ABSTRACT: Cracks in silicon wafers or solar cells reduce their mechanical stability and may lead to the breakage of the wafer. Since the trend in silicon solar cell technology is to reduce fabrication costs by means of reduction of the wafer thickness, the mechanical stability of the wafers plays a major role. Therefore there is a need for a rapid detection method of cracks and microcracks in wafers before processing or detection of cracks in solar cells before encapsulating as a module. Using ultrasound lock-in thermography (ULT) cracks caused by the impact of a steel ball on silicon wafers can be detected. Also optically invisible cracks induced artificially by notch impact could be found. Also microcracks on the edge of EFG material could also be detected, in this case not by the creation of heat, but rather by scattering of IR light guided through the wafer.

Keywords: Cracks, Lock-in Thermography, Qualification and Testing

1. INTRODUCTION

It is well known that cracks reduce the mechanical stability of silicon wafers and/or are leading to the breakage of the wafers. On the other hand the clear trend in silicon solar cell technology is to reduce the cost of fabrication by means of reduction of the wafer thickness. Here also the mechanical stability plays a major role. Therefore there is a need for a rapid detection system for cracks and micro cracks in wafers before processing or detection of cracks in solar cells before the encapsulating as a module. The aim of this paper is to show that Ultrasound Lock-in Thermography (ULT) is able to detect cracks in Silicon wafers and solar cells.

Lock-in Thermography is already an established techniques for detecting shunts in solar cells [1, 2]. ULT is based on the periodic introduction of ultrasound (US) energy into the wafers. This technique is already widely used in nondestructive testing of composite materials, where it allows the detection of local delaminations in the material [3]. US energy of variable frequency has been coupled into Si wafers also by Belyaev and Ostapenko [4], leading to so-called "whistling" at certain frequencies. The appearance and threshold energy for "whistling" was found to depend on the wafer quality, and a local mapping of the sound intensity reflected the crystal symmetry. However, according to the knowledge of the authors, this method was not used for imaging cracks so far. In our system the US energy is generated by a commercial US transducer at a fixed frequency of 20 kHz [5]. A special resonant US coupler is used to feed-in the US energy into the Si wafer. Under US excitation the friction at the edges of cracks is generating periodic local heating, which is detected by the IR camera and converted into an image by the Lock-in Thermography (LIT) system.

2. EXPERIMENTAL

Figure 1 Photograph of the ULT arrangement. The wafer is vacuum-sucked to the ultrasound transducer in the upper right corner.

The Ultrasound Lock-in Thermography (ULT) system is based on the TDL 384 M 'Lock-in' thermography system available from Thermosensorik GmbH (Erlangen, Germany [1, 2]). It uses a 384x288 pixel Stirling-cooled mercury-cadmium-telluride focal plane array thermocamera with a noise level below 20 mK at a full frame rate of 130 Hz. The lock-in frequency can be set between <1 and 30 Hz, all images shown here have been obtained at a lock-in frequency of 10 Hz. A SONOPULS HD 2070 ultrasound (US) generator is used working at a fixed frequency of 20 kHz enabling a maximum power of 70 W. As a rule a lower power has been used, which could be pulsed externally using a relais.
The resonant US coupler has been developed by the maker of the US generator BANDELIN electronic [5]. It couples the sample to the transducer via two concentric rubber rings, the outer one also being necessary to suck the sample to the holder by a vacuum. Fig. 1 shows the experimental system.

In order to increase the IR emissivity of the sample and make it opaque with respect to the IR light, in some cases the sample has been covered by a black paint using commercially available graphite spray, which can easily be removed by using acetone. Depending on the IR emissivity of the sample, the measurements shown here need an integration time between a few seconds and some minutes.

3. RESULTS

3.1 Steel ball impacts

A 10g weighting steel ball was dropped from different heights onto the surface of a number of cast multicrystalline wafers, which were elastically supported. Afterwards, bending experiments with 3-point support were performed on 30 wafers with different dropping height to test their mechanical strength. On 17 other wafers ULT investigations were made in order to see the impact points. Fig. 2 shows an ULT image of a wafer with such an impact point near the middle of the image. The two concentric rings in the upper left corner are an inevitable artifact coming from the US feed-in region. Both the amplitude (a) and the phase image (b) are shown. The phase image is a measure of the time delay between pulsed US energy introduction and T-modulation. It also shows local heat sources but has the advantage that its contrast is less dependent on the magnitude of the heat sources. The lock-in thermograms in Fig. 2 were taken within 30 min measure time on a bare wafer (no black paint). Fig. 2 (c) shows the results of the strength testing together with an evaluation of the results of the ULT imaging. From the strength testing experiments it can be concluded that a dropping height of 20 cm is the limiting height, from which on the strength is significantly reduced. In very good agreement with this observation no cracks could be observed for a dropping height below 15 cm, in some cases cracks were observed for 15 ... 20 cm, and for dropping heights above 20 cm in 100 % of all cases cracks were observed. Note that in some cases cracks have been seen in ULT where no cracks could be observed optically (see below).

3.2 Cracks introduced by notch impact

Cracks were also induced by notch impact. Fig 1a shows the topography image (which is a single IR image from the camera), (b) shows the amplitude image of the lock-in thermography, and (c) the corresponding phase image of cracks generated by this technique in another cast silicon wafer. In this case the cracks in the upper right corner were visible neither in the IR image nor by the naked eye. Again, the concentric rings in the middle are due to the US feed-in region. The horizontal stripes in the middle are probably an overloading effect of the camera. Again we see that in the amplitude image the brightness strongly varies along the crack line, whereas it is more homogeneous in the phase image.

3.3 The effect of paint covering

Unprocessed silicon wafers are actually less appropriate for IR thermography, since they are essentially transparent and provide only a weak IR emissivity. Therefore the IR signals are expected to be weak. Moreover, IR light can be guided within the wafer over significant distances of several cm and escape towards the camera in positions, where it was not generated. The most prominent pulsed heat source is the US feed-in region. This "light guiding effect" may produce artifacts; hence certain IR sources may be misinterpreted as local heat generation regions. This effect can easily be avoided by covering the sample with a paint layer, which is opaque and shows a high emissivity in the IR region used (3-5 μm). Commercial graphite spray has been
found to be very appropriate for this purpose and easily removable by acetone. It has been found that the light guiding effect is strongest on Edge-defined Film-fed Growth (EFG) wafers, which show a very flat surface. Fig. 4 shows a topography image (a) and an amplitude image (b) of such a wafer without any crack, and (c) shows the amplitude image of the same wafer covered with black paint. It is clearly visible that the features visible in (b) outside of the US feed-in region are artifacts caused by the light guiding effect.

**Figure 4:** Topography image (a) and lock-in thermogram (amplitude image, b) of a multicrystalline EFG wafer without painting. (c): amplitude image with black paint

### 3.4 Results on microcracks

Finally, it was attempted to detect microcracks at the edge of EFG wafers by ULT using a microscope IR objective. For attaining a better optical visibility, the wafers had been SIRTL etched before. As Fig. 5 (b) shows, there was an ULT signal in a crack position on the bare wafer. However, after covering the sample with black paint this signal disappeared. This is a clear indication that this signal was not due to local heat generation by friction but by the light guiding effect (see below). It is understandable that these crack are not generating local heat sources, since this wafer was SIRTL etched before. This widens the gap of the crack so that there was no friction possible anymore between the edges of the crack, which could generate heat by applying the US signal. Even if the crack edges would be touching, the low length of the microcracks may lead to a considerably reduced amount of locally generated heat.

In order to further investigate this effect, a sample without any damage etching was investigated. The SEM image of the edge of this sample (Fig 6a) indicates microcracks with a length of 50...100 µm. The gap of the microcracks is about 2 µm, so that there was no friction possible between the edges of the crack, which could generate heat by applying the US signal. Also here the signals detected by ULT disappeared after covering the sample with black paint. Thus, the detection of an IR signal at the microcracks can only be interpreted in terms of light guiding effect, which will be explained in more detail in the following.

**Figure 5:** Topography image (a) and amplitude image (b) of the edge region of an etched EFG wafer containing a microcrack. (c): amplitude image of the same region after covering with black paint

**Figure 6:** Phase image (a) and amplitude image (b) of the edge region of an EFG wafer containing a microcrack. (c) Topography image and (d) SEM image of the region marked in (a)

**Figure 7:** Free carrier absorption versus wavelength at different doping levels (n-Si) at 300 K [6]. Our case corresponds to curve 1 with $n = 10^{16}$ cm$^{-3}$

The contact between the sample and the transducer is realized in our system by 2 cylindrical rubber rings, which are dissipating US energy (see Fig 4c). The silicon wafer is a very good wave guide for this radiation because of the high index of refraction of Si. The infrared refractive index is about $n = 3.42$ at 300 K. Scattering occurs at crystal defects or microcracks. The dominant light absorption mechanism in the wavelength range 3 ... 5 µm used here is free carrier absorption. The free carrier absorption of n-type silicon is presented in Fig 7 [6].
doping level of the wafer was below $10^{16}$ cm$^{-3}$, corresponding to the curve No. 1. The wavelength of the IR Camera is 3.5 $\mu$m, in this case the absorption coefficient is below 0.2 cm$^{-1}$, corresponding to an absorption length of more than 5 cm. If a crack is visible in ULT by this light guiding and scattering effect, this provides no advantage anymore compared to a simple optical inspection of the samples.

4. CONCLUSIONS

It has been shown that ultrasound lock-in thermography (ULT) can image cracks in bare silicon wafers as well as in solar cells (not shown here). The phase image has been found to be more reliable for crack identification than the amplitude image. Even optically invisible cracks could be detected, but etched cracks do not lead to local heat sources. Macroscopic cracks can be detected reliably on bare wafers, but covering the surface with black paint considerably enhances the IR signal. The light guiding and scattering effect must be taken into account in order to avoid any misinterpretation of the lock-in results. In doubt covering the sample with black paint allows to distinguish real heat sources from signals caused by the light guiding effect. If certain defects are visible in ULT only by the light guiding effect, ULT provides no more advantage against a simple optical inspection of the samples. In this sense the potential of ULT to detect also microcracks has not been proven yet, hence all microcracks visible in ULT were also visible optically and disappeared after covering the surface with black paint. Nevertheless, ULT provides an interesting alternative to other crack imaging techniques like CrackDeTec [1] and a new application for lock-in thermography in solar cell research.

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REFERENCES

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