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Final Technical Report
ULTRASONIC TECHNOLOGIES, INC.

DE-FG02-07ER84790

Final Technical Report

SBIR award DE-FG02-07ER84790

Sergei Ostapenko

4/3/2013

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DOE award: **DE-FG02-07ER84790**
Recipient: Ultrasonic Technologies, Inc.
Principal Investigator: Sergei Ostapenko, PhD
Project Title: "In-Line Crack and Stress Detection in Silicon Solar Cells Using Resonance Ultrasonic Vibrations"
DOE Program: SBIR Phase II
Date of Report: June 20, 2007 – August 14, 2010

Prepared By:

Document Owner(s)	Project/Organization Role
Sergei Ostapenko	Principal Investigator
Karen Oberne	Program Assistant

1 FINAL TECHNICAL REPORT PURPOSE

The Final Technical Report is a document that the Project Manager/Principal Investigator will use as a means of formal reporting on the status of a project to the U.S. Department of Energy.

2 TECHNICAL REPORT DETAILS

2.1 Objectives of the Awarded Project

- (1) Develop and justify a fully automatic, computer-controlled RUV-2MB system prototype that meets major specifications for an in-line crack detection unit such as high throughput rate (currently at 2.0 seconds per cycle), high level of stability and reproducibility of data acquisition and analyses, high sensitivity with respect to crack length and crack location, low percentage of "false positive" and "false negative" events;
- (2) Select optimal configuration of both hardware and operational software elements for the RUV-2MB system component;
- (3) Design a RUV-2MB system platform that allows easy integration and adaptation into belt-type solar cell production lines including final solar cells and solar cell strings;

- (4) Optimize basic system parts using computational analyses of the resonance vibration modes in wafers coupled with a transducer and ultrasonic probe;
- (5) Develop a testing protocol required for RUV-2MB system certification leading to a full production-grade RUV system.

2.2 Accomplishments Summary

- **Established physical reasons of a long-term instability in high volume RUV measurements, localized the problem in the RUV system hardware, and performed experimental troubleshooting;**
- **Completed a development project to eliminate the effect of temperature variation that negatively affected repeatability and accuracy of the RUV measurements;**
- **Designed and manufactured an advanced ultrasonic module (actuator and probe) to deliver highly stable and sensitive RUV measurements and tested the module in a production environment;**
- **Performed successful high volume crack detection in production facilities with customers; Jumao Photonics (China), Rimas Systems (Netherlands), Innotech Solar (Norway);**
- **Experimentally demonstrated reduction of the breakage rate in solar cells and solar panel factories after RUV testing of incoming solar cell wafers and cells (Helios Technologies, Italy; Photovoltech, Belgium; Ubbink Solar, Holland); (Appendix A, slides 8-9)**
- **Performed Finite Element Analysis (jointly with Georgia Tech as a sub-contractor) of the effect of vacuum stress applied to thin silicon wafer from the resonance transducer (Appendix B);**
- **Exhibited a prototype of the RUV-2MB system at the PV Show, San Diego, October 2008; technical presentations on Crystalline Silicon Workshop (Norway, 2009), IEEE PVSC Conference (Philadelphia, 2009), and 35th PVSC Conference (Honolulu, 2010);**
- **Based on customer's requests, developed protocols of crack rejections (recipes) using the RUV system at various steps in solar cell and solar panel lines. Implemented these recipes in the RUV**

software for convenient operation in solar cell and module production

- Developed an algorithm to optimize sensitivity of the RUV system for in-line crack detection to achieve maximum reduction of the breakage rate with minimum number of false positive and false negative events. Demonstrated this algorithm in production facilities with high volume crack tests at collaboration facilities (Innotech Solar, Norway); and
- Performed a prototype development of the fully automated RUV system matching throughput rate of Si cell/module production lines. Performed feasibility laboratory testing with commercial customers from the PV community (Sun Power, Solar World, Sanyo, Solartech, Mitsubishi, Innotech Solar).

2.3 Project Tasks and Schedule

Task #	Task Description	Scheduled dates	Actual Completion dates
Task 1	<i>System Specification.</i> Develop technical documentation including parts list and suggested vendors for a basic RUV-2MB system configuration with integrated mini-belt conveyor and pick-and-place robotic rejection unit allowing in-line crack control.	10/1/2008	10/1/2008
Task 2	<i>Finite Element Analysis.</i> Perform FEA computer modeling of the resonance vibrations of a silicon wafer coupled with a transducer and ultrasonic probe.	3/23/2009	5/30/2009
Task 3	<i>System Optimization.</i> Optimize ultrasonic parts for the RUV-2MB system based on FEA conclusions and recommendations. Experimentally test variation of the frequency curve parameters using an experimental RUV-2MB system.	9/2/2009	1/30/2009
Task 4	<i>Assembling and Testing.</i> Assemble, troubleshoot, and test RUV-2MB system integrated with mini-belt and using pick-and-place robotic arm.	1/29/2010	08/14/2010
Task 5	<i>Statistical Algorithm Development and Verification.</i> Develop statistical algorithm for rejection of mechanically cracked wafers based on normal distributions of the RUV curve parameters. Implement this algorithm in system's operational software.	11/19/2009	08/14/2010
Task 6	<i>System Testing Protocol.</i> Develop RUV-2MB system	7/1/2010	08/14/2010

	testing protocol to assure quality certification of the production-grade system.		
Task 7	<i>Final Report Preparation.</i> Prepare a report detailing the developments of the experimental and computational aspects that enable the commercial implementation of the RUV technique.	7/30/10	2 nd year

2.4 Detailed Deliverables:

- (a) Test results at the Innotech Solar (Norway) – Appendix C and D.
- (b) Breakage reduction test performed at Helios Technologies (Italy), Ubbink Solar (The Netherlands) and Photovoltech (Belgium) – Appendix A.
- (c) Statistical RUV algorithm for comprehensive crack cell rejection - Appendix E

2.5 Cost Status

The budget for the entire project of \$836,929 was approved by DOE. Current costs incurred as a combination of the direct and indirect costs was invoiced to DOE with total of \$836,929.

2.6 Publications

[1] Belyaev, Yu. Emirov, S. Ostapenko, I. Tarasov, V. Verstraten, M. Van Dooren, P.G. Fumei, G. Van Veghel, P. Bentz, A. Van Der Heide "YIELD ENHANCEMENT FOR SOLAR CELL MANUFACTURING USING RESONANCE ULTRASONIC VIBRATIONS INSPECTION", Proceedings of 34th PVSC Conference, Philadelphia, PA, May 2009, p. 001918

[2] Hao Wu; Melkote, S.N.; Belyaev, A.; Tarasov, I.; Cruson, D.; Ostapenko, S., "Effect of handling stress on resonance ultrasonic vibrations in thin silicon wafers," *Proceedings of the 35th IEEE Photovoltaic Specialists Conference*, Honolulu, 2010, pp 3642-3646.

2.7 Industrial Collaborations

- Rimas Systems (Netherlands)
- Jumao Photonics (China)
- Suniva Inc. (USA)
- Helios Technologies (Italy)
- Ubbink Solar (The Netherlands)
- Photovoltech (Belgium)

Appendix A: SBIR Program Review (May 24-27, 2010)

Solar Energy Technologies Program Peer Review		U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy
Ultrasonic Technologies, Inc. ULTRASONIC CRACK DETECTION		Fully automated RUV-2.2 system
In-line Crack Detection in Silicon Solar Cell Production Using Resonance Ultrasonic Vibrations (RUV)		Presenter Organization: Ultrasonic Technologies, Inc. Contact Info: Sergei Ostapenko, PhD Date: May 26, 2010	
This presentation does not contain any proprietary, confidential, or otherwise restricted information			
Overview		U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy	
Timeline <ul style="list-style-type: none"> Project start date: 06/20/2007 Project end date: 08/15/2010 Percent complete: 100% 		Barriers <ul style="list-style-type: none"> Fast in-line inspection of crystalline silicon wafers and solar cells with throughput rate of 2.0 sec/wafer. 	
Budget <ul style="list-style-type: none"> Total project funding <ul style="list-style-type: none"> DOE share: \$ 836,929 Contractor share: None Funding in FY07- 08: \$ 99,650 Funding in FY09: \$371,650 Funding for FY10: \$ 365,629 		Partners <ul style="list-style-type: none"> Project lead: Ultrasonic Technologies, Inc (Tampa, FL) Interactions/collaborations: Georgia Institute of Technology; University of South Florida 	
2 Solar Energy Technologies Program		2 eere.energy.gov	

Challenges, Barriers or Problems

- Cracks in c-Si wafers and cells reduce production yield and increase the cost of PV modules;
- Cracked wafers must be identified in real-time and removed from PV production;
- RUV technology perfectly fits to overcome the problem of in-line crack inspection;
- RUV method is applicable for major c-Si wafers and solar cells.

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Relevance

Objectives:

- (a) develop and justify a fully automated, computer-controlled RUV system prototype that meets major specifications for in-line crack detection unit;
- (b) select optimal configuration of hardware and operational software elements for the RUV system component;
- (c) design the RUV system platform that allows easy integration and adaptation into belt-type solar cell and module production lines;
- (d) optimize ultrasonic parts using computational analyses of the resonance vibration modes in wafers coupled with a transducer and probe
- (e) develop a testing protocol required for RUV system certification leading to a fully production-grade RUV system

Impact: The project will lead to fully operational RUV system prototype available for commercial solar cell and solar module lines.

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Relevance

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POSITION OF RUV SYSTEM IN SOLAR PRODUCTION CHAIN

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Approach

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Figure 1: RUV system schematic

- Si wafer is vacuum coupled with external transducer;
- The transducer generates a resonance frequency sweep in the wafers (Fig. 2);
- Ultrasonic probe measures the resonance curve;
- The wafer with crack has resonance curve different vs normal wafer

Figure 2: Deviations of peak parameters caused by a crack

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Collaborations

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- Project collaborators:

(a) industry partners – Suniva Inc. (Norcross, GA); SunPower Corp. (Philippines), Rimas Systems (Netherlands), Helios Technologies (Italy), Jumao Photonics (China); Solar Fabrik (Germany), Photovolttech (Belgium); Ubbink Solar BV (Netherlands). Partners provided material for high-volume testing; potential customers.

(b) universities: University of South Florida – leasing of analytical tools (Scanning Acoustic Microscope, SEM, AFM), Georgia Institute of Technology – computer modeling.

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Accomplishments / Progress / Results

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BREAKAGE HIGH VOLUME TESTS: wafers – cells, cells – modules

Objective: validate RUV yield improvement in PV production

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Accomplishments / Progress / Results

U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

TEST RESULTS Breakage reduction:

Case	Product	Breakage % normal *	Breakage % with RUV*	Δ % Breakage reduction
1	Wafers	5,5%	1%	82%
2	Wafers	5,5%	0,7%	88%
3	Wafers	1,38%	0,42%	69%
4	Cells	0,9%	0,37%	59%
5	Cells	0,75%	0,15%	80%

Conclusion: RUV dramatically reduces PV wafers and cell breakage

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Accomplishments / Progress / Results

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Pinhole / micro crack detection:

- A small, sub-millimeter pinhole represents a seed point defect which dramatically reduces cell strength and leads to breakage and yield reduction.
- UST developed capability to detect sub-millimeter defects using the Activation Station.
- Pinhole defects are identified with 100% accuracy
- The method is included into RUV prototype

Image of 3.6 x 3.5 mm map with pinhole and sub-millimeter cross-cracks in Cz-Si cell. Unopened cross-cracks provide directions of the cell cleavage.

RUV system eliminates the pinhole breakage caused by production flaws

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Budget Status and Potential for Expansion

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- Total project funding by DOE/SBIR program (Phase I and Phase II) - \$ 836,929
- In-kind cost sharing was provided by commercial partners including free supply of Si wafers and solar cells (required for high-volume testing). The project is on budget.
- Additional funds would allow to optimize Activation Station for pinhole and micro-crack detection by performing FEA analyzes, engineering design, hardware optimization and software modification. AS will be fully integrated into in-line RUV automatic system.

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Future Plans (FY 2011 and beyond)

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- Perform “true-false” validation and statistical justification of the RUV method;
- Perform high-volume testing in 3 production facilities to address long-term reliability and potential flaws in RUV system prototype;
- Create a Bill of Material to begin a commercialization phase with launching customers;
- Perform CE and TUV certification of the RUV in-line tool.

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Mandatory Summary Slide

- Fully automated Resonance Ultrasonic Vibrations (RUV) system prototype was developed and build by the Ultrasonic Technologies. The system uses original RUV technology;
- RUV system parameters match throughput rate of cell and module production, currently at 2.0 sec per wafer;
- RUV system is characterized by high stability, repeatability, and accuracy for crack detection at the level up to 95%;
- RUV system validated during a high volume breakage test in wafer-to-cell and cell-to-module lines;
- Breakage reduction up to 88% was confirmed by the customers;
- First off-line RUV-system was installed at launching customers.

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Appendix B

EFFECT OF HANDLING STRESS ON RESONANCE ULTRASONIC VIBRATIONS IN THIN SILICON WAFERS

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ABSTRACT

Resonance Ultrasonic Vibration (RUV) metrology offers a sensitive non-destructive real-time solution to silicon wafer crack detection. The stresses generated in the wafers by the handling device used in the RUV method may have a significant influence on the effectiveness of this method, particularly for thinner wafers. The handling stresses produced by different designs of the vacuum wafer holders and their effects on the resonance properties of the ultrasonically excited wafer are studied using Finite Element Analysis (FEA) and confirmed by RUV tests. FEA results and RUV experiments show that optimization of the wafer handling stress obtained by redesigning the wafer holder does not alter the resonance frequencies and mode shapes of the wafer significantly compared to the free vibration case. Therefore, it is possible to use RUV approach for crack detection in thin silicon wafers without significant modification.

INTRODUCTION

Reduction of in-line breakage caused by cracks in crystalline silicon (Si) solar cells presents a main challenge for product quality and process control in photovoltaic manufacturing. Resonance Ultrasonic Vibration (RUV) metrology enables fast and accurate crack detection with simple criteria for wafer rejection from solar cell production lines [1-2]. The RUV system relies on changes in modal vibration characteristics due to physical variations in the wafers caused by cracks. Ultrasonic vibrations are induced in an as-cut or processed silicon wafer through a vacuum coupled high frequency piezoelectric transducer beneath the wafer (see Figure 1). Standing longitudinal waves are set up at resonance frequencies with peak positions controlled primarily by the wafer's geometry and size, and the material's elastic properties. The differing physical attributes of each Si wafer, especially the existence of cracks, lead to altered resonance mode shapes including peak position, peak bandwidth and peak amplitude. Therefore, wafers with defects can be detected by identifying differences in their resonance characteristics from a non-cracked wafer.

While the Si wafers are gripped by the vacuum wafer holder (or chuck) to ensure firm coupling between the wafer and the transducer in the RUV setup, the handling

stresses generated by the vacuum chuck, which to a large extent are determined by the geometrical design of the chuck, may influence the effectiveness of the RUV approach. In this paper, the handling stress produced by different designs of the vacuum wafer holders and their effects on the resonance properties of the ultrasonically excited wafer are studied using Finite Element Analysis (FEA) and confirmed by the RUV tests.

Figure 1 Schematic of the RUV experimental systems [1]

The first part of the paper presents distributions of elastic stress produced in the Si wafer by vacuum applied through various transducer configurations as a function of the wafer thickness. In the second part, FEA calculated resonance frequencies of the wafer coupled with transducer are compared with experimental data. RUV experiments show that optimization of the wafer handling stress by redesigning the wafer holder does not alter the resonance frequencies and mode shapes of the wafer significantly compared to the free vibration case. It is concluded that the RUV method can be applied for crack detection in thinner solar silicon wafers without significant modification.

ANALYSIS OF HANDLING STRESS GENERATED BY TRANSDUCERS OF DIFFERENT GEOMETRIC DESIGNS

The geometric design of the transducer can be optimized to maximize the holding force and at the same time minimize the handling stresses produced in the wafer. Four designs are proposed with their geometric configurations shown in Figure 2. Design I is the transducer with radial and circumferential vacuum grooves, while distributed circular vacuum grooves are used in the transducer in Design II. In design III the radial vacuum ports are connected by vertical and horizontal channels. Design IV is the transducer with only a central hole.

Appendix C

RUV-2.2 system Graphic User Interface at Innotech Solar, Norway.

Comments: (1) "Total Count = 4,748,036" - total number of cells passed through the system; (2) "Reject/Box (%) = 3.5" - percentage of cracked cells in the box, (3) "Total Cycle = 1.74 sec" - system throughput per cell.

Appendix D

- (a) RUV parameters of single batch cells (1,064 total), red line show a floating threshold used in the RUV algorithm

(b) RUV parameters of rejected cells from the same batch (40 total)

Appendix E

Comprehensive RUV statistical flow chart for in-line rejection of cracked cells.