# YIELD ENHANCEMENT FOR SOLAR CELL MANUFACTURING USING RESONANCE ULTRASONIC VIBRATIONS INSPECTION

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## ABSTRACT

Resonance Ultrasonic vibrations (RUV) methodology was developed and applied to access mechanical quality of crystalline silicon wafers and solar cells. RUV approach is based on fast non-destructive measurement of specific resonance vibration mode generated in the tested object using external ultrasonic transducer. Crack introduced into the object alters the resonance properties of the mode and allows sensitive diagnostics of the crack appearance. The paper describes our recent results of applying RUV method at industrial environment with objective to reduce a breakage rate in solar cell and solar module lines.

## INTRODUCTION

To compete with traditional fossil energy sources, the solar industry is driven by economic reasons to make solar panels of the highest power conversion efficiency along with high reliability at the lowest possible production cost. Crystalline silicon (Si) has taken a dominant role in contributing to over 90% of the entire power module production. It is important to recognize that the silicon wafer is a large contributor, up to 75%, to the overall cost of the solar cell. To contribute in cost reduction and compensate for the feedstock shortage, solar Si wafers are sliced thinner with thicknesses down to 150 microns. These technological trends make wafer handling in production more challenging and reduce the yield of solar cell lines due to increased wafer and cell breakage. To improve the economics of cell manufacturing, the PV industry requires that a special inspection and quality control tool be developed for integration into the production process. This in-line tool will allow (1) rejection of mechanically unstable Si wafers after ingot cutting before they are introduced into further cell processing, (2) to identify wafers with mechanical defects (such as cracks) during production to avoid their in-line breakage, (3) to find cracked cells before they will be laminated into modules to avoid panel efficiency reduction and product return from the field. The testing tool must possess the following features at a minimum:

- high speed data acquisition and analysis, matching the approximately 2 seconds per wafer throughput rate of typical cell lines
- high stability (reliability and duty cycle) of the hardware performance including wafer loading/unloading and parts movement
- easy integration into a belt conveyor configuration or cell testing station
- user-friendly algorithm for wafer/cell rejection with a minimum number of false positives

Various research groups have presented laboratory results of experimental methods for non-destructive crack detection in Si wafers. They can be divided on two groups (i) optical methods specifically optical transmission [1], photoluminescence [2] or electro-luminescence imaging [3], infrared lock-in ultrasound thermography [4], and (ii) ultrasonic methods such as scanning acoustic microscopy [5], impact testing [6]. To our knowledge, none of these techniques completely satisfies all of the specifications listed above for in-line testing and mechanical quality control of Si wafers and solar cells. Resonance Ultrasonic Vibrations (RUV) methodology shows high potential to be adopted for non-destructive crack detection in full-size silicon wafers for solar cells as a quality control and in-line production tool. In this paper we report recent results and outline technical barriers for the RUV system to reject wafers with peripheral and bulk cracks with throughput rate matching solar cell and module production lines.

## RUV METHODOLOGY

The details and fundamentals of the RUV method were published elsewhere [7]. In short, a full-size Si wafer or cell is excited with the external transducer in a resonance mode, and characteristics of vibrations such as resonance peak position, amplitude and bandwidth and measured using highly sensitive ultrasonic probe. Fast positioning stages allow synchronized movement and precise positioning of the wafer and probe for RUV measurements. The entire system is computer controlled and programming devices are operated by

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Windows-based original software. A schematic to the RUV system is presented in Fig. 1.

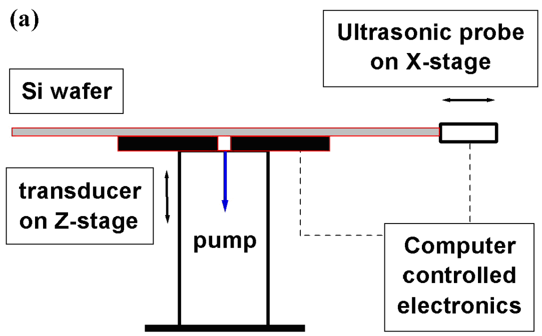


Fig. 1. A schematic of the experimental RUV system for crack identification in full-size Si wafers and cells.

When crack is introduced into the wafer three parameters of the resonance curve are altered, specifically, the peak position is shifted downward, amplitude is reduced and bandwidth is increased. The illustrative example of this crack effect on a shape of the RUV curve is demonstrated in Fig. 2. To compensate for variation of the RUV parameters in a similar size and type of wafers a statistical algorithm is introduced into the RUV software. This algorithm is specific for different type of Si material (single or multi-crystalline) and also various for bare wafers and finished cells.

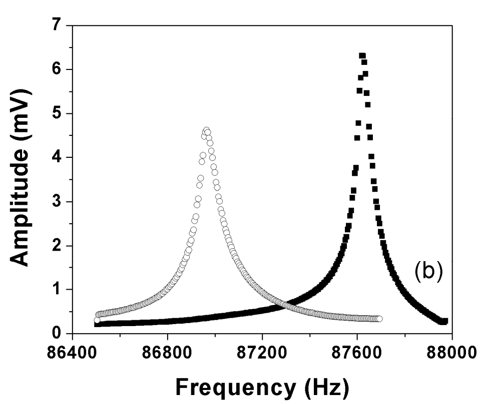


Fig. 2. Two RUV scans measured on non-cracked regular wafers (closed marks), and the wafer with 3 mm crack (opened marks).

The RUV unit may be (a) integrated into an automatic belt-type solar cell and module production lines, (b) used as a stand-alone testing system for mechanical quality control or (c) serve as a QC tool to perform equipment quality control regarding crack initiation. We report here on three case studies of using the RUV system as a tool for incoming inspection of wafers/cells in a production environment.

**Case Study A**. Single crystal Si wafers and finished cells were selected from the same vendor. Five batches of as-cut, textured, diffused, AR coated wafers and cells with approximately 100 units per batch were inspected. Two RUV settings with various crack sensitivities, defined as "low" ($3\sigma$) and "high" ($2\sigma$) thresholds were used. RUV rejected wafers/cells were measured with Scanning Acoustic Microscope to identify cracks with a 100 microns spatial resolution. This approach created a comparative data base of the RUV method sensitivity confirmed by the independent technique. Note that percentage of errors which is a total of the "false positives" and "false negatives" is noticeably reduced when $3\sigma$ threshold is changed to $2\sigma$. Concurrently, the number of 'true positive" events when RUV rejects were confirmed by SAM is increased. We found that the RUV method provided identification of wafers/cells with cracks length down to 1 mm with 95% accuracy. Typical SAM image of the cell with crack is presented in Fig. 3. It is illustrative to show here that other imaging techniques based on photo- or electroluminescence in some cases give false positive results with regards to cracks [8]. The reason is that different surface features such as scratches may be easily identified as cracks with the imaging software. In Fig. 4 we present a comparative study of the EL and SAM imaging showing this effect.

**Case Study B**. Two equal lots of 1000 wafers from the same 156 mm mc-Si ingot were selected. The first lot passed through the RUV system to reject and remove mechanically unstable fragile wafers, the second lot served as a control. The RUV system was set at $3\sigma$ sensitivity threshold. Both lots of wafers were put through production solar cell line to compare breakage results. The control lot of mc-Si wafers had shown a 5.52% breakage, while the RUV screened lot exhibited 0.94% breakage. The rejection percentage was close to the breakage reduction, which indicated an optimum setting of the RUV system sensitivity.

**Case Study C**. Two batches of mc-Si solar cells (approximately 1500 each) were used. The first batch of cells passed the RUV system and rejected cells were removed. The second served as a control. Both cell batches passed the same module production facility. Breakage percentage was calculated as following: 0.9% in control and 0.37% in RUV tested. Similar experiment was performed in a different production facility with following results: 1.40% (control) and 0.27% (RUV tested). Both times the rejection was close to the breakage reduction, which indicated an almost optimum system setting.

## CONCLUSIONS

The RUV methodology was successfully implemented in an incoming inspection of Si wafers and cells in the cell and module production lines. The high crack detection sensitivity in the range of 90-95% was confirmed using Scanning Acoustic Microscopy. This was directly related to a noticeable reduction of the breakage rate in the cell and module lines, which in the optimal RUV settings are equal to 4% (wafers) and 0.5-1.0% (cells).


## ACKNOWLEDGEMENTS

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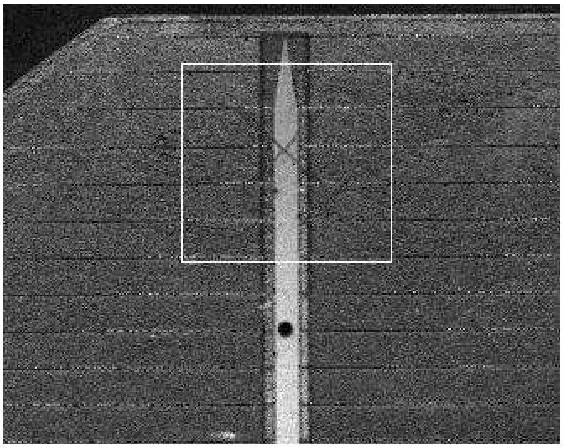
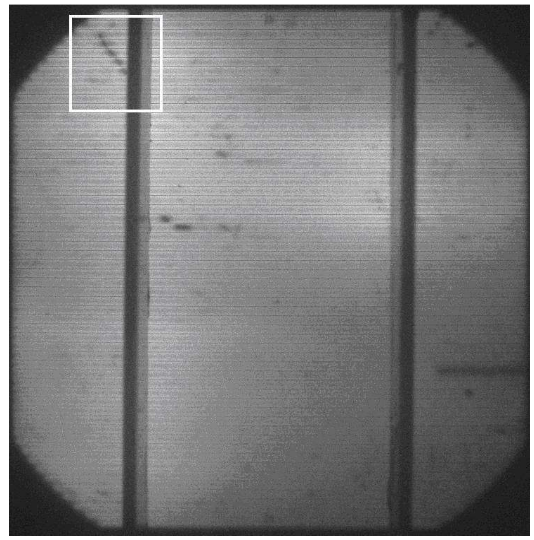
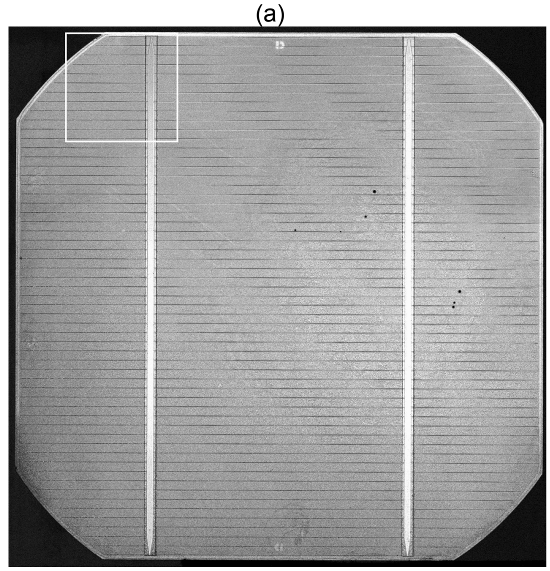


(b)

Fig. 3. Scanning Acoustic Microscopy of the crack in full-size Cz-Si solar cells rejected by the RUV technique. The mm-length cross crack is located beneath the bus-bar and invisible with optical inspection technique.



(a)



(b)

Fig. 4. (a) EL image of the Cz –Si solar cells shows a "suspect" for the crack (framed area). (b) SAM mapping shows that no crack is attributed to this area.

| Process | Number of Wafers | Number of RUV Rejects | | Number of True Positives | | Number of False Positives | Number of False Negatives | |
|---|---|---|---|---|---|---|---|---|
| | | $3\sigma$ | $2\sigma$ | $3\sigma$ | $2\sigma$ | | $3\sigma$ | $2\sigma$ |
| As-cut | 112 | 1 | 1 | 1 | 1 | 0 | 0 | 0 |
| Texturing | 98 | 5 | 5 | 5 | 5 | 0 | 0 | 0 |
| Diffusion | 100 | 10 | 10 | 10 | 10 | 0 | 0 | 0 |
| AR coating | 99 | 3 | 3 | 3 | 3 | 0 | 0 | 0 |
| Solar cells | 110 | 8 | 12 | 7 | 11 | 1 | 5 | 1 |
| Total | 519 | 27 | 31 | 26 | 30 | 1 | 5 | 1 |

Table 1. Summary of RUV/SAM comparison on 125 mm x125 mm wafers/cells.

## REFERENCES


[1] Rueland E, Herguth A, Trummer A, Wansleben S, Fath P, “Optical u-crack Detection in Combination with Stability Testing for In-line Inspection of Wafers and Cells” Proceedings of 20th EU PVSEC Barcelona, 2005 pp. 3242 – 3245.

[2] Trupke T, Bardos R A, Schubert MC, Warta W, “Photoluminescence Imaging of Silicon Wafers” Appl. Phys. Lett. , **89,** 044107 (2007)

[3] Fuyuki T, Kondo H, Yamazaki T, Takahashi Y, Uraoka Y, “Photographic Surveying of Minority Carrier Diffusion Length in Polycrystalline Silicon Cells by Electroluminescence” Appl. Phys. Letters, 86, 262108 (2005).

[4] Rakotoniaina J P, Breitenstein O, Al Rifai M H, Franke D, Schnieder A, “Detection of Cracks in Silicon Wafers and Solar Cells by Lock-in Ultrasound Thermography” Proceedings of PV Solar conference (Paris, June 2004), pp. 640-643.

[5] Belyaev A, Polupan O, Ostapenko O, Hess D, Kalejs J P, “Resonance Ultrasonic Vibration Diagnostics of Elastic Stress in Full-Size Silicon Wafers” Semicond. Sci. Technology **21**, (2006), 2540260.

[6] C. Hilmersson, D. P. Hess, W. Dallas, S. Ostapenko “Crack detection in single crystalline silicon wafers using impact testing”, Applied Acoustics **69**, pp. 755-760, (2008).

[7] Dallas W, Polupan O, Ostapenko S “Resonance ultrasonic vibrations for crack detection in PV silicon wafers”, *Meas. Sc. Technol.*,**18**, 2007, 852. (2007)

[8] Monastyrskyi A, Polupan O, Ostapenko S„Resonance Ultrasonic Vibrations for In-line Crack Detection in Silicon Wafers and Solar Cells”, IEEE PVSC-33, in press.