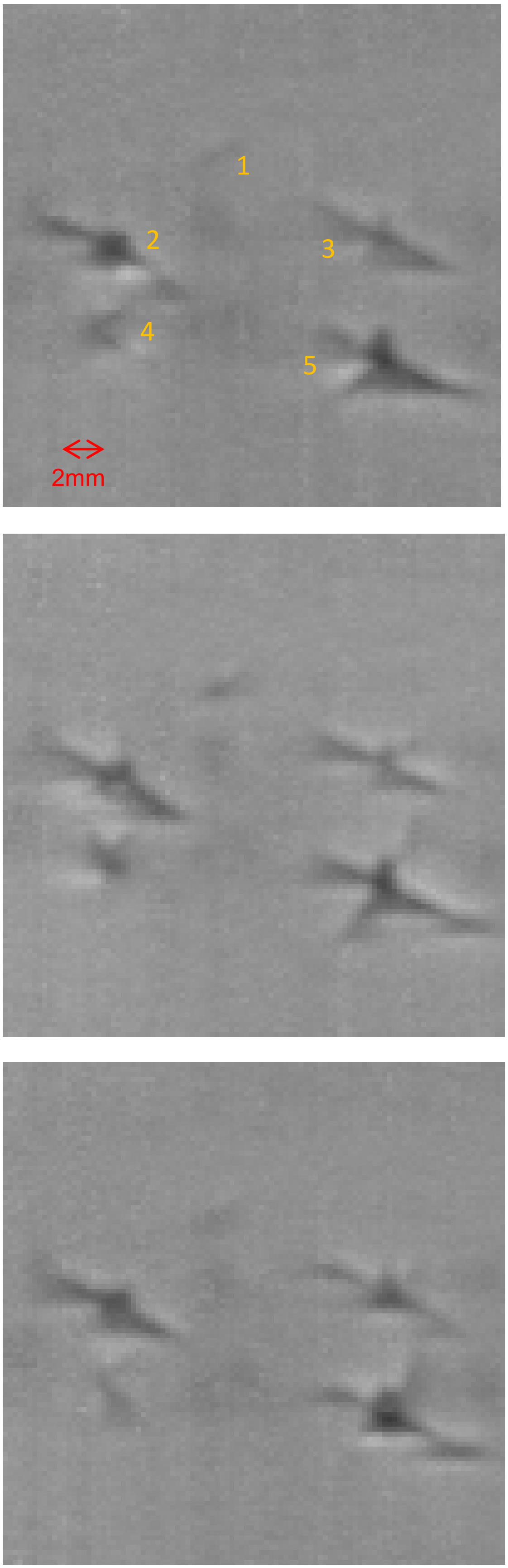

Figure 8: Imaging of cracks with the transflection method. Results for three different illumination geometries are presented in the Upper, center and lower image. Image resolution: 1000pixels/157mm

7 CONCLUSIONS

The transflection method is a promising illumination technique for crack detection. Several of the challenges in crack detection are addressed:

- Detection of small cracks. The cracks create shadows increasing the signature of small cracks.
- Invisible/hidden cracks can be revealed by applying different illumination geometries.
- Image intensity variations due to different crystal grain orientations in mc-Si wafers.
- Inherent despeckling allowing high efficiency and high intensity lasers to be used for illumination resulting fast image capture.

8 ACKNOWLEDGEMENTS

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