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Full Field Birefringence Measurement of Grown-In Stresses in Thin Silicon Sheet

Final Technical Report
2 January 2002 – 15 January 2008

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Subcontract Report
NREL/SR-520-44237
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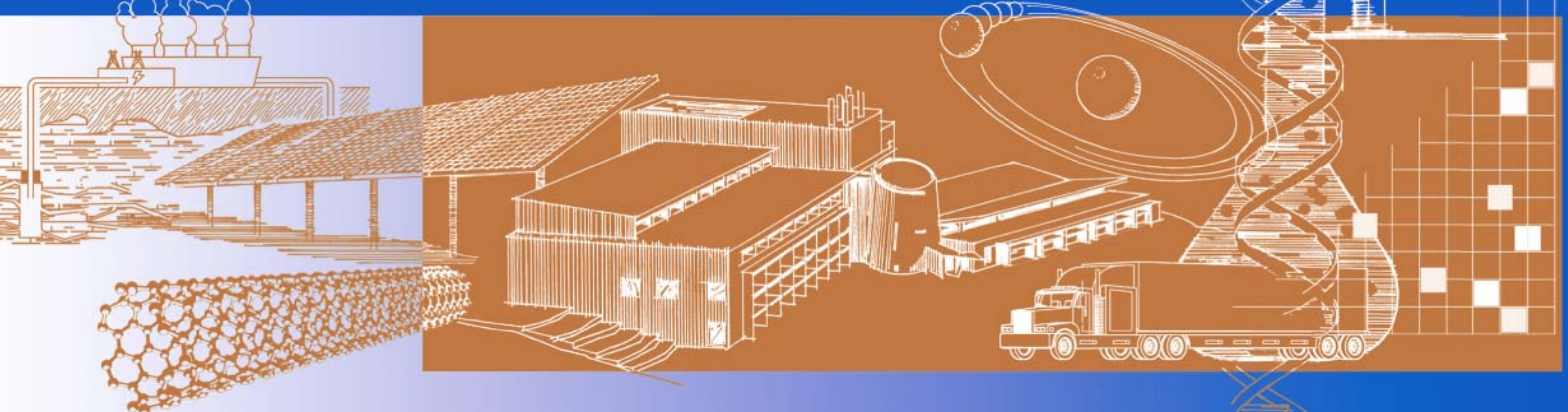

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Executive Summary

This is the Final Report of the project, "Full Field Birefringence Measurements of Grown-in Stresses in Thin Silicon Sheet," that has been conducted at the Georgia Institute of Technology by Steven Danyluk, a Professor in the George W. Woodruff School of Mechanical Engineering, and the University of South Florida by Sergei Ostapenko, an Associate Scientist in the Center for Microelectronics Research.

The primary concern of this research has been to develop fundamental knowledge about residual stresses and microcracks and defects in silicon sheet. In the course of the work, the two groups developed new experimental techniques to obtain shear stresses and microcracks in sheet silicon. One of the techniques involves infrared photoelasticity, which measures the residual stress-induced birefringence. The residual stresses are related to the birefringence through the stress-optic coefficient described in this report. Anisotropy, thickness, and microstructure are some of the key parameters that effect birefringence, and these topics have been investigated as they relate to in-plane residual stresses. In the experimental system developed at Georgia Tech, the anisotropy thickness and microstructure were accounted for by the use of a four-point bending technique, and ultimately used to determine the principal stresses in silicon wafers.

The work at the University of South Florida has focused on using acoustic techniques (resonance ultrasonic vibrations) to determine the existence of microcracks – usually edge cracks – in thin silicon wafers. This work has led to the development of hardware that can be used to screen wafers for edge defects.

There have been numerous papers and reports written and these documents summarize the detailed technical elements of the work. These papers are listed in Appendix A of this report. There have been graduate students supported by this project and their names and other data regarding these are listed in Appendix B of this report.

The key findings of our work may be summarized as follows:

1. The polariscopy work has led to the development of a prototype non-contact, near-infrared light-transmission system for the inspection of thin, flat, large-area silicon wafers. Anisotropy, light scattering by thin wafers, influence of dislocations on stresses, and the extraction of principal in-plane stresses have been studied. This method is now ready for commercialization and in-line inspection of wafers at various stages of photovoltaic cell processing.
2. The acoustic work has led to the development of a commercially viable system to inspect wafers for microcracks. Technical issues such as the influence of crack length on vibration frequencies of thin silicon wafers have been studied and solved. This method of crack detection has been commercialized by Dr. Ostapenko.

The balance of this report summarizes some of the technical details.

A. Summary of the Polariscopy Study

The Georgia Tech group has been working on developing a non-destructive, non-contact optical technique to measure the residual stress in thin silicon sheet. Figure A1 shows a schematic diagram of the polariscope system. Circularly polarized light, which is provided by the first polarizer and quarter waveplate, is used to illuminate the silicon sample. The residual stresses in the sample change the polarization state of the transmitted light, and the second wave plate and polarizer measure the change. A tungsten lamp with adjustable power up to 250W is used as the light source, and an infrared camera captures the images. In the camera, a band-pass infrared filter is used to pick a near-infrared wavelength center at 1150 nm with a bandwidth of 10 nm.

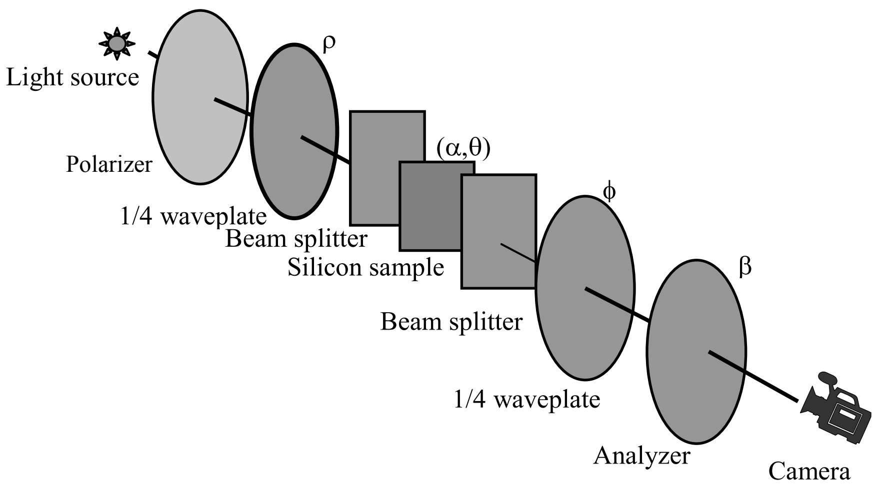


Figure A1: Setup of the residual stress polariscope

The stress optic law can be used to obtain the maximum shear stresses in the beam if the stress- optic coefficient is known. The stress optic law is given as:

$$\sigma_1 - \sigma_2 = \frac{\lambda}{2\pi\, t\, C(\theta, \varphi)}\delta \qquad (1)$$

where C is the stress-optic coefficient, which is a function of θ (the principal stress orientation) and φ (the crystal-grain orientation); t is the thickness of the sample; λ is the wavelength of the light source; and σ1, σ2 are the two principal stresses. δ is the phase retardation that can be measured by the six-step phasing method. In this equation, δ is related to the in-plane residual stresses and the maximum sheer stress is then

$$\left|\sigma_1 - \sigma_2\right| = 2\tau_{max} \qquad (2)$$

Equation (2) shows that only the absolute value of the difference in principal stresses is measured, and this value will be influenced by the crystal orientation, defect (dislocation) density, and thermal effects as a result of the infrared illumination.

A1. Goals and Objectives

The goals and objectives of the residual stress work were to determine the influence of anisotropy on the stress-optic coefficient, develop a method for separation of the residual stress components, investigate the relationship between residual stress and dislocation density, and analyze the thermal effects on residual-stress measurements.

A2. Summary of Approaches

1. Calibration of anisotropic stress-optic coefficient

The stress-optic coefficient, a parameter used in polariscopy, is orientation dependent, because light scattering will depend on the location of the atoms in the crystal structure. A back Laue X-ray diffraction system (at Oak Ridge National Laboratory) was used to determine the grain orientations in edge-defined film-fed growth (EFG) and cast silicon wafers and to find φ (2). Reference 1 describes some of the details of how the anisotropic stress-optic coefficient is obtained. Reference 2 describes a four-point bending technique used to introduce known in-plane stresses so as to calibrate the anisotropic stress-optic coefficients. In both cases, it is possible to extract the anisotropic stress-optic coefficient for single and polycrystalline silicon wafers.

2. Method for stress separation

Photoelasticity provides information on the principal shear stress and its orientation in the wafer. To obtain the full state of stress (σ_x, σ_y and τ_{xy}), stress separation must be used. Four-point bending, together with shear-difference technique, has been developed to determine stress separation. Four-point bending can tell whether the measured shear stress is positive or negative. The shear-difference technique is based on the direct integration of the equilibrium equations in the following finite-difference format:

$$\sigma_x = \sigma_x(boundary) - \sum \frac{\Delta \tau_{yx}}{\Delta y} \Delta x \quad \text{and/or} \quad \sigma_y = \sigma_y(boundary) - \sum \frac{\Delta \tau_{yx}}{\Delta x} \Delta y \quad (3)$$

Using equations (1) and (3) and the basic stress transformation equations of mechanics, the full state of stress (σ_x, σ_y and τ_{xy}) can be calculated (Reference 3).

3. Relationship between residual stress and dislocation density

To determine the relationship between dislocation density and residual stress, optical microscopy and image analysis were used, in addition to polariscope residual-stress measurements. EFG wafers were used for the dislocation-density experiment because their crystal structure is relatively constant and the surface relatively smooth. A Sopori etch was used to reveal etch pits on the surface of EFG wafers. Etch-pit density was assumed to be the same as the dislocation density. Wafers were also subjected to polariscopy to obtain the residual-stress maps, and the results of etch-pit density and residual stress were analyzed to find their relationship (4).

4. Analysis of thermal effect on residual stress measurement

This task addressed measurement resolution and reliability issues associated with the infrared (IR) polariscope. In particular, the task was designed to systematically study the role of temperature rise in the silicon wafer due to IR light absorption on the residual-stress output by the system. The nonuniform energy profile of the light source can produce a thermal gradient in the Si sample and, as a result, a thermal stress may be induced in the wafer, that will increase the system error. An ANSYS thermal model was built to calculate the temperature in the silicon wafer. This temperature profile was used as input to a structural model that calculated thermal stress.

5. Relation of residual stresses to dislocation density

There has been considerable discussion in the literature relating to the relationships of dislocation density to residual stresses and eventually to cell efficiencies. We have addressed this issue and a Georgia Tech student, Vicky Garcia, has published a thesis (5) that relates the residual stresses to electron-hole lifetime. There appears to be a linear correlation to these two parameters, as described in the thesis.

A3. Key Findings

The key findings of the residual stress work are as follows:

The major preferential crystallographic orientation in cast wafers is (111) and near (111), but other orientations are (100), (210), (110), (144), (211), (321), and (431). The stress-optic coefficient varied with orientation and the variation between the maximum and minimum value.

Full components of stresses have been obtained for several silicon beams. The maximum principal stress was found to be about 30 MPa for EFG wafers.

A relationship was found between dislocation density and residual stress. The graph in Figure 2 shows the behavior of residual stress at high values of dislocation density. Equations are shown in the graph to quantify the relationship. There is an uncertainty in which stress relaxation occurs because since there are sources of residual stress other than dislocations.

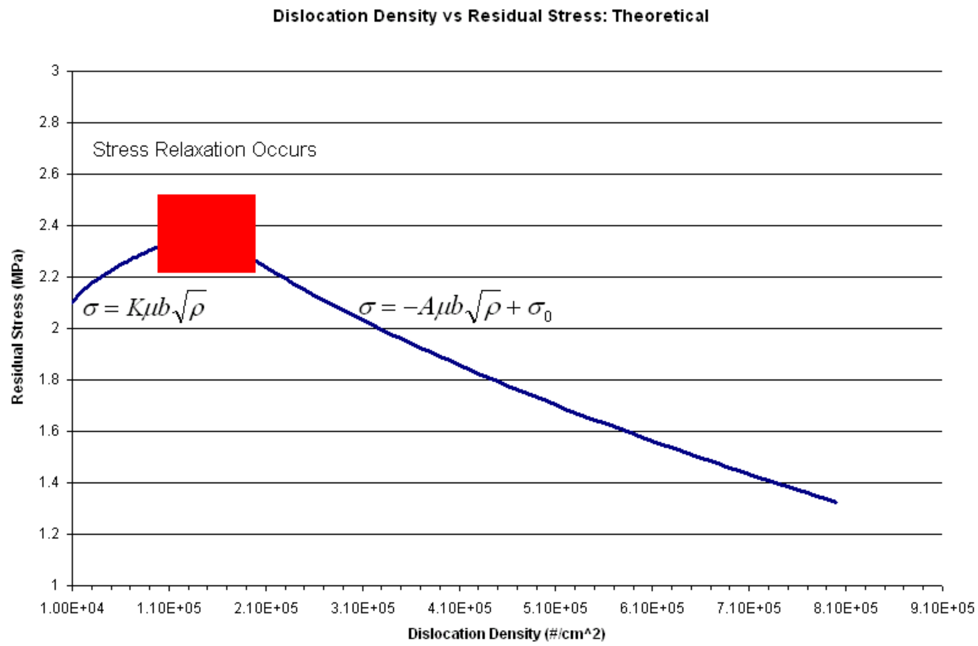


Figure A2. Relationship between dislocation density and residual stress

Thermal modeling shows that the polariscope system needs about 1 to 2 minutes to achieve steady-state.

B. Summary of the Resonance Ultrasonic Vibration Study

The Resonance Ultrasonic Vibrations (RUV) technique was adapted for non-destructive crack detection in full-size silicon wafers for solar cells [7]. Other experimental approaches targeting crack detection in PV silicon wafers and solar cells are described elsewhere. The RUV methodology relies on deviation of the frequency response curve of a wafer with a periphery crack versus regular non-cracked wafers. Crack detection is illustrated on a set of square-shaped production-grade Si wafers and confirmed by finite element analysis (FEA). The modeling is accomplished for the different modes of the resonance vibrations of a wafer with a periphery crack to assess the sensitivity of the RUV method relative to crack length and crack location. Crack-elongation experiments were performed using a specially designed tool. A statistical approach was proposed for crack detection in full-sized silicon wafers.

B1. Goals and Objectives

The goals and objectives of the crack detection work were to develop the methodology to detect resonance in thin silicon wafers, investigate the relationship between known crack sizes and ultrasonic signatures, and develop an experimental system that could be used by the PV community to inspect wafers.

B2. Summary of Approaches

Ultrasonic vibrations are induced into an as-cut or processed silicon wafer of symmetrical geometry through a vacuum-coupled high-frequency piezoelectric transducer beneath the wafer as illustrated in Figure B1. A transducer frequency can be swept in the ultrasonic range from 20 kHz to 100 kHz. Standing longitudinal waves are set up at resonance frequencies with peak positions controlled primarily by the wafer's geometry, size, and material's elastic characteristics. The differing physical attributes of each Si wafer lead to altered resonance-mode shapes including peak position, peak bandwidth, and peak amplitude. The vibrations are detected using a broadband ultrasonic probe attached with a sensor-controlled force to the edge of the wafer. Stepper motors 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 Windows-based original software. The RUV unit may be integrated into an automatic belt-type solar cell production line or used as a stand-alone testing system for mechanical quality control.

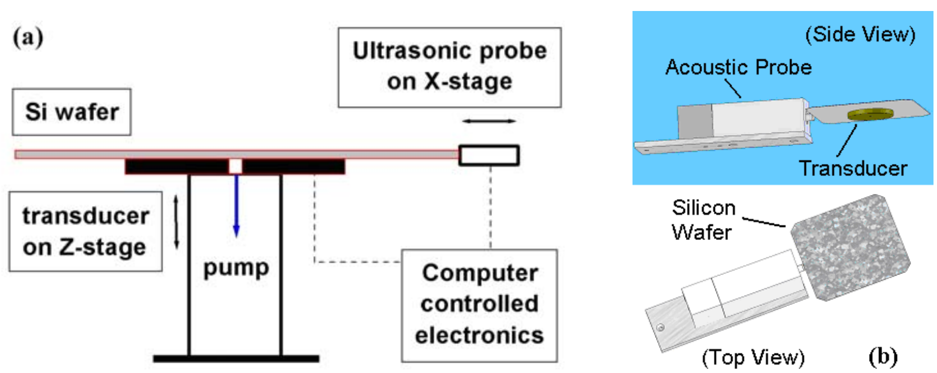


Figure B1. (a) A schematic of the experimental RUV system; (b) mutual layout of the transducer, wafer, and probe in the RUV setup

The transducer beneath the wafer serves as both a holding stage via the vacuum coupling with the wafer, as well as serving its primary purpose of inducing resonance vibrations in the form of standing waves into the wafer. The acoustic probe transmits the electrical signal to a computer-controlled lock-in amplifier allowing detection of mV-scale ultrasonic signals with sufficient signal-to-noise ratio. In our experiments, the wafer was excited with longitudinal vibrations and a peak resonance of vibrations was detected at specific frequencies controlled primarily by the wafer's size and elastic properties.

When performing RUV experiments with wafers of new sizes or geometries, full-spectrum measurements are conducted to locate the exact position of suitable resonance peaks. By exciting the wafers over a wide range of frequencies, we can define the natural resonance frequencies. These peaks are characterized by narrow bandwidth, large amplitude, and peak separation. Once the resonance peaks are located, further crack analysis is possible on a set of similar wafers. By comparing resonance-peak properties, including frequency position, bandwidth, and amplitude, of wafers with similar geometries, crystal defects such as cracks or chips can be quickly detected. The RUV method is capable of fast, precise measurements within seconds. The interval includes wafer loading, data acquisition, analyses, and wafer unloading. This high-speed measurement makes the RUV system a potential candidate for in-line crack detection matching the throughput rate of the production line. Scanning Acoustic Microscopy (SAM) was used as a supporting method to visualize cracks with highest resolution of 10 microns. SAM techniques are described elsewhere [8].

B3. RUV Mode Identification

Specific resonance vibration modes were found by first measuring a full-spectrum frequency scan on the representative cast and Cz-Si wafers with an illustrative example presented in Figure B2 for a 156 mm x 156 mm cast Si wafer. RUV in square-shaped wafers of different accepted photovoltaic industry standard sizes were measured and their peak positions are summarized in Table 1. Each experimental peak represents a particular vibration mode that is compared with FEA results. FEA parameters for analysis include a size-specific mesh with square-shaped 1-mm or 2-mm individual elements. The silicon wafer is modeled as an isotropic thin plate with a Young's modulus of 167 GPa, a Poisson ratio of 0.3, and a density of 2.3 x 10^3 kg/m^3. Free vibrations of the plate were calculated neglecting the effect of the transducer coupling and acoustic probe contact.

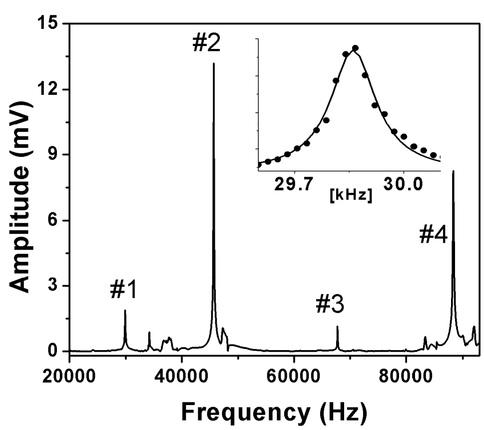


Figure B2. Broad-range frequency scan of 156mm x 156mm cast-Si wafer. Four individual RUV modes are shown. Inset zooms on the #1 mode at ~30 kHz (points) with Lorentzian fit (solid line).

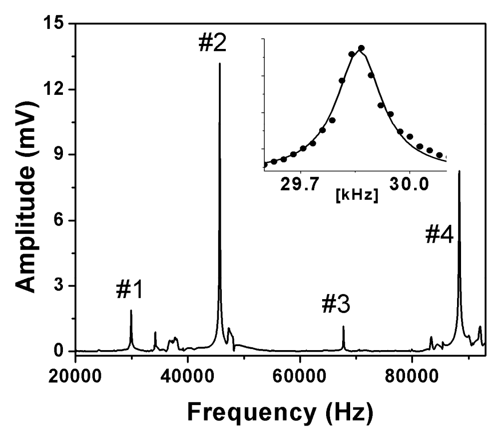


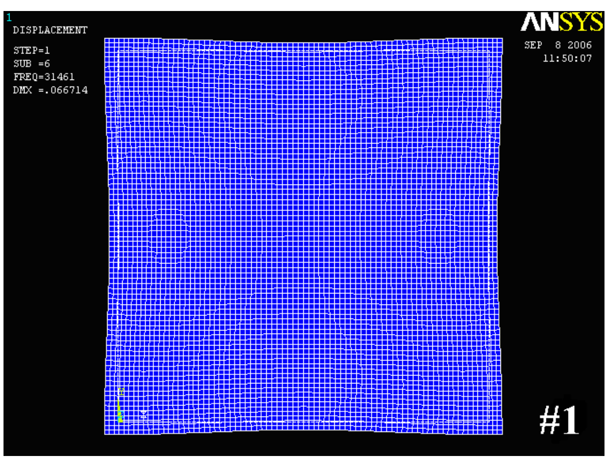
Figure B2. Broad-range frequency scan of 156mm x 156mm cast-Si wafer. Four individual RUV modes are shown. Inset zooms on the #1 mode at ~30 kHz (points) with Lorentzian fit (solid line).

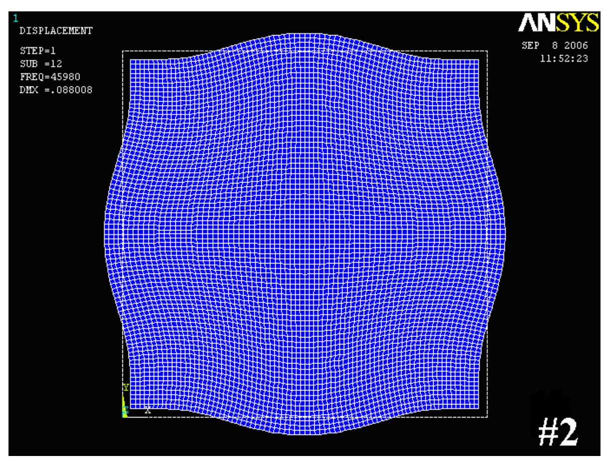
Even in this simplified model, we found a close match of the experimental and calculated frequencies (Table 1) in wafers of different sizes. As expected, the resonance frequency of a specific mode (f_{res}) shifts upward with reducing wafer size (a) and obeys a simple relation, such as $f_{res} \sim a^{-1}$, which is illustrated in Figure B3 in the case of the four vibration modes numbered in Figure 2.

Table 1 Resonance-peak frequencies for four vibration modes in Si wafers of different sizes: (a) experimental data, (b) FEA calculations. Calculated frequencies are rounded to the last digit.

Wafer Size (mm) \ Mode #	1		2		3		4	
	Peak Frequency (kHz)							
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
103 x 103	42.5	47.6	69.8	69.6	-	103.1	-	135.3
125 x 125	37.3	39.3	57.4	57.4	83.8	84.9	-	111.5
156 x 156	29.7	31.5	45.7	45.9	68.2	68.1	87.4	89.3

In Figure B4 (a-d), we present FEA mode shapes for resonance vibrations indicated by arrows and numbers in Figure 2. The data closely follows the experimental and calculated resonance frequencies as seen in Table 1, so we are confident of this mode identification. To further verify this mode identification and to assure that FEA modeling matches the experimental data and provides correct representation of the vibration modes, we conducted an experiment to determine the mode shape from a series of amplitude measurements along a wafer's edge. Once the peak vibration frequency of a specific mode was found, the mode shape was analyzed by conducting a single peak scan along one edge of the symmetrical wafer, noting the amplitude change from point to point that is consistent with peaks and nodes in the modal standing waveform. The resonance peaks were measured with a step size between 3 and 5 mm to construct a representative mode shape. The change in peak amplitude along the edge of the vibrating wafer was found to be similar to the mode shapes at the respective frequency as predicted by FEA. Some asymmetry of the experimental data can be attributed to angular distribution of the transducer's vibrations.





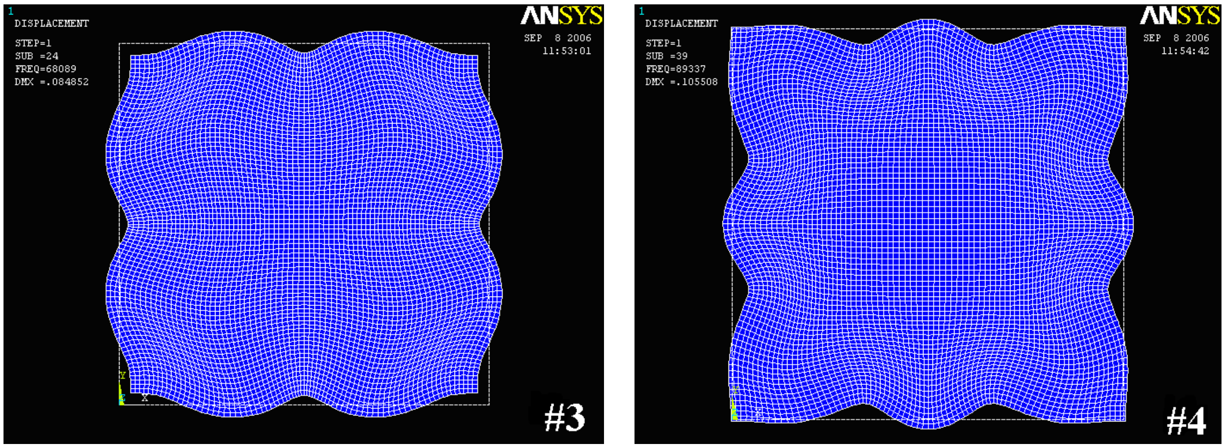


Figure B4 FEA calculated mode shapes corresponding to peaks # 1-4 as seen in Figure 2.

Two unique resonant modes were analyzed at about 30 and 45.6 kHz, which correspond to peaks #1 and #2, respectively (Figure B2), for a 156 mm x 156 mm square-shaped cast-silicon wafer. Figure B5 demonstrates the correlation between the amplitudes of the experimental data and theoretical FEA results. Experimental edge scans on other two vibration modes, #3 and #4, also show close relevance to calculated edge scans. The number of vibration nodes matches for both of the modes. However, an accurate fit of the experimental data is complicated due to a larger number of vibration periods for these high-frequency modes and limited spatial resolution of the probe. Good correlation between the experiment and the FEA modeling will serve as a guideline for crack-influenced frequency-shifting behavior.

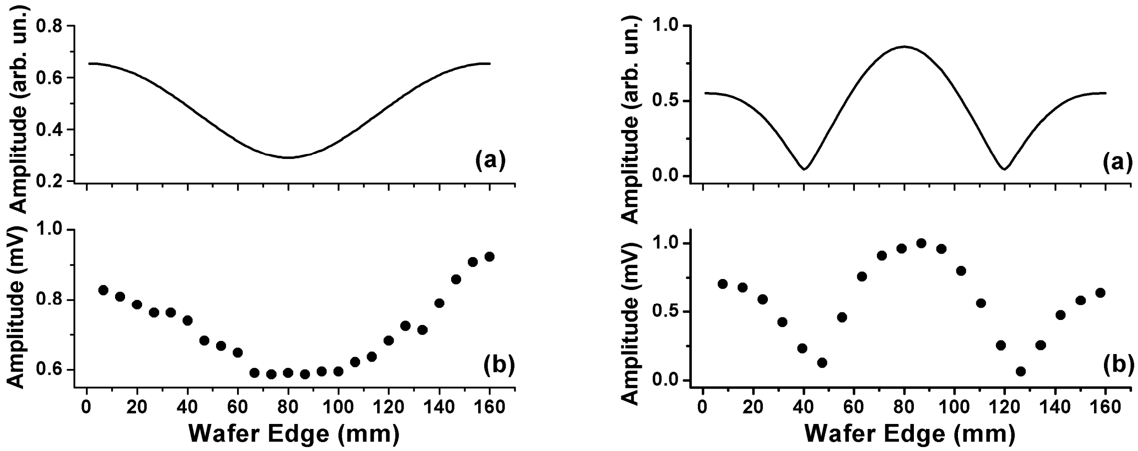


Figure B5 Amplitude variation of the RUV mode along the wafer edge representing Peak 1 at 30 kHz (left) and peak 2 at 45.6 KHz (right). (a) FEA modeling, (b) experimental data.

B4. RUV Crack Detection [9]

Due to the fact that finding naturally occurring cracks with the precise position and length necessary for analysis is nearly impossible, cracks were intentionally introduced into the

(100)-oriented Cz-Si wafer. This was achieved by notching the wafer near the edge at the intended crack location with a diamond-tipped scribe. Consistently increasing the pressure until a cracking sound was heard usually achieved the desired results (Figure 6).

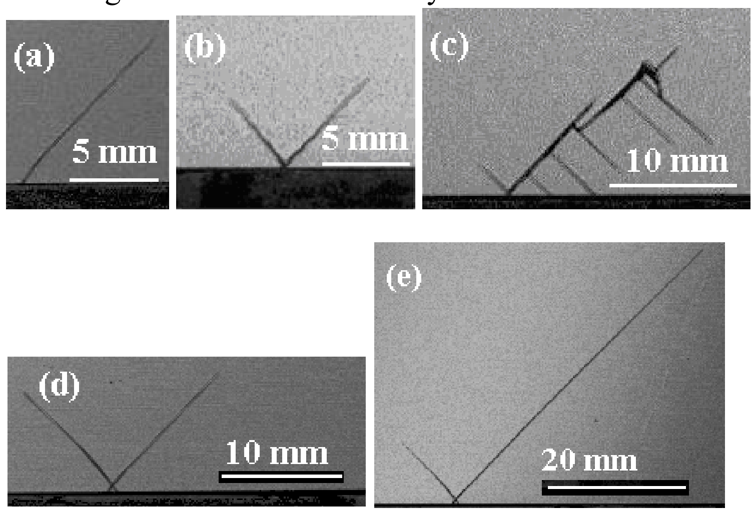


Figure B6. SAM images present possible crack-propagation orientations a) single, b) dual, c) incorrectly formed branched crack, d) wafer with initial induced crack, and e) same wafer after successful elongation.

Because of the possibility for crack propagation in either of two cleavage crystallographic <110> directions, the crack had to be coaxed to propagate in the required direction. This could generally be achieved by scratching (mm-length) the wafer surface along the intended propagation direction and then poking the wafer edge with the diamond scribe. Crack generation without initial directional forcing damage was often used due to its ease and lack of extra wafer damage from scribing. Single cracks typically appeared in either 'left' or 'right' crystal directions or as dual cracks heading in both directions simultaneously from the point of pressurization. Crack elongation can be achieved by finding the tip of the initial crack and slightly pressurizing it with the diamond scribe; this can lead to crack "branching," as illustrated in Figure B6c. To avoid this undesirable effect, a consistent crack elongation without 'branching' cracks can be achieved by precise pressurizing at the crack tip, as seen in Figures B6e and B6f.

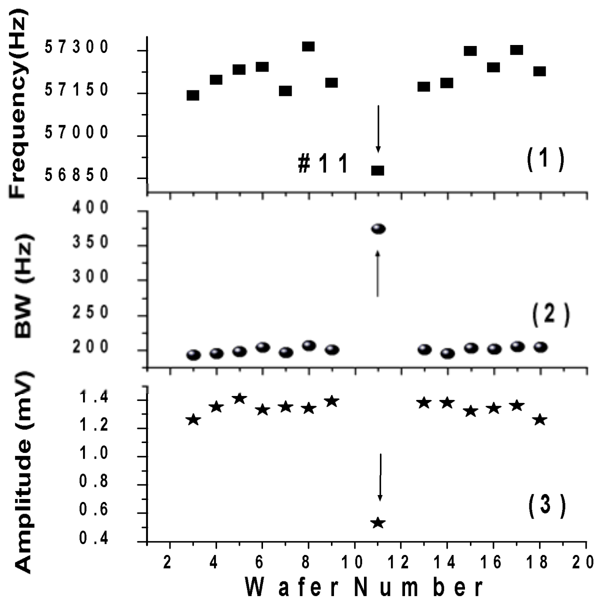


Figure B7 Crack-detection run on a set of 125mm x 125mm cast wafers with the wafer #11 possessing 10 mm periphery crack identified by RUV parameter variations (1) peak position, (2) peak bandwidth, and (3) peak amplitude.

We performed an RUV experiment on a set of identical (125 mm x 125 mm) production-grade cast wafers with the results presented in Figure B7. This sequential RUV data collection and analysis is closely relevant to the solar cell testing routine targeting to reject mechanically unstable Si wafers in PV production. Three parameters of the RUV peak were analyzed: peak position, peak bandwidth, and peak amplitude. One of the wafers (# 11) was clearly an outlier inconsistent with the other wafers. Using SAM measurements, we confirmed that this wafer had a 10-mm periphery crack that was clearly observed in the RUV testing.

B5. Crack Elongation

In Figure B8, we show a variation of the RUV f-scan of the resonance vibration peak at 41.4 kHz (non-cracked wafer) caused by the 16-mm crack located on the wafer's corner and the same wafer with the crack elongated up to 34 mm. The data are presented for 125 mm x 125 mm Cz-Si wafer (#27a) with 220-micron thickness. This is the very first experimental justification on a gradual variation of the RUV peak parameters with crack length performed on the same Si wafer. For this study, we used a specially designed experimental apparatus that allowed the wafer with initial "seed" crack to be bent with constant computer-controlled bending speed and bending amplitude. The wafer was positioned in a clamping device with a single corner exposed. The device was clamped along a 45-degree angle relating to a crystallographic <110> direction. The alignment was achieved using a previously cleaved Cz-Si "dummy" wafer. With the wafer clamped in the machine along its edge, a stepper-motor-controlled rod exerted downward pressure at the exposed corner of the wafer. Slow stepping speeds of about 40 microns per second were used with maximum amplitude of the wafer's exposed corner deflection varied from 1 to 3 mm. In Figure B9, we present SAM images of the wafer part subjected to initial crack (a) and elongated crack (b). The effect of a crack elongation is quite substantial. It can be specified as a gradual downward peak shift, increase of the peak and width, and a strong reduction of the peak amplitude. These RUV signatures of the crack are consistent with previously observed data in Ref. [1].

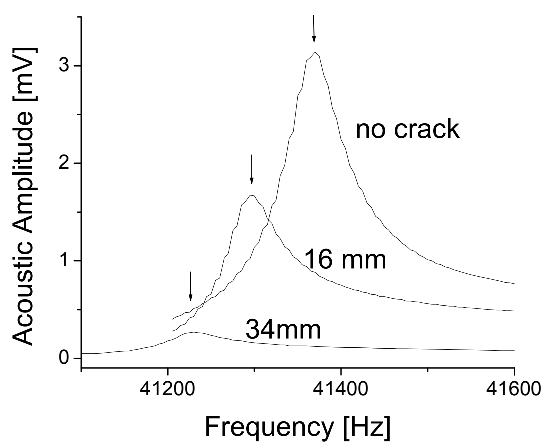
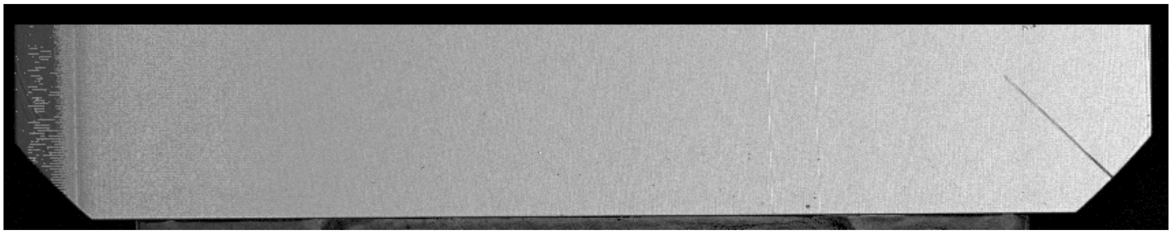


Figure B8: RUV scans on the same Cz-Si wafer (#27A) after two consecutive crack elongations.



(a)

(b)

Figure B9: Scanning Acoustic Microscopy images measured in the reflection ultrasonic beam mode at 75 MHz with 50 microns lateral resolution on the wafer #27a with crack length of (a) 16 mm and (b) 34 mm. Initial wafer (data not shown) had no crack longer than 50 µm.

B6. Cz-Si Wafers – Statistical Study

To justify the applicability of the RUV method on processed silicon wafers and identify potential problems, we performed a statistical study using a set of 100 as-cut Cz-Si wafers (125 mm x 125 mm, nominal thickness 220 microns) that was initially measured with the RUV technique. This set then passed through consecutive solar cell production steps, which included surface texturing, centrifuge drying, diffusion, plasma and HF etching, anti-reflecting (AR) coating with SiN layer, metallization with front and back contacts, and contact stripes soldering. The processing was performed in commercial facilities of a solar cell producer. After each step, the entire set was returned and remeasured with the RUV technique. The objective of this study was to justify usage of the RUV system at different solar cell production steps. In Table 2, we present data of

Table 2: RUV statistics in as-cut Cz-Si wafers

	Mean Value	Std.Dev	% Std.Dev.
Amplitude	0.47	0.09	19.1
Bandwidth	122.0	14.7	12.0
Peak	58616	71	0.12

the RUV statistics in as-cut wafers. It is clear that, compared to cast wafers, the standard deviation (S.D.) of all parameters is much smaller, confirming a high level of identity of the Cz wafers. Specifically, we observed the bandwidth S.D. of only 14.7 Hz compared to 33 Hz in cast and 171 Hz in EFG wafers. As a result, crack-detection sensitivity is highest in Cz-Si wafers, followed by cast and then by EFG.

These data, along with variation of the standard deviation (not shown), document that RUV method sensitivity with respect to crack length is highest at the initial processing steps due to narrow statistical distribution and is lowest after contact stripe soldering.

B7. Ruv System Stability and Accuracy: Fast Mode

To explore stability and performance of the RUV system, we performed experiments by using RUV metrology with different cycling time by reducing measurement time down to a targeted 2.0 seconds per cycle. The entire RUV measurement cycle consisted of the consecutive steps: wafer loading from a home position on the transducer by vacuum-coupling the wafer and transducer, lifting the transducer with the wafer to a measuring position using computer-controlled Z-stage, contacting the wafer's edge by ultrasonic probe using computer-controlled X-stage, data acquisition by measuring f-scan, Lorentzian fit of the experimental data, and wafer unloading to the home position. The duration of the measuring cycle can be varied by changing the number of data points per f-scan or lock-in amplifier integration time. In Figure B10, we show the frequency sweeps performed with different data points per f-scan (from 100 to 10) and cycling time from 12.4 seconds down to 2.0 seconds per cycle. We found that 2.0 seconds per wafer is an achievable throughput rate of the RUV system. Reduction of the data points per scan provides only a small variation of the f-scan parameters. Specifically, peak amplitude is reduced by 16%, peak bandwidth is reduced by 7 Hz (5%), and peak position is changed by 14 Hz. These variations are much smaller compared to typical standard deviations of corresponding distributions for any type of silicon-wafer technology. Therefore, a fast 2.0 seconds cycle time was used in these experiments.

Another practical aspect explored in this project is how a minimum cycle time of 2.0 seconds depends on specific hardware parameters. In Figure B11, we show a dependence of the cycle time versus integration time-constant of different lock-in amplifiers used in this study. It is obvious that reduction of the acquisition time with the lock-in time-constant provides speeding up of the entire process but leads to deterioration of signal/noise ratio. We noticed that various hardware systems respond differently to this parameter. According to the data in Figure B11, the lock-in amplifier #2 shows a superior performance reducing a cycling time below 2.0 seconds. This is a very encouraging result, proving that further acceleration of the RUV technique is possible with optimizing regime of the hardware and software.

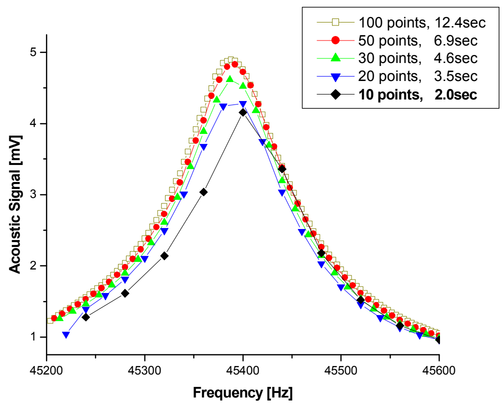


Figure B10: RUV scans measured with different time. The shortest time is 2.0 sec per scan.

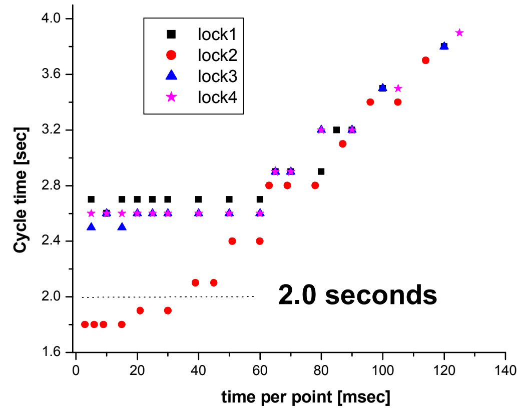


Figure B11: comparison of different lockin detectors for fast RUV scans.

In Figure B12, we show a special experimental setting that essentially models a practical use of the RUV system in a solar cell production line. In this experiment, the same Si wafer was multiple measured by the RUV system in the same manner through an entire measuring cycle and data of individual measurements were compared and plotted after Lorentzian fit of the f-curve. Two runs each of 582 cycles were performed with the same cast-Si wafer. Though generally we found a consistency between these two runs, a slow variation of the RUV parameters is recorded. For instance, peak position is shifted upward by about 60 Hz, peak amplitude is reduced from 0.5 to 0.4 mV (20%), and bandwidth is essentially not changed. One technical problem was identified as a gradual variation of a vacuum coupling between the transducer and wafer. This effect has to be eliminated to assure higher stability of the RUV system as a production-grade in-line testing system. We documented that statistical variations of the data during each run are relatively small, showing a standard deviation of 0.06 mV for peak amplitude, 9-11 Hz for peak bandwidth, and 14 – 16 Hz for peak

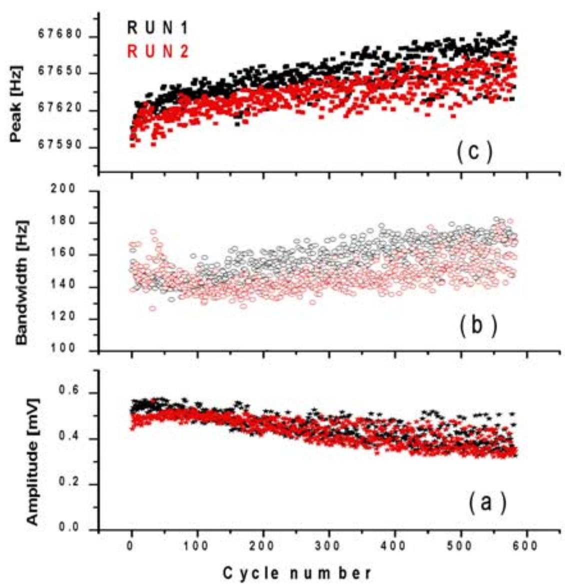


Figure B12: Two runs of the multiple RUV scans performed on the same cast silicon wafer measured consecutively 582 times per each run. Individual cycle time was 2.0 seconds with 1.0 second pause between the cycles.

position. These values are substantially lower than the similar parameter of the wafer's statistical variations as presented in previous sections.

Key Findings:

The key findings of the resonance ultrasonic vibrations study are as follows:

- Vibration modes observed in the range from 20 to 100 kHz in silicon wafers of different standard size and geometry were identified.
- Applicability of the RUV method for periphery crack detection in production-grade cast wafers was justified.
- RUV method sensitivity was demonstrated using a crack-elongation study.
- Statistical analyses on the production-grade set of cast wafers to reject wafers with cracks was performed.
- RUV methodology is applicable to all major Si wafer technologies used in solar cell production, such as single-crystal (Cz), cast, and ribbon (EFG). RUV method sensitivity is different for each type of Si materials due to the statistical distribution of the wafer's characteristics. It is highest in Cz-Si, followed by cast and EFG.
- The experimental RUV system (hardware and software) can match the 2.0 seconds per wafer throughput rate in state-of-art solar cell production lines. This time can be further shortened by optimizing system hardware and programming options.

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Appendix A

Listing of Reports and Papers Published

2002

Danyluk, S.[1], Ostapenko, S.[2], He, S.,[1] Tarasov, I.[2], Lulu, S.[2], and Belyaev, A.[2], "Full Field Birefringence Measurements of Grown-in Stresses in Thin Silicon Sheet," [1]Georgia Institute of Technology, Atlanta, GA, [2]University of South Florida, Tampa, FL, Quarterly Report for period of January 2 – March 31, 2002.

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2008

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Danyluk, S., Li, F., “Li, F., and Danyluk, S., “Extraction of Principle Stresses from Polariscopy Measurements,” Presented at the 18th Workshop on Crystalline Silicon Solar Cells & Modules: Materials & Processes, Vail, CO, August 3-6, 2008.

Appendix B

Students Trained Under the Program

Student Name	Thesis Title	Graduation Date/Degree	Current Employment
Georgia Tech			
Shijiang He	Near Infrared Photoelasticity of Polycrystalline Silicon and it's Relation to In-Plane Residual Stress	Fall 2005/PhD	Intel
Victoria Garcia	Effect of Dislocation Density on Residual Stress in Polycrystalline Silicon Wafers	Spring 2008/MS	NASA, Huntsville, AL
Fang Li	TBD	Summer 2009/PhD	Georgia Institute of Technology
University of South Florida			
Igor Tarasov	Scanning Photoluminescence in PV Silicon Wafers	2004/PhD	SDI
Anton Belyaev	Stress Diagnostics and Crack Detection in Full-Size Si Wafers using Resonance Ultrasonic Vibrations	2005/PhD	SDI
William Dallas	Resonance Ultrasonic Vibrations for Crack Detection in Si Wafers for Solar Cells	2006 /MS	
Andrii Monastyrskyi	RUV Technique for In-Line Crack Detection in PV Silicon Wafers and Solar Cells	2008/MS	
Christina Hilmerson	Detection of Cracks in Single-Crystalline Si Wafers using Impact Testing	2006/MS	
Oleg Polupan	None	2007/Bachelor	

REPORT DOCUMENTATION PAGE

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14. ABSTRACT *(Maximum 200 Words)*
The primary concern of this research was to develop fundamental knowledge about residual stresses and microcracks and defects in silicon sheet. During the work, two groups developed new experimental techniques to obtain shear stresses and microcracks in sheet silicon. One technique involves infrared photoelasticity, which measures the residual stress-induced birefringence. The residual stresses are related to the birefringence through the stress-optic coefficient described in this report. Anisotropy, thickness, and microstructure are some of the key parameters that affect birefringence, and these topics were investigated as they relate to in-plane residual stresses. In the experimental system developed at Georgia Tech, the anisotropy thickness and microstructure were accounted for by using a four-point bending technique, and were ultimately used to determine the principal stresses in silicon wafers. The work at the University of South Florida focused on using acoustic techniques (resonance ultrasonic vibrations) to determine the existence of microcracks – usually edge cracks – in thin silicon wafers.

15. SUBJECT TERMS
PV; full-field birefringence; residual stress; silicon sheet; infrared photoelasticity; silicon wafer; crack detection; resonance ultrasonic vibration;

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