Stress diagnostics and crack detection in full-size silicon wafers using resonance ultrasonic vibrations

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Stress Diagnostics and Crack Detection in Full-Size Silicon Wafers Using Resonance Ultrasonic Vibrations

by

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Table of Contents

List of Tables 4
List of Figures 5
Abstract 8

1. Introduction 10
   1.1. Scope and motivation 10
   1.2. Objectives 12

2. Literature Survey 14
   2.1. Introduction 14
   2.2. Silicon as solar cell material 15
       2.2.1. Single-crystalline silicon 17
       2.2.2. Multicrystalline silicon 18
       2.2.3. Amorphous silicon 19
   2.3. Elastic stress and cracks in commercial silicon solar cells 20
   2.4. Experimental methods for measuring residual stress 23
       2.4.1. Raman spectroscopy 23
       2.4.2. X-Ray diffraction 29
       2.4.3. Polariscope technique 35
           2.4.3.1. Linear scanning polarscope technique 35
           2.4.3.2. Full-field near infrared polarscope technique 40
   2.5. Experimental methods for crack detection 46
       2.5.1. Scanning acoustic microscopy 47
       2.5.2. Ultrasound lock-in thermography 52
       2.5.3. Millimeter waves 55

3. Experimental 59
   3.1. Hardware 59
       3.1.1. Setup for resonance ultrasonic vibrations (RUV) measurements 59
       3.1.2. Infrared polarscope setup for residual elastic stress measurements 62
       3.1.3. Scanning acoustic microscope 64
   3.2. Finite element modeling 67
   3.3. Samples 68

4. Results and Discussion 69
   4.1. Resonance ultrasonic vibrations approach for stress evaluation in full-sized silicon wafers 69
       4.1.1. Single crystal Czochralski silicon 70
4.1.1.1. Analytical modeling
4.1.1.2. Resonance ultrasonic vibrations data
4.1.1.3. Chladni figures
4.1.2. Edge-defined film-fed growth silicon wafers
   4.1.2.1. Scanning acoustic microscopy results
   4.1.2.2. Residual elastic stress data by linear infrared polariscopy technique
   4.1.2.3. Resonance ultrasonic vibrations data
   4.1.2.4. Bending test
4.2. Crack detection and analyses using resonance ultrasonic vibrations
   4.2.1. Initial measurements
   4.2.2. Crack engineering
5. Conclusions and Recommendations

References
About the Author
List of Tables

Table 1  The set of vital parameters of the methods for measuring residual elastic stresses 45

Table 2  The set of vital parameters of the methods for crack inspection in wafers 58

Table 3  The set of roots of the equation (11) 73

Table 4  Resonant frequencies [Hz] of radial angular independent longitudinal vibrations 76

Table 5  Average thickness, average and peak stress, and resonance vibration frequencies of 100mm x 100mm EFG wafers 87

Table 6  Average experimental resonance frequencies [Hz] of the three selected longitudinal vibration modes 89
List of Figures

Figure 1  A typical photovoltaic cell diagram 15
Figure 2  Energy distribution of scattered light 24
Figure 3  Energy level diagram for Raman scattering 26
Figure 4  Schematic diagrams of brittle fracture and ductile removal in lapping process when mediated by metallization of the surface 27
Figure 5  Typical Raman spectra taken from lapped silicon wafer surfaces 28
Figure 6  A Raman map from the edge of a wafer after edge-grinding 29
Figure 7  Different schematics of XRD techniques 30
Figure 8  X-ray images of a 7 μm thickness epitaxial film on (100)-oriented silicon wafer 33
Figure 9  Rocking curve of a heteroepitaxial Si_{0.80}Ge_{0.20} film (150 nm) on (100) Si [35] 34
Figure 10 Infrared birefringence experimental layout 36
Figure 11 Result of strain field mapping in EFG multicrystalline Si wafers. Mapping size 100mm x 100mm, step= 1.0mm 39
Figure 12 Experimental setup of the full field infrared residual stress polariscope 41
Figure 13 Fringe multiplier with two beam splitters 42
Figure 14 Mapping of residual stresses of the same EFG-Si wafer 44
Figure 15 SAM image of the initial crack on the wafer captured in the red box 49
Figure 16 SAM image of the same area of the wafer as Figure 15 after applied stress 50
Figure 17  SAM image of internal crack  51
Figure 18  Principle of ultrasound lock-in thermography  52
Figure 19  The ULT principal setup  53
Figure 20  ULT image of the inner crack in mc-Si wafer  54
Figure 21  Principal configuration of the millimeter wave measurement system  56
Figure 22  Millimeter wave image of the 125x125mm polycrystalline silicon wafer  57
Figure 23  Experimental set-up for resonance ultrasonic vibration (RUV) measurements  60
Figure 24  Schematic of the setup for scanning linear infrared polariscopy measurements  62
Figure 25  Principal setup for SAM operation  65
Figure 26  Cross section of the transducer and the intensity of acoustic field  66
Figure 27  Normal frequencies of the longitudinal vibrations in circle silicon wafers of different diameters  74
Figure 28  Frequency scan measured on 300mm Cz-Si wafer with indicated by arrows first three radial modes  75
Figure 29  Chladni sand patterns on 300mm Cz-Si wafers for different mode shapes  78
Figure 30  Computed mode shape for 300mm Cz-Si wafer  79
Figure 31  Chladni’s sand patterns observed on 100x100mm EFG-Si wafers, m=2  81
Figure 32  SAM image of the 100mm x 100mm EFG wafer with periphery crack  82
Figure 33  Result of infrared polariscopy stress field mapping  84
Figure 34  Frequency scans at one of principal maximum on two EFG wafers  86
| Figure 35 | Experimentally measured frequencies of the resonance longitudinal vibration mode versus average stress in a set of 100mm x 100mm EFG wafers |
| Figure 36 | Finite element analysis calculations of the first two principal mode shapes |
| Figure 37 | Schematics of the four-point bending test |
| Figure 38 | Frequency curves of the resonance vibration mode at different load values using 5-point bending test |
| Figure 39 | Full range ultrasonic frequency spectrum obtained on Cz-Si wafer #1 |
| Figure 40 | SAM image of the 125mm x 125mm Cz-Si wafer with introduced 28mm periphery crack |
| Figure 41 | The A-mode spectra of non cracked wafer and wafers with different crack lengths |
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ABSTRACT

Non-destructive monitoring of residual elastic stress in silicon wafers is a matter of strong concern for modern photovoltaic industry. The excess stress can generate cracks within the crystalline structure, which further may lead to wafer breakage. Cracks diagnostics and reduction in multicrystalline silicon, for example, are ones of the most important issues in photovoltaics now. The industry is intent to improve the yield of solar cells fabrication. There is a number of techniques to measure residual stress in semiconductor materials today. They include Raman spectroscopy, X-ray diffraction and infrared polariscopy. None of these methods are applicable for in-line diagnostics of residual elastic stress in silicon wafers for solar cells. Moreover, the method has to be fast enough to fit in solar cell sequential production line. In photovoltaics, fast in-line quality control has to be performed within two seconds per wafer to match the throughput of the production lines.

During this Ph.D. research we developed the resonance ultrasonic vibration (RUV) approach to diagnose residual stress non-destructively in full-size multicrystalline
silicon wafers used in solar cell manufacturing. This method is based on excitation of longitudinal resonance ultrasonic vibrations in the material using an external piezoelectric transducer combined with high sensitive ultrasonic probe and data acquisition of the frequency response to make the method suitable for in-line diagnostics during wafer and cell manufacturing. Theoretical and experimental analyses of the vibration mode in single crystal and multicrystalline silicon wafers were used to provide a benchmark reference analysis and validation of the approach. Importantly, we observed a clear trend of increasing resonance frequency of the longitudinal vibration mode with higher average in-plane stress obtained with scanning infrared polariscopy.

Using the same experimental approach we assessed a fast crack detection and length determination in full-size solar-grade crystalline silicon wafers. We demonstrated on a set of identical non-processed crystalline Si wafers with introduced periphery cracks that the crack shifts a selected RUV peak to a lower frequency and increases the resonance peak’s half-width. Both characteristics are gradually increased with the length of the crack. This was confirmed also theoretically by performing finite element analysis of longitudinal vibrations of wafers with cracks. The frequency shift and peak half-width were found to be reliable indicators of the crack appearance in silicon wafers suitable for mechanical quality control and fast wafer’s inspection.

Resonance ultrasonic vibrations metrology is a promising technique to provide quality control in full-size silicon wafers. This approach has the potential to be further developed into a diagnostic tool to address the needs of silicon wafer manufacturers, both in the microelectronic and the solar cell industries.
1. Introduction

“Sooner or later we shall have to go directly to the Sun for our major supply of power. This problem of the direct conversion from sunlight into power will occupy more and more of our attention as time goes on and eventually it must be solved…”

Edison Pettit, Wilson Observatory, 1932

1.1. Scope and motivation

The energy consumed by mankind now is mostly dependent on fossil fuels such as oil and coal. They are the cheapest and the most affordable sources of energy known to man today. Mankind is now facing the problem of shortage in fossil fuels and also the trend of environment pollution increase that has been observed over recent decades. Therefore, the possibility of using safe and virtually inexhaustible solar power draws a vast attention of scientists and engineers.

At the present moment, renewable energy technologies continue to grow and develop. Being one of its major players, the photovoltaic (PV) industry, with crystalline silicon as a dominant segment, is expanding rapidly to meet growing energy demands all
over the world [1]. However, for crystalline silicon (Si) cells to satisfy future energy requirements, there is still a significant need for improvements in manufacturing to increase throughput and production yield. One of the current technological problems is to identify and eliminate sources of mechanical defects such as thermo-elastic stress and cracks leading to the loss of wafer integrity and, ultimately, breakage of Si wafers and cells during the production process.

Stress in solar-grade silicon wafers is one of the sources of wafer breakage which reduce the production yield of solar cells by up to 25% depending on wafer technology and processing steps. Moreover, stress can be a driving force for various types of defect reactions, such as precipitation of residual impurities at dislocations deteriorating the electronic quality of material [2]. There are a number of experimental techniques available to diagnose residual stress and detect cracks in wafers used in the semiconductor industry. However, none of these methods are suitable in their present form for rapid in-line stress diagnostics of as-grown and processed Si wafers. In the PV industry fast in-line quality control requires methods which achieve measurement times of around 2 seconds per wafer to match the throughput of typical production lines.

Ultrasonic testing is a well-established approach in the family of methods classified as non-destructive analyses in materials and devices. One can use ultrasonic vibrations for quality assurance purposes detecting both micro and macro defects. An approach to measure stress and assess factors which affect the mechanical quality of full-size silicon wafers was proposed by Ostapenko et al [3]. It was based on the excitation of a specific flexural resonance vibration mode, assigned as “whistle” mode in the wafer using an external piezoelectric transducer combined with a non-contact acoustic sensor
and high speed data acquisition to provide information on the frequency response over the entire wafer area. In the case of the circular 200 mm Czochralski silicon wafers, this approach allowed tracking of stresses in wafers with nanometer thick oxides, and also to assess wafers with as-grown bulk defects [4]. A similar ultrasonic technique utilizing flexural vibrations was later extended to multicrystalline silicon wafers [5]. The principal goal of this presented work was to establish the fundamentals of the resonance ultrasonic vibration (RUV) methodology, analyze its physical aspects in terms of wafer integrity and provide diagnostics on stress and detection of cracks in commercial grade full-size crystalline silicon wafers.

1.2. Objectives

The objectives of the research project were:

i) To develop a non-destructive methodology of the RUV technique applicable to full-size single-crystal and multi-crystalline silicon wafers primarily for photovoltaic application.

ii) To develop a physical model of the RUV method based on excitation of the longitudinal ultrasonic vibrations in wafers of different shape and size.

iii) To perform computer simulations using the physical model and compare theoretical results with experimental RUV data.

iv) To apply the RUV method to non-destructive rapid diagnostics of residual elastic stress in multicrystalline silicon wafers used in solar cell production.
v) To make the method suitable for crack detection and its length determination in full-size solar-grade crystalline silicon wafers.

vi) To design the prototype hardware system for mechanical quality control and fast wafer inspection.
2. Literature Survey

2.1. Introduction

The market for commercial photovoltaics today is fully dominated by silicon-based technology. It has been predicted that the mc-Si efficiency of commercial solar cells would reach 18 to 20% in 5 years, which is confirmed by record numbers of laboratory efficiencies of 17.8% (Georgia Institute of Technology, 2003) and crystalline silicon will be the dominant PV technology for the next 15-20 years [6]. Besides, there is currently no promising technology that can compete with crystalline silicon. The ultimate challenges are still the same: to increase solar cell efficiency and to reduce cost, which is, obviously, difficult to achieve at the same time. There also will be continuous increases in wafer size, yield and power output, while the wafer thickness decreases. And one of the current technological problems is to identify and eliminate sources of mechanical defects such as thermo-elastic stress and cracks leading to the loss of wafer integrity and ultimate breakage of as-grown and processed Si wafers and cells. The problem is enhanced as a result of the current strategy of reducing wafer thickness down to 100 microns. For instance, cracks generated during wafer sawing or laser cutting can propagate due to wafer handling and during solar cell processing such as, phosphorous diffusion, anti-reflecting coating, front back contact firing, and soldering of contact
“fingers” (Figure 1). It is recognized that the development of a methodology for fast in-line crack detection and control is required to match the throughput of typical production lines.

![Diagram of a photovoltaic cell](Image)

Figure 1. A typical photovoltaic cell’s diagram (Property of DoE).

2.2. Silicon as solar cell material

Solar cells can be made from a wide range of semiconductor materials, which can be subdivided into three categories: crystalline bulk silicon, polycrystalline thin films and single-crystalline thin films. Polycrystalline thin films include copper indium diselenide, cadmium telluride, and thin-film silicon. Single-crystalline thin films cover high-efficiency materials such as gallium arsenide. Crystalline silicon segment of the PV market is the largest and still the most popular. Silicon is being used in three different
forms of crystallinity: crystalline Si, multicrystalline Si, and amorphous Si. Silicon is the second-most abundant element in the Earth's crust, after oxygen. However, to be useful as a semiconductor material in solar cells, silicon must be refined to a purity of 99.9999%.

In single-crystalline silicon, the molecular structure, which is the arrangement of atoms in the material, is uniform, because the entire structure is grown from the same crystal. This uniformity is ideal for transferring electrons efficiently through the material. To make an effective PV cell, however, silicon has to be doped with other elements to make it n-type or p-type.

Polycrystalline silicon also known as multicrystalline Si (mc-Si), in contrast, consists of several smaller crystals or grains, which introduce boundaries. These boundaries impede the flow of electrons and encourage them to recombine with holes to reduce the power output of the solar cell. However, mc-Si is much less expensive to produce than single-crystalline silicon. Therefore researchers are working on other ways to minimize the effects of grain boundaries and inter-grain defects.

Silicon is obtained from the reduction of quartzite or sand. The first technological step is to derive the metallurgical-grade silicon (MGS) which contains large quantities of impurities. Various refining processes are utilized to remove those impurities. These refining processes have to be effective but inexpensive – it is an ultimate benchmark for modern PV industry nowadays. So far, solar grade Si is still a low quality Si, with a high concentration of impurities and defects ($10^{12}$-$10^{14}$ cm$^{-3}$), whose effects may be crucial for the final photovoltaic devices [7].
2.2.1. Single-crystalline silicon

In order to create silicon in a single-crystal state, one must to first melt high-purity silicon. One then causes it to solidify very slowly in contact with a single crystal "seed." The silicon replicates the crystal structure of the single-crystal seed as it cools and gradually solidifies. Several different processes can be used to grow a boule of single-crystal silicon. The most well-known and reliable processes are the Czochralski (Cz) method and the float-zone (FZ) technique. The "ribbon-growth" technique will also be discussed as it has been employed by the PV industry.

In the Czochralski method, a seed crystal is dipped into a crucible of molten silicon and withdrawn slowly, pulling a cylindrical single crystal as the silicon crystallizes on the seed [8].

The float-zone growth technique makes purer crystals than the Cz method, because they are not contaminated by the crucible used in growing Cz crystals. In the FZ growth, a silicon rod is located atop a seed crystal and then lowered through an electromagnetic coil. The coil's magnetic field induces an electric field in the rod, heating and melting the interface between the rod and the seed. Single-crystal silicon starts formation at the interface, growing upward as the electromagnetic coils are slowly raised [9].

Once the single-crystal rods are produced, by either with the Cz or FZ method, they are usually sliced to form thin wafers a few hundred microns in thickness. The resulting thin wafers are doped, followed by a coating to reduce reflection, and coated
with electrical contacts to form functioning PV solar cells. However, such slicing is a source of wasting as much as 20% of the silicon ingot in the form of sawdust. Therefore, there is always a trend of searching for cheaper ways of production.

2.2.2. Multicrystalline silicon

Devices built of multicrystalline silicon (mc-Si) are generally less efficient than those of single-crystal silicon, but they are less expensive to make. There are several methods of producing multicrystalline silicon such as ingot casting, Tri-crystal growth or ribbon growth. The most popular methods use a casting process in which molten silicon is directly cast into a mold and allowed to solidify into an ingot. The starting material for this method is usually lower-grade silicon, unlike the higher-grade semiconductor grade required for single-crystal material. The cooling rate is one factor that determines the final size of crystals in the ingot and the distribution of impurities [10].

The "ribbon growth" technique - edge-defined film-fed growth (EFG) - starts with two crystal seeds that grow and capture a sheet of material between them as they are pulled from a source of molten silicon. A frame holds the thin sheet of material when pulled from the melt. This technique does not waste much material, but the quality of the material is not as high as Cz and FZ silicon [10].

It should be noted that mc-Si wafers contain impurities and crystal defects, such as grain boundaries and dislocations with a higher concentration than found in single-crystalline Si [11].
2.2.3. Amorphous silicon

Amorphous silicon is produced in high frequency furnaces in a partial vacuum atmosphere. In the presence of a high frequency electrical field, gases like silane, B$_2$H$_6$ or PH$_3$ are blown through the furnaces supplying silicon with boron or phosphorus [12].

Amorphous silicon does not have the structural uniformity of single- or multicrystalline silicon. Small deviations in this material result in defects such as "dangling bonds", where atoms lack a neighbor to which they can bond. These defects provide places for electrons to recombine with holes, rather than contributing to the electrical circuit [13]. Generally speaking, amorphous silicon would be unacceptable for electronic devices, because defects limit the flow of current. But it can be deposited so that it contains a small amount of hydrogen, in a process called "hydrogenation." The result is that the hydrogen atoms combine chemically with many of the dangling bonds, essentially removing them and permitting electrons to move through the material [14]. Today, hydrogenated amorphous silicon is used to produce low efficiency (~ 10%) solar-powered consumer devices that have low power requirements, such as wristwatches and calculators.
2.3. Elastic stress and cracks in commercial silicon solar cells

One of the major current technological problems for the PV industry is to identify and eliminate potential sources of mechanical defects such as thermo elastic stress and cracks leading to the loss of wafer integrity and ultimate breakage of as-grown and processed silicon wafers and finished solar cells. The problem is of increase concern as a result of the current strategy of reducing wafer thickness down to 100 microns. Wafers having high level of residual elastic stresses behave extremely unpredictably during processing and handling.

The single-crystal Cz ingots for PV are pulled at growth rates that can be many times faster (~ cm/min) than that of the conventional growth for microelectronics. These fast cooling rates are accompanied by excessive thermal stresses that lead to the generation of growth defects: dislocations, defect precipitates, thermo-elastic stresses. It should be noted, that residual elastic stresses caused by ingot sawing, the formation of the front and back contacts, diffusion of the emitter, and deposition of the antireflecting coating may even increase compared to as-grown material. Consequently, the single-crystal material is expected to have high concentrations of nonequilibrium point defects. In some cases, a portion of the ingot may acquire a high density of crystal defects (primarily dislocations) and even lose crystallinity and become multicrystalline [15]. Speaking of which – it should be said that in a case of multicrystalline silicon, stress issues are much more severe. Stress levels in mc-Si wafers are orders of magnitude
higher than in single-crystalline silicon wafers. So, there is always a goal to keep stresses as low as possible after every processing step of solar cell production.

For example, thin solar cells are difficult to interconnect with standard soldering techniques. High temperature during soldering, between 250-400°C, introduces stress on the joints and cells. This can cause warping and possible breakage of cells and decreases yield. The front side of cells suffers from extra stress caused by the tabs going from front to rear in series interconnection. Moreover, extra losses occur due to anti-reflecting coating deposition. Therefore, substituting conventional soldering technique for a low temperature joining method would avoid building up of mechanical stress, again, increasing process yield and reliability [16].

Another issue is the cracks in silicon. Wafer breakage during processing is a very high cost issue. This is particularly true when wafers fail during one of the print steps, generally resulting in several minutes of downtime while the operator cleans up the scattered parts and the wet paste. This is also a source of potential contamination. It is believed that wafers frequently fail at the print steps because they come into the process already cracked and the crack then fails when it is stressed during the process step. Wafer cracks can also cause electrical failure at cell or module test [17].

It was shown that cracks in readily processed solar cells lead to a weak recombination current. However, if a crack is already presented in the wafer before processing, or if it appears during processing before screen-printing the contact metallization, cracks may lead to serious ohmic shunts. If during screen-printing some metal paste penetrates a crack, after firing this may produce especially strong shunts. The
shunts described above may also emerge if there are any holes presented in a cell, e.g., resulting from laser cutting [18]. An example of such a crack in readily processed solar cell is shown in Figure 14.
2.4. Experimental methods for measuring residual stress

2.4.1. Raman spectroscopy

Raman spectroscopy has been utilized to investigate the stresses and phase transformations in semiconductors [19, 20]. Stress maps of Si around indentations have been generated [21]. Quantification of residual stress in a silicon wafer in plane stress was also obtained [22]. Internal stress in semiconductors after machining has also been measured using Raman tensometry [23, 24]. Perhaps, the greatest advantages of Raman spectroscopy are its non-destructive character, the simplicity of the equipment set-up and the short time required for obtaining data with essentially no sample preparation process required and no surface damage. It is also attractive because it can detect both organic and inorganic species and measure the crystallinity of solids. In addition, it is free from charging effects that can influence electron and ion beam techniques.

The light scattered from the surface of the wafer has basically three components (Fig. 2). There are Raleigh scattering (scattering with the incident frequency), Raman and also Brillouin scattering.
The interaction of the incident light with optical phonons is called Raman scattering while the interaction with acoustic phonons results in Brillouin scattering. Optical phonons have higher energies than acoustic phonons giving larger photon energy shifts. However, even for Raman scattering, the energy shift is small. Since the intensity of Raman scattered light is very weak, Raman spectroscopy is only practical when an intense monochromatic light source like laser is used [25].

The Raman effect arises when a photon is incident on molecules comprising a solid state and interacts with the electric dipole of the molecules. When light is scattered from a molecule most photons are elastically scattered. The scattered photons have the
same energy (frequency) and, therefore, wavelength, as the incident photons. However, a small fraction of light (approximately 1 per $10^7$ photons) is scattered at optical frequencies different from, and usually lower than, the frequency of incident photons (Fig. 3). The process leading to this inelastic scatter is termed the Raman effect [26].

![Energy level diagram for Raman scattering (a) Stokes Raman scattering, (b) anti-Stokes Raman scattering.](image)

Figure 3. Energy level diagram for Raman scattering (a) Stokes Raman scattering, (b) anti-Stokes Raman scattering.

The energy difference between the incident and scattered photons is represented by the arrows of different lengths in Figure 3a. The energy is ultimately dissipated as heat. Because of the low intensity of Raman scattering, the heat dissipation does not
cause a measurable temperature rise in a material. A small fraction of the molecules are in vibrationally excited states. Raman scattering from excited molecules leaves the molecule in the ground state. The scattered photon appears at a higher energy, as shown in Figure 3b. This anti-Stokes-shifted Raman spectrum is always weaker than the Stokes-shifted spectrum, but at room temperature it is strong enough to be useful for frequencies less than about 1500 cm$^{-1}$. The Stokes and anti-Stokes spectra contain the same frequency information. The ratio of anti-Stokes to Stokes intensity at any vibrational frequency is a measure of temperature. Anti-Stokes Raman scattering is used for contactless thermometry. The anti-Stokes spectrum is also used when the Stokes spectrum is not directly observable, for example because of poor detector response or spectrograph efficiency.

Cz Si wafers were successfully studied by Raman spectroscopy methods [27]. In these studies wafers were investigated after being subjected by brittle fracture and ductile removal during the lapping process when mediated by metallization of the surface (Fig. 4).
Figure 4. Schematic diagrams of brittle fracture and ductile removal in lapping process when mediated by metallization of the surface. (a) The abrasive grain comes in contact with the surface and a layer is removed by micro fractures, which leaves micro cracks in the underlying layer as deep as 5 to 10 µm. (b) The abrasive grain comes in contact with the surface and pressure-induced metallization. Metallic Si is removed in a ductile manner, the surface is left with a transformed layer approximately 0.1 µm thick.
Pristine Si peaks are shifted from 521 cm\(^{-1}\) to as much as 517 cm\(^{-1}\) due to residual tensile stress at many points of the lapped Cz-Si wafers (Fig. 5). If a compressive stress exists before moving the tool, tensile stress is expected to occur on the surface behind the tool. A shift of 3.2 cm\(^{-1}\) corresponds to 1 GPa [28].

Figure 5. Typical Raman spectra taken from lapped silicon wafer surfaces. (a) Pristine Si, (b) Si under residual tensile stress.

Hence, the evidence of residual stresses comes in the form of shifted peak position. Up-shift of the Raman band is caused by compression while a down-shift is caused by tension. Compression makes the lattice spaces smaller which leads to an increase of the phonon frequencies. The reverse effect, caused by tension, leads to the down-shift of the Raman band. Compressive stresses on the surface are non-uniform with significant variations across most areas.
Since the laser beam can be focused to a small diameter, one can measure stress in localized regions and do mapping of specific interested areas [28].

**2.4.2. X-Ray diffraction**

X-Ray Diffraction (XRD) topography is a nondestructive technique for measuring structural crystal defects [29]. It is attractive due to easy sample preparation and it can give structural information over entire semiconductor wafer. Unlike optical methods, the XRD image cannot be magnified because no lenses are used. X-rays typically have special resolution of 100 microns and above.
If one will consider a defectless crystal subjected to different monochromatic X-rays of wavelength $\lambda$ from lattice planes spaced $d$. There are many possibilities to see what happens to incident beam. One can detect either reflection or transmission of X-rays through the crystal (Fig. 7).

Figure 7. Different schematics of XRD techniques: (a) Berg-Barrett reflection topography, (b) Lang transmission topography, (c) double crystal topography with a rocking curve.
First, consider the Berg-Barrett XRD technique. The X-rays are incident on the sample at an angle $\alpha$, as shown in Figure 7a. The diffracted beam emerges at twice the Bragg angle $\theta_B$ defined by

$$\theta_B = \sin^{-1}(\lambda / 2d)$$  \hspace{1cm} (1)

The diffracted X-rays are detected on a high-resolution, fine-grained photographic plate as close as possible to the sample without intercepting the incident beam. If the lattice spacing or lattice plane orientation vary locally due to structural defects, equation (1) no longer applies simultaneously to the perfect and the distorted regions. Obviously there is a difference in X-ray intensity from the two regions. For example, the diffracted beam from dislocations is more intense than from an area without defects caused by Bragg defocusing. Dislocations produce a more heavily exposed image on the film. The image is formed as a result of diffraction from an anomaly such as strain in the crystal but does not image the defect directly. One can define strain as the amount of elastic deformation

$$S = \frac{d_{\text{strained}} - d_{\text{unstrained}}}{d_{\text{unstrained}}}$$  \hspace{1cm} (2)

Measuring $d$ in unstrained and strained regions, one can determine the strain [30]. It is the simplest X-ray topography method. There are neither lenses nor moving parts except for the sample alignment goniometer. This method is used to determine dislocation densities
up to about $10^6$ cm$^{-2}$. The resolution is about $10^{-4}$ cm, and areas as large as 200 mm diameter wafers can be examined with the Berg-Barrett method.

The most popular XRD technique so far is illustrated in Fig. 7b and was introduced by Lang in 1959 [31]. Monochromatic X-rays pass through a narrow slit and hit the sample aligned in an appropriate Bragg angle. The tall and narrow primary beam is transmitted through the sample and strikes a lead screen. The diffracted beam falls on the photographic plate though a slit in the screen. X-rays are absorbed in a solid according to equation:

$$I(x) = I_o e^{-(\mu/\rho)x}$$

where $(\mu/\rho)$ is the mass absorption coefficient, $\rho$ the detector material density, $I(x)$ the X-ray intensity in the detector, and $I_o$ the incident X-ray intensity.

To “pick up” defects, one usually uses a weakly diffracting plane. A uniform sample gives a featureless image. Structural defects cause stronger X-ray diffraction. For semiconductors, the Lang method is used primarily to study defects introduced during crystal growth or during wafer processing [32]. Transmission images provide information on defects through the entire sample; reflection images provide information of 10 to 30 $\mu$m depth from the surface. X-ray images of silicon wafers are shown in Figure 8.
Double-crystal diffraction provides higher accuracy because the beam is more highly collimated than is possible with single crystal topography [34]. The technique consists of two successive Bragg reflections from reference and sample crystals (Fig. 7c). Reflection from the first “defectless” crystal produces a monochromatic and highly parallel beam to probe the sample. The double crystal technique is used not only for topography, but also for rocking curve determination (Figure 9).
To record a rocking curve, the sample is slowly rotated (“rocked”) about an axis normal to the diffraction plane and the scattered intensity is recorded as a function of the angle as shown in Fig. 7c. The rocking curve width at full width half maximum is a measure of crystal perfection. The narrower the curve, the more perfect is the material. For epitaxial layers it can give data on lattice mismatch, layer thickness, layer and substrate perfection, and wafer curvature.
2.4.3.  Polariscopy technique

2.4.3.1. Linear scanning polariscopy technique

If a crystalline material plastically deforms because of an external force, upon removal of that force, a “frozen-in” (residual) stress will exist in the interior of the material. Stresses of this type have been studied principally by XRD techniques. Unfortunately, these techniques are limited because the stresses vary over distances much greater than the width of the X-ray beam. Another method for the investigation of stress utilizes the photoelastic effect in transparent crystals. These photoelastic patterns give a direct picture of the magnitude, direction, and distribution of internal stress [36].

When electromagnetic radiation is transmitted through a material in all directions, equally, the material is assumed to be isotropic. This generally defines the optical character of crystals in the cubic system. The great majority of crystalline materials are anisotropic, however, and transmission of an electromagnetic wave will vary in velocity according to the direction of the ray in the crystal.

Associated with anisotropy is a property of the birefringence, which gives rise to a photoelastic pattern. Amorphous materials like glass behave as isotropic crystals for all vibration directions of light, but when in a state of strain, however, they acquire the optical properties of anisotropic crystals. Similarly, crystalline silicon, which should be isotropic because of its cubic lattice, has been observed to be birefringent when strained.
The presence of birefringence in silicon has been interpreted from these studies to be the result of strain caused by severe thermal gradients and uneven temperature distribution in the crystal following solidification and cooling to room temperature.

Silicon has a strong metallic reflection for incident radiation below 1.1 microns, but above that threshold silicon is transparent in the infrared range [37]. The absorption coefficient is a function of wavelength in silicon. For wavelength about 1 micron, the absorption coefficient appears to be $\sim 10^2 \text{ cm}^{-1}$ [38, 39]. The typical infrared birefringence experimental layout also known as polariscopy is shown in Figure 10 [40].

Figure 10. Infrared birefringence experimental layout.
The experimental details of scanning infrared polariscopy applied to multicrystalline Si wafers for solar cells are discussed in [41]. For scanning measurements of the residual strains, a linear or circular polariscopy technique can be used. In linear polariscopy, collimated light from a 75 W halogen tungsten lamp is focused down to 60 µm on the sample. The intensity of the optical transmission is measured in a spectral region of a transmission window where Si is transparent, near $\lambda = 1.3 \, \mu m$. Additionally, two infrared linear polarizers are used in the transmission experiment. They can be oriented with respect to a pre-selected crystal direction, such as a grain boundary in mc-Si. One of them (polarizer) is located in front of the sample and the second (analyzer) immediately behind the sample. In general, the intensity of polarization transmission can be expressed as follows [42]:

$$I = I_o (1 - R^2) [\cos^2 \chi - \sin 2(\varphi - \psi) \cdot \sin 2(\varphi - \psi + \chi) \cdot \sin^2 \delta / 2]$$  \hspace{1cm} (1)$$

where $I_o$ is the intensity of incident light, $R$ is the reflectivity, $\psi$ is the principal angle which determines the orientation of the stress axis at the plane, $\chi$ is the angle between polarizer and analyzer and $\varphi$ is the azimuth angle of the polarizer (Figure 10b).

The polarization intensity, $I$, measured at selected orientations of the polarizer and analyzer, depends on the optical retardation parameter $\delta$, which in turn is directly related to the value of the residual elastic strain. To derive this relationship, the following algorithm is applied [42]. Two transmitted intensities of the polarized light are measured: one with the polarizer and analyzer parallel to each other, $I_{||} = I (\chi = 0)$, and the second when the polarizer is orthogonal to the analyzer, $I_{\perp} = I (\chi = \pi/2)$. By measuring the
angular \( \phi \)-dependence of the ratio \( I_{\perp}/(I_{\parallel} + I_{\perp}) \) one can determine quantitatively the optical retardation, \( \delta \), and the direction of the principal stress angle, \( \psi \), using the equation

\[
I_{\perp}/(I_{\parallel} + I_{\perp}) = \sin^2(\phi - \psi) \sin^2\delta/2. \tag{2}
\]

As the last step of the analysis, two strain components, \( |e_{zz} - e_{xx}| \) and \( |e_{xz}| \), can be calculated. The first term represents a difference in tensile strains along the crystallographic \( Z \) and \( X \) directions, while the second term is the shear strain component between \( Z \) and \( X \). The following can be used for calculating strains [42]:

\[
|e_{zz} - e_{xx}| = \left( \frac{\lambda}{\pi n_o^3} \right) \left[ \frac{\delta}{(p_{11} - p_{12})} \right] \cos(2\psi) \tag{3a}
\]

\[
|e_{xz}| = \left( \frac{\lambda}{\pi n_o^3} \right) (\delta / p_{44}) \sin 2\psi \tag{3b}
\]

where \( p_{ij} \) are photoelastic constants, \( d \) is sample thickness and \( n_o \) is the refractive index of the unstrained material. In the case of mc-Si wafers, the following values were used: \( \lambda = 1.3 \ \mu m, n_o = 3.5, d = 300 \ \mu m, p_{11} = 0.081, p_{12} = 0.001, p_{44} = 0.075 \) [43].
Figure 11. Result of strain field mapping in EFG multicrystalline Si wafers.

Mapping size 100mm x 100mm, step= 1.0mm.

A typical result of strain field mapping is presented in figure 11 for a full-size 100x100 mm$^2$ wafers measured with a 1mm step. The strain field component, $|ezz - exx|$, calculated using equation (3a), has a linear geometry and mirrors the orientation of the nearby grain.
boundary. The maximum value of the stress is ~100 MPa in the high-stress wafer and 63 MPa in low-stress wafer. In mapping the entire 100 × 100 mm² wafer, regions with a stress as high as 250 MPa were observed. This polariscopy technique will be applied in a current project to correlate the data of the resonance acoustic measurements by measuring the elastic stress in EFG wafers.

2.4.3.1. Full-field near infrared polariscopy technique

Similarly to linear polariscopy, the full-field near infrared polariscopy technique measures changes in the polarization of transmitted light, which is caused by the residual stress-induced birefringence of principal shear stress [44]. Near infrared optical irradiation, which is transparent to silicon, was used as a light source. The phase stepping technique was applied to determine photoelastic parameters, which, then, could have been used to calculate the residual stress using the anisotropic piezo-optical law [45, 46].

The experimental setup of the full-field infrared polariscope is shown in Figure 12 [47]. A fringe multiplied was used to increase the resolution of the system. The following was achieved by two beam-splitters placed before and behind the sample.
Figure 12. Experimental setup of the infrared residual stress polariscope.

The light reflected by these two splitters passes through the sample several times as shown in Figure 13, and the photoelastic effect is amplified accordingly. The disadvantage of the fringe multiplier is the loss of light intensity and spatial resolution. However, the spatial resolution can be increased by minimizing distance between the two partial mirrors. To compensate the light loss, a high intensity light source and a sensitive camera were used [47].
Phase stepping provides the full-field mapping of the relative retardation and the isoclinic angle. By selecting six angular positions of the quarter waveplate and the analyzer, a sequence of simultaneous equations in relative retardation and the isoclinic angle were obtained. The simultaneous equations were solved for the isoclinic angle as:

$$\tan 2\theta = \frac{I_5 - I_3}{I_6 - I_4}$$  \hspace{1cm} (1)$$

and the retardation
\[
\tan \alpha = \frac{\sqrt{(I_4 - I_6)^2 + (I_5 - I_3)^2}}{I_1 - I_2}
\]  
(2)

where \(I_n(\phi, \beta)\) is the light intensity during phase stepping as a function of different angles of waveplate, \(\phi\), and analyzer, \(\beta\).

These parameters have been used together with anisotropic piezo-optic law to extract the residual stresses [48, 49, 47].

The correlation experiments have been carried out [47]. Six 100x100mm EFG-Si wafers were measured by the two polariscope systems. Typical results of the particular EFG wafer are shown in Figure 14. The maximum shear stress in this sample is about 22MPa and the average is around 3MPa. As one can see, the results showed that linear and full-field infrared polariscopy methods were in good agreement.
Figure 14. Mapping of residual stresses of the same EFG-Si wafer measured by linear (a) and full-field (b) infrared polariscopy.
Table 1 represents a summary of the methods for measuring residual stress in silicon wafers for photovoltaics.

Table 1. The set of vital parameters of the methods for measuring residual stresses.

<table>
<thead>
<tr>
<th>Method</th>
<th>Stress sensitivity level [MPa]</th>
<th>Spatial resolution</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raman</td>
<td>~10 MPa</td>
<td>&gt;10⁻³mm</td>
<td>Single crystalline wafers only.</td>
</tr>
<tr>
<td>X-Ray</td>
<td>n/a</td>
<td>&gt;10⁻³mm</td>
<td>Qualitative analysis only.</td>
</tr>
<tr>
<td>Linear IR</td>
<td>~1 MPa</td>
<td>&gt;1mm</td>
<td>Time consuming if used in scanning mode.</td>
</tr>
<tr>
<td>Full-field IR</td>
<td>~ 1 MPa</td>
<td>&gt;0.2mm</td>
<td>Reference calibration needed.</td>
</tr>
</tbody>
</table>
2.5. Experimental methods for crack detection

Cracks generated during wafer sawing or laser cutting can propagate due to wafer handling and solar cell processing such as, phosphorous diffusion, anti-reflecting coating, front and back contact firing, and soldering of contact ribbons. It is recognized that development of a methodology for fast in-line crack detection and control is required to match the throughput of typical production lines. At this time, there are several experimental methods, which address the problem of crack detection. They include Scanning Acoustic Microscopy [50], ultrasonic lock-in thermography [51] and millimeter wave techniques [52]. In this chapter, we discuss those three major methods, mentioned above, and compare ones to an alternative approach based on the recently developed RUV methodology, which also can be used to monitor elastic stress in multi-crystalline silicon solar-grade wafers [53].

2.5.1. Scanning acoustic microscopy

The ultrasound methods for industry have been established in the early 1900s. The PV industry has recently entered the territory of ultrasonics with the introduction of high frequency immersion systems or, so called, C-Mode Scanning Acoustic Microscope (C-SAM). Initially, C-SAM tools have demonstrated their usefulness for non-destructive testing of plastic and ceramic packaged integrated circuits at Texas Instruments in the late 1980s, early 1990s [50].
The first prototype of scanning acoustic microscope was designed and developed in Stanford University [54]. But before that the C-scan was used by nondestructive testing industry (NDT) since the 1950s [55]. Modern SAMs are the hybrids tools with characteristics of both the first Stanford’s SAM and the C-scan. We will briefly review the characteristics of each of these methods.

The term C-scan originated from early NDT specification. The C-scan image is an image of a planar region at a constant depth within the sample. The C-scan is obtained by mechanically scanning a piezoelectric transducer above the specimen and electronically gating the signal in time. The broad-band C-scan transducer has a small numerical aperture lens for sub-surface imaging. C-scan has played a major role in the microscopic imaging of sub-surface flaws in industrial components with resonance frequencies in the range of 1-10MHz. In the C-scan technique the echo signal has traditionally been rectified for easier interpretation, so all phase information was not used [56].

The scanning acoustic microscope was first demonstrated by Lemmons and Quate at Stanford in 1973 [54, 57]. The SAM employs a large numerical aperture lens in order to excite surface waves on the sample. Instead of the large water baths of C-scan, they use a water droplet to acoustically couple the transducer and the sample. The lens are formed by grinding a hemispherical cavity into the tip of a sapphire rod. The large difference in acoustic velocities between the sapphire and the water droplet produces good focusing. Image contrast is formed by the combined interference of longitudinal and flexural waves reflected from the surface and from beneath the surface. Narrow-band RF pulses with frequencies in the range of 100MHz-3GHz are used. Precision mechanical scanning is used for microscopic imaging. Both amplitude and phase of the reflected
pulses are measured to produce images of the mechanical properties of the near-surface region. Sub-micron lateral resolution is achieved at the highest frequencies. In the C-scan method, lateral resolution is typically limited by absorption in the sample. In the case of SAM, lateral resolution is limited by high frequency attenuation in the coupling water droplet [54].

SAM has started to be employed widely in the semiconductor field after it became commercially available in 1982. The application of SAM in the semiconductor industry was initially the high frequency inspection of thin dielectric layers and conductors on the device surface [58]. Optional broad-band transducers in the intermediate frequency range of 30-100MHz were available for sub-surface studies such as die attach inspections [59]. SAM was used by the IC industry extensively for a long time, although the PV manufacturers began to employ acoustic microscopy technique for crack detection in silicon wafers and solar modules relatively not long ago.

For instance, one of the largest solar cells manufacturers – BP Solar – in collaboration with the Nanotechnology and Nanomanufacturing Research Center at the University of South Florida proposed to use SAM in order to characterize the formation of cracks under constant stress conditions and classify different types of cracks after various technological steps of solar cell manufacturing [60]. The initial experiments were conducted with single crystal cells because a production yield problem with this cell type indicated that a significant fraction of these cells were susceptible to breakage. Figure 15 shows one of the cells as it was initially placed in the SAM system. The crack was initially ~1÷5mm in length, but it eventually propagated across the wafer leading to wafer breakage, as shown in Figure 16. Figure 16 looks exactly like the IR image of the
modules that incorporate these problem cells. The SAM system was able to see the small (micro-) crack (Figure 15) that later lead to the break (Figure 16).

Figure 15. SAM image of the initial crack on the wafer captured in the red box.
Figure 16. SAM image of the same area of the wafer as Figure 15 after applied stress. The initial crack had propagated across the wafer’s corner causing it to break.

The SAM process was also able to identify internal cracks. An example is shown in Figure 17.
Figure 17. SAM image of internal crack.

SAM has proven to be an accurate method for identifying cracks and micro-cracks in wafers and partially processed solar cells. In this case it provided BP Solar with information about where cracks and microcracks were first occurring and therefore has provided valuable information to assist in reducing breakage and increasing yield.

However, each SAM wafer measurement took 20 minutes for sample set-up and data collection. This is clearly not an in-line production process. The data from this effort was very useful as the sample set evaluated by SAM can now be used to calibrate and verify the accuracy of any new methods developed for crack detection.
2.5.2. Ultrasound Lock-in Thermography

Ultrasound lock-in thermography (ULT) was established a few years ago for remote non-destructive testing. It is based on propagation and reflection of thermal waves which are generated by ultrasound transducer from the surface into the inspected component by absorption of modulated radiation [61]. The schematics of the ULT principle are illustrated in Figure 18.

While thermography generates images where the contrast is provided by local thermal emission, lock-in thermography means that one investigates a coded heat flow by analyzing the temperature modulation that is induced by periodical heat deposition. Absorption of modulated optical radiation results in a temperature modulation that propagates as a thermal wave into the inspected component. As the thermal wave is
reflected at the boundaries of subsurface features, its superposition to the original thermal wave causes a signal change that depends on the depth of the hidden boundary. [62, 63].

In ULT, the attached ultrasonic transducer drives modulated acoustic waves into the sample where they propagate until they disappear since they are converted into heat in the high-loss-angle areas of defects. That is why the defect reveals itself by the internally generated and emitted thermal wave that is phase sensitively monitored when it arrives at the sample surface. Therefore, only the defect is detected and not the intact areas of the inspected component. As the phase difference between the modulation and the thermal wave is proportional to the depth where the defect is located, local depth information is obtained. The typical setup for ULT measurements is shown in Figure 19 [64].

![ULT principal setup diagram](image_url)

Figure 19. The ULT principal setup.
Again, the use of ULT technique for PV industry has initiated not long ago. Recently, a group of German researchers had employed ULT method for detection of cracks in silicon wafers and solar cells [65]. The principle of crack detection by ULT is based on the heat created of the cracks flanks because of their friction caused by the ultrasound driven into silicon wafer. The ULT image of one of the cracks in mc-Si wafer is illustrated in Figure 20.

![ULT image of the inner crack in mc-Si wafer](image)

**Figure 20.** ULT image of the inner crack in mc-Si wafer [65].

The special resolution of the method depends on the quality of IR camera incorporated into the ULT setup. Their lock-in thermography system allowed imaging of periodic surface temperature modulations at frequencies up to 54 Hz having an effective value as low as 10 mK using 1/2 hour measure time. This is still far too long for using this method as an in-line module for solar cells manufacturing.
2.5.3. Millimeter waves

Millimeter wave is an electromagnetic wave having a wavelength of 1 mm to 10 mm. Millimeter wave has an advantage that it can propagate well in air, unlike scanning acoustic microscopy and ultrasound lock-in thermography where a coupling medium is needed. The absence of coupling is extremely important in nondestructive testing. In the 1970s, some researchers have attempted using microwave to detect surface cracks in metallic components [66], where a horn antenna was used. In recent years, some researchers have suggested the use of an open-ended rectangular waveguide in a near-field fashion [67]. Very recently, a millimeter wave system has been developed utilizing an open-ended coaxial line sensor for detection and evaluation of small fatigue cracks on metal surface [68]. But the spatial resolution and scanning speed of millimeter wave setups used in papers referenced above were not sufficient to satisfy the PV assembly lines where 2-3 seconds per wafer are required. In 2004, Y. Ju et al. demonstrated the detection of small crack in the polycrystalline silicon substrate by using a slit aperture sensor with a high testing speed of 35mm/s [69].

In this paper, a millimeter wave signal of 110GHz was used and the amplitude of the reflection coefficient was measured. The configuration of the millimeter wave measurement system is shown in Figure 21. The design of the setup is attractive due to its simplicity. A network analyzer was used to generate a continuous wave signal fed to the sensor and to measure the amplitude of reflection coefficient at the sensor aperture. A computer was used to synchronize the stage movements for x-y scanning process. In
order to apply technique to in-line testing, a high speed testing of 35 mm/s was kept. Therefore, for testing an area of 50x35 sq.mm only 1 second was needed.

Figure 21. Principal configuration of the millimeter wave measurement system [69].

Figure 22 shows the photograph of the sample. There is no indication of the crack size, but assuming that the silicon substrate had a dimension of 125x125 mm then rough estimations gives the crack size to be about 2-3 cm. It is still unclear whether or not the method is capable to detect cracks not only in bare but processed, after metallization, wafers. A good example is when the crack is located beneath the metal contact.
Figure 22. Millimeter wave image of the 125x125mm polycrystalline silicon wafer [69].

In Table 2 we presented a summary of the methods for crack monitoring in silicon wafers for photovoltaics.
Table 2. The set of vital parameters of the methods for crack inspection in wafers.

<table>
<thead>
<tr>
<th>Method</th>
<th>Time required to inspect 100x100mm wafer</th>
<th>Minimum crack length</th>
<th>Additional comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAM</td>
<td>~ 10-15min (Depends on scanning resolution)</td>
<td>&gt;5-10 microns</td>
<td>Acoustic coupling required.</td>
</tr>
<tr>
<td>ULT</td>
<td>~ 5-10s (Depends on camera’s resolution)</td>
<td>&gt;100 microns</td>
<td>Thermal coupling required.</td>
</tr>
<tr>
<td>MW</td>
<td>~ 3-5s</td>
<td>&gt;400 microns</td>
<td>Wafers before metallization only.</td>
</tr>
</tbody>
</table>

As one can see there is no common and yet accepted method for mechanical quality control in solar-grade commercial full-size silicon wafers. The in-line quality control requires methods which can achieve measurement times of around 2 seconds per wafer to match a throughput of typical production lines. Therefore, the efforts of the current research in creating a reliable and versatile tool for stress monitoring and crack detection were highly motivated by today’s state of the photovoltaic industry.
3. Experimental

All experimental work has been done using research facilities of the Spectroscopy Laboratory at USF. The setup for resonance ultrasonic vibrations for measuring flexural vibrations in silicon wafers was designed and developed previously and described in my master’s thesis [78] and with important upgrade, it was rebuilt for the longitudinal mode. The setup for scanning infrared polariscopy was built and described by Dr. I. Tarasov in [79]. Scanning acoustic microscopy results were obtained on HS1000 HiSPEED™ produced by Sonix Inc. Finite element analysis and calculations were performed in collaboration with Mr. O. Polupan.

3.1. Hardware

3.1.1. Setup for resonance ultrasonic vibrations measurements

In the resonant ultrasonic method, ultrasonic vibrations of a tunable frequency and adjustable amplitude are applied to the entire silicon wafer. Ultrasonic vibrations are generated in the wafer using a resonating piezoelectric transducer. Two circular
transducers of different size (2 or 3 inches in diameter) were used. The transducers were manufactured from a piezoelectric ceramic material (PZT-5H). The transducer contains a central hole which provides a reliable vacuum coupling between the wafer and transducer by applying a small (~ 50 kPa) negative pressure to the backside of the wafer (Figure 23).

Figure 23. Experimental set-up for resonance ultrasonic vibration (RUV) measurements.

Ultrasonic vibrations are propagated into the wafer from the transducer and form standing acoustic waves at specific resonance frequencies. This vacuum method, to couple the wafer and transducer, allows fast wafer exchange and provides simple wafer alignment within 100 micron accuracy. The amplitude and spatial distribution of the standing waves are measured using a broad-band ultrasonic probe. A function generator (WaveTek 10 MHz DDS 29) and a broadband power amplifier (Samson Servo-240)
provide an *ac* driving voltage to the transducer with a tunable frequency and adjustable amplitude. This geometry of acoustic loading offers a quick sample exchange and does not damage the front surface or bulk region of the wafer. The *ac* voltage from the acoustic probe is recorded using a lock-in amplifier (*Stanford Research Systems SR850*), which is synchronized to the frequency, *f*, and phase of the driving generator. In the present design, the ultrasonic probe measures the longitudinal vibration mode characteristics by contacting the edge of the wafer with a controlled force.

The resonance frequency of the longitudinal vibration mode is independent of the wafer thickness (*h*), in contrast to the flexural vibration mode, which is proportional to \( h^{3/2} \) [74]. This is especially beneficial in the mc-Si ribbon wafers which may have significant thickness variations of up to 20% across the wafer, as well as from wafer to wafer. The RUV system is computer controlled to achieve fast data acquisition and analyses.

Additionally, the transducer and wafer can be rotated using a rotary table. A 8” linear moving stage (*New England Affiliated Technologies Inc.*) was used for radial probe movement. Step motors were synchronized by a digital movement controller (*Unindex-11 by Aerotech*). This allowed us to acquire the spatial distribution data with a minimum step size of 10-microns.
3.1.2. Infrared polariscopy setup for residual elastic stress measurements

To characterize and quantify the level and spatial distribution of in-plane stresses in the material, we have used a scanning linear infrared (IR) polariscopy technique [3]. In linear IR polariscopy, a collimated light from a 75 W halogen tungsten lamp can be focused from a 1 mm diameter down to 60 µm. The intensity of the optical transmission is measured at a 1.3 µm wavelength corresponding to a spectral region where Si is transparent (Fig. 24).

![Schematic of the setup for scanning linear infrared polariscopy measurements.](image)

Figure 24. Schematic of the setup for scanning linear infrared polariscopy measurements.
Additionally, two infrared linear polarizers are used and oriented with respect to a pre-selected crystal direction, such as the growth direction of the mc-Si ribbon. One of them (the polarizer) is located in front of the sample and the second (the analyzer) immediately behind the sample. The polarization intensity is measured at selected orientations of the polarizer and analyzer and depends on the optical retardation parameter, which in turn is directly related to the value of the residual elastic stress. In general, the intensity of polarization transmission can be expressed as follows [42]:

\[ I = I_o (1 - R)^2 [\cos^2 \chi - \sin 2(\varphi - \psi) \cdot \sin 2(\varphi - \psi + \chi) \cdot \sin^2 \delta / 2] \]  

(1)

where \( I_o \) is the intensity of incident light, \( R \) is the reflectivity, \( \psi \) is the principal angle which determines the orientation of the strain axis at the plane, \( \chi \) is the angle between polarizer and analyzer and \( \varphi \) is the azimuth angle of the polarizer.

The polarization intensity, \( I \), measured at selected orientations of the polarizer and analyzer, depends on the optical retardation parameter \( \delta \). To derive the relationship between \( \delta \) and stress components, the following algorithm is applied. Two transmitted intensities of the polarized light are measured: one with polarizer and analyzer parallel to each other, \( I_\parallel = I (\chi = 0) \), and the second when the polarizer is orthogonal to the analyzer, \( I_\perp = I (\chi = \pi/2) \). By measuring the angular \( \varphi \)-dependence of the ratio \( I_\parallel/(I_\parallel + I_\perp) \) one can determine quantitatively the optical retardation, \( \delta \), and the direction of the principal stress angle, \( \psi \), using the equation

\[ I_\parallel/(I_\parallel + I_\perp) = \sin^2 2(\varphi - \psi) \cdot \sin^2 \delta / 2. \]  

(2)
As the last step of the analysis, two strain components, $|u_{zz} - u_{xx}|$ and $|u_{xz}|$, can be calculated. The first term represents a difference in tensile strains along the crystallographic $Z$ and $X$ directions, while the second term is the shear strain component between $Z$ and $X$. The following can be used for calculating strains:

\[
|u_{zz} - u_{xx}| = (\lambda / \pi d n_o^3)[\delta / (p_{11} - p_{12})] \cos(2\psi) \tag{3a}
\]

\[
|u_{xz}| = (\lambda / \pi d n_o^3)(\delta / p_{44}) \sin 2\psi \tag{3b}
\]

where $p_{ij}$ are photoelastic constants, $d$ is sample thickness and $n_o$ is the refractive index of the unstrained material. In the case of EFG-Si wafers, the following values were used: $\lambda = 1.3 \ \mu m$, $n_o = 3.5$, $p_{11} = 0.081$, $p_{12} = 0.001$, $p_{44} = 0.075$. Strain components can be converted to matching values of stress using elastic constants of silicon: $c_{11} = 1.657e12 \ \text{dyn/cm}^2$, $c_{12} = 0.639e12 \ \text{dyn/cm}^2$, $c_{44} = 0.7956e12 \ \text{dyn/cm}^2$ [43].

### 3.1.3. Scanning acoustic microscope

The $HS1000 \ HiSPEED^{TM}$ Scanning Acoustic Microscope (SAM) by Sonix Inc was used for surface morphology and structural (bulk) integrity evaluation. In SAM, a focused acoustic beam is scanned over the front and back surfaces of the wafer (Fig. 25).
Figure 25. Principal setup for SAM operation.

The sound pulses are transmitted through the wafer and the reflection from the wafer interfaces is monitored. The ultrasonic pulses are generated by a high-frequency piezoelectric transducer. An electrical pulse from a high voltage transmitter is converted to mechanical energy. This activation causes the transducer to vibrate at a specific frequency causing ultrasonic pulses to be transmitted from the transducer. These pulses travel through the material at the material's velocity and are reflected at the interfaces of the material it strikes. The ultrasonic energy does not travel well through air, so the wafers have to be placed in a coupling medium (deionized water bath). The system uses the pulse echo technique and operates at frequency up to 250 MHz. The pulses are repeated at the repetition rate of 20 KHz, so echoes from one pulse do not overlap those
from the next. The returned echoes are received by the transducer and converted back to voltages.

The voltage data is amplified and digitized, providing peak amplitude, peak phase and “time-of-flight” (TOF) data. The TOF represents the time required for a pulse to travel back and forth across the wafer thickness. TOF data were further used to obtain thickness maps on mc-Si wafers. We used a typical value for the longitudinal speed of sound in silicon of 8600 m/s to calculate the thickness. Each map was measured over a full wafer area, with a step size of 50 $\mu$m. Steps as small as 5 $\mu$m can also be used for high-resolution imaging, although this significantly decreases the data acquisition time.

![Cross section of the transducer (a) and the intensity of acoustic field (b).](image)

Figure 26. Cross section of the transducer (a) and the intensity of acoustic field (b).
Spatial resolution of the method is strongly dependent on the ultrasonic beam spot size formed by the piezoelectric high-frequency transducer. Figure 26 shows the cross section of the transducer (a) and the intensity of acoustic field (b) generated by it. The beam spot size at 6dB is governed by following relationship:

\[ X_{\text{6dB}} = \frac{1.028 \cdot F \cdot c}{f \cdot d}, \]  

where \( F \) is a focal length in water, \( c \) is the sound velocity of the sample’s material (silicon in our case), \( f \) is an operational frequency of the transducer, \( d \) is an active piezoelectric element diameter. Assuming, that \( F=5.9\text{mm} \), \( c=8600\text{m/s} \), \( f=250\text{MHz} \) and \( d=5\text{mm} \), a beam spot size of about 4 microns was obtained.

### 3.2. Finite element modeling

Modal analysis of the free edge silicon wafers’ vibrations was performed using ANSYS 7.0-8.0 software packages based on the finite element analysis [73].

The EFG-Si 100mm by 100mm wafers were modeled using a 100x100 mesh, which makes the size of individual shell element to be equal to 1 mm x 1mm. The square wafers are modeled as an isotropic material with a Young modulus of \( 1.67 \cdot 10^{12} \text{ dyn/cm}^2 \), a Poisson’s coefficient of 0.3 and a density of 2.329 g/cm\(^3\).

In a case of Cz-Si 125mm by 125mm pseudo square wafers were modeled using the 125x125 mesh, with the size of individual elements being 1.25 mm x 1.25mm. The pseudo-square wafers are modeled with isotropic eight-node planar elements with a
Young modulus of $1.67 \times 10^{12}$ dyn/cm$^2$, a Poisson’s coefficient of 0.3 and a density of 2.329 g/cm$^3$.

### 3.3. Samples

Silicon wafers used during this research may be subdivided in two groups. The first group of wafers was formed by those which had been used for stress evaluation. The second group was formed in order to perform experiments on crack detection in silicon wafers.

Two types of silicon wafers have been included in the first group. The first type is circular single crystalline Cz-Si wafers of three different diameters of 150, 200 and 300 mm, which are typically used in the microelectronic industry. The second type is square mc-Si ribbon wafers produced by the Edge-defined Film-fed Growth (EFG) technique used in solar cell manufacturing. A set of twelve 100x100mm as-grown EFG wafers with thicknesses between 340 and 370 µm was chosen.

A set of identical 125mm x 125mm pseudo-square shaped (100) oriented Cz-Si wafers formed the second group. The pseudo-square shape represents one of the accepted photovoltaic industry standards. The wafers were as-grown with a nominal thickness of 0.035 cm.
4. Results and Discussion

4.1. Resonance ultrasonic vibrations approach for stress evaluation in full-sized silicon wafers

In this chapter a resonance vibration approach applied to measure non-destructively residual stress in full size multicrystalline silicon wafers used in solar cell manufacturing will be presented. This method is based on excitation of the longitudinal resonance ultrasonic vibrations in the material using an external piezoelectric transducer combined with a highly sensitive ultrasonic probe with data acquisition of the frequency response to make the method suitable for in-line diagnostics during wafer and cell manufacturing. Theoretical and experimental analyses of the vibration mode in single crystal and multicrystalline silicon wafers are used to provide a benchmark reference analysis and validation of the approach.
4.1.1. Single crystal Czochralski (Cz) silicon

The main purpose of this theoretical analyses and experimental data on Cz-Si wafers was to validate our approach. First the resonance ultrasonic methodology for circular single crystal silicon wafers was implemented. These wafers have typically internal stress values below 1MPa and can serve here as model objects allowing solving analytically a general equation of the free longitudinal vibrations and to calculate resonance vibration frequencies.

4.1.1.1. Analytical modeling

Pure radial vibrations in a thin circular plate with radius \( R \) and thickness \( h \), assuming that \( h \ll R \) are considered. The equations for elastic strain, \( u_{ij} \), and stress, \( \sigma_{ij} \), tensors’ components in the Cartesian coordinate system can be written as follows [70]:

\[
\begin{align*}
    u_{xx} &= \frac{1}{E} \left( \sigma_{xx} - v \sigma_{yy} \right) \\
    u_{yy} &= \frac{1}{E} \left( \sigma_{yy} - v \sigma_{xx} \right) \\
    u_{xy} &= \frac{1 + v}{E} \sigma_{xy}
\end{align*}
\] (4)
where $E$ and $\nu$ are Young modulus and Poisson coefficient in x-y plane respectively. For further consideration of the longitudinal vibrations it is convenient to rewrite (4) in polar coordinates $r, \theta$. Let $U_r$ and $U_\theta$ be the respective components of the strain vector $U$. Then, using the symmetry of the problem, these components may be written as $U_\theta=0$, $U_r=U$. Thus the components of $u_{ij}$ in polar coordinates are:

$$u_{rr} = \frac{\partial U}{\partial r}, \quad u_{\theta\theta} = \frac{U}{r}, \quad u_{r\theta} = 0$$

Therefore the equations (4) in polar coordinates can be expressed as follows:

$$\begin{cases}
\sigma_{rr} &= \frac{E}{1-\nu^2} \cdot (u_{rr} + \nu u_{\theta\theta}) \\
\sigma_{\theta\theta} &= \frac{E}{1-\nu^2} \cdot (\nu u_{rr} + u_{\theta\theta})
\end{cases}$$

(6)

The equation for longitudinal vibrations in polar coordinates had been given in many sources (see for example [71]). In our case, for radial strain, we have:

$$\rho \cdot \frac{\partial^2 U}{\partial t^2} = \frac{\partial \sigma_{rr}}{\partial r} + \frac{\sigma_{rr} - \sigma_{\theta\theta}}{r},$$

(7)

where $\rho$ is a density of Si. Substituting (6) in (7) and using the expressions for $u_{ij}$ described by (5) one can apply the method of separation of the variables for equation (7). The above procedure transforms (7) to the following form:
\[ r^2 \cdot \frac{d^2 U}{dr^2} + r \cdot \frac{dU}{dr} + (q^2 r^2 - 1) \cdot U = 0, \quad (8) \]

where

\[ q = \frac{\omega}{\sqrt{E}} \cdot \frac{1}{\sqrt{(1 - \nu^2) \cdot \rho}} \quad (9) \]

Equation (8) represents the Bessel equation of the first order and one of its solutions is

\[ U(r) = AJ_1(qr), \quad (10) \]

where \( J_1(qr) \) is the Bessel function of the first order. Applying the free edge boundary condition, \( \sigma_r \mid_{r=R} = 0 \), it yields:

\[ \beta \cdot J_0(\beta) - (1 - \nu)J_1(\beta) = 0, \quad (11) \]

where \( \beta \) is a dimensionless variable equal to \( qR \). The first ten roots \( (m=1 \div 10) \) of equation (11) for \( \nu=0.3 \) are presented in Table 3. The respective resonance frequencies of these modes, \( f_m \), can be calculated using the following relation:
\[ f_m = \frac{\beta_m \sqrt{\frac{E}{(1-v^2) \cdot \rho}}}{2\pi R} \]  

(12)

Table 3. The set of roots of the equation (11).

<table>
<thead>
<tr>
<th>m</th>
<th>( \beta_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.049</td>
</tr>
<tr>
<td>2</td>
<td>5.389</td>
</tr>
<tr>
<td>3</td>
<td>8.572</td>
</tr>
<tr>
<td>4</td>
<td>11.732</td>
</tr>
<tr>
<td>5</td>
<td>14.862</td>
</tr>
<tr>
<td>6</td>
<td>18.025</td>
</tr>
<tr>
<td>7</td>
<td>21.173</td>
</tr>
<tr>
<td>8</td>
<td>24.318</td>
</tr>
<tr>
<td>9</td>
<td>27.463</td>
</tr>
<tr>
<td>10</td>
<td>30.612</td>
</tr>
</tbody>
</table>

These values are plotted in Figure 27 for Cz-Si wafers of the three diameters 150, 200 and 300mm. In calculations of the resonant frequency the following material constants \( E=1.67 \times 10^{12} \text{dyn/cm}^2 \), \( v=0.3 \), \( \rho=2.329 \text{ g/cm}^3 \) were used.
Figure 27. Normal frequencies of the longitudinal vibrations in circular silicon wafers of different diameters: (circles) – 150mm, (triangles) 200mm, and (squares) 300mm.
4.1.1.2. Resonance ultrasonic vibrations data

The calculated frequencies are in a good agreement with RUV data on the 300 mm Cz-Si wafer (Figure 28). Table 4 compares the first three theoretically predicted resonant frequencies for the 300 mm wafer to the experimentally measured resonant frequencies.

![Acoustic signal vs Frequency](image)

Figure 28. Frequency scan measured on 300mm Cz-Si wafer with indicated by arrows first three radial modes. The insert zooms in the mode for m=2.

Finite element analysis (FEA) has also been employed to compare experimentally obtained data with theory presented in Table 4. As one can see, the measured, analytically calculated and FEA modeled resonant frequencies are well correlated (with
deviations of less than 1%). This confirms the model that was applied to explain the origin and the type of ultrasonic excitations exhibited in the wafer. Some deviation of the experimental data is anticipated because of the ultrasonic transducer used in mechanical contact with wafer is a source of vibrations that could cause perturbation to the free wafer vibration spectrum. There are also a number of other resonant frequencies shown in Figure 28 which are generated by asymmetric longitudinal vibrations.

Table 4. Resonant frequencies [Hz] of radial angular independent longitudinal vibrations measured experimentally on 300mm diameter Cz-Si wafer compared to calculated using Eq. (12) and modeled with Finite Element Analyses.

<table>
<thead>
<tr>
<th>m</th>
<th>Experiment [Hz]</th>
<th>Theory [Hz]</th>
<th>FEA [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20071</td>
<td>19425</td>
<td>19297</td>
</tr>
<tr>
<td>2</td>
<td>51809</td>
<td>51063</td>
<td>50760</td>
</tr>
<tr>
<td>3</td>
<td>80688</td>
<td>81224</td>
<td>80734</td>
</tr>
</tbody>
</table>
4.1.1.3. Chladni figures

The theoretical model was further validated through classic Chladni type patterns presented in Figure 29. These were obtained by sprinkling fine sand on the wafer while dwelling at each mode frequency. The sand collects at the nodal lines of the mode shapes [72].

Historically, this method is considered to be the oldest experimental way to study the nodes of vibration of circular and square plates. Ernst Chladni first demonstrated this at the French Academy of Science in 1808, it caused such interest that the Emperor offered a kilogram of gold to the first person who could explain the patterns.

Comparing the nodal lines from the calculated mode shapes in Figure 30a with the nodal sand lines in Figure 29 for mode with m=2 shows excellent agreement.
Figure 29. Chladni sand patterns on 300mm Cz-Si wafers for different mode shapes.
Figure 30a. Computed mode shape for 300mm Cz-Si wafer, $n=5$
Figure 30b. Experimental radial distribution of the normalized vibrations’ amplitude versus theoretical curve.

In addition, notice that the same type of experiments were carried out on square shaped 100x100mm EFG-Si wafers, but unfortunately the transducer used disturbed significantly the sand patterns around the central area of the wafer. Therefore, it would be problematic and inappropriate to compare experimental distribution with theoretically modeled. Some examples of Chladni patterns on 100x100mm EFG-Si wafers are presented in Figure 31.
4.1.2. Edge-defined Film-fed Growth (EFG) silicon wafers

4.1.2.1. Scanning acoustic microscopy results

To study longitudinal vibrations in square shaped wafers using the RUV technique, twelve 100 mm x100 mm mc-Si EFG wafers with thicknesses ranging from 340 to 370 µm and a set of 125mm x125mm cast wafers were screened using a high resolution SAM technique, as described above, to check that cracks over 10 µm length...
were not present at the wafer periphery. As an example, Figure 32 shows a full image of the EFG wafer with a mm-size peripheral crack. The wafer was rejected from the RUV experiments based on SAM screening. The crack initially had a length of a few mm and eventually propagated to cause the wafer breakage (Figure 32b).

Figure 32. SAM image of the 100mm x 100mm EFG wafer with periphery crack: (a) image of the entire wafer, the crack is boxed out in white, (b) zooming area of the crack with 5 micron step.
4.1.2.2. Residual elastic stress data by infrared polariscopy technique

In the set of EFG wafers measured, the spatial distribution of the in-plane stress using scanning linear IR polariscopy, and stress maps of all test wafers were obtained using the algorithm described in Section 3.1.2. Representative maps of “low”-stress and “high”-stress wafers are presented in Figure 33. Each stress map contains 100x100 data points obtained with a 1 mm spatial resolution. Figure 32a shows an example of a fairly uniform stress distribution over most of the low-stress EFG wafer #16 with stress average value of 2.8MPa. In contrast, significant variation in residual stress within EFG wafer #22 (average stress is 5.6MPa) is shown in Figure 33b. To quantify the stress mapping, we present in Figure 33c two line scans measured across the growth directions in both wafers. These show quite different stress distributions. The values of measured wafer thickness and calculated average and peak stress are presented in Table 5. The stress values are corrected to account for the average wafer thickness, which was measured using the SAM TOF technique and also confirmed by data of the wafer weight and density ($\rho_{\text{Si}} = 2.329 \text{ g/cm}^3$).
Figure 33. Result of infrared polariscopy stress field mapping: (a) low-stress wafer (#16, Avg. Stress = 2.8MPa) and (b) high-stress wafer (#22, Avg. Stress = 5.6MPa). Contrast bar is [MPa] values. The dotted line on maps indicates the position of scan lines we have shown in (c).
4.1.2.3. Resonance ultrasonic vibrations data

Using the RUV technique described above, frequency scans from 10 to 100 kHz were performed on EFG wafers. A typical f-scan is presented in the insert in Figure 34. A dominant vibration mode at ~48 kHz was selected in order to correlate the resonant frequencies with the respective values of the elastic stress. A noticeable variation of the resonance frequency on a set of identical test wafers (Table 5) was observed, which can be attributed to the stress variations. In Figure 35 the dependence of the resonance frequency on the average value of in-plane stress for these EFG wafers is presented. Data points show a trend of a resonance frequency shift to higher values with the increase of the average stress in the wafer. The resonance ultrasonic mode frequency increases with increasing stress suggesting that residual stress increases wafer stiffness.

Modal analysis of the free edge square wafer’s vibrations is performed using ANSYS software package based on the finite element method [73]. The wafer is modeled as a 100x100 mesh, which makes the size of individual shell element to be equal to 1 mm × 1mm or 1.25 mm x 1.25mm. The square wafers are modeled as an isotropic material with a Young modulus of $1.67 \times 10^{12}$ dyn/cm$^2$, a Poisson’s coefficient of 0.3 and a density of 2.329 g/cm$^3$. Table 6 demonstrates calculated resonant frequencies of 100mm x 100mm and 125mm x 125mm square wafers compared to the experimentally measured ones. Two computed vibration modes are illustrated in Figure 36.
Figure 34. Frequency scans at one of principal maximum on two EFG wafers: high-stress wafer #22 with average stress of 5.65 MPa, and low-stress wafer #16 – with average stress of 2.81 MPa. The insert shows a typical frequency scan in a range from 10kHz to 100kHz.
Table 5. Average thickness, average and peak stress, and resonance vibration frequencies of 100mm x 100mm EFG wafers.

<table>
<thead>
<tr>
<th>Wafer I.D. [#]</th>
<th>Thickness [microns]</th>
<th>Average Stress [MPa]</th>
<th>Peak Stress [MPa]</th>
<th>Resonance frequency [KHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>348</td>
<td>5.06</td>
<td>28.58</td>
<td>47.80</td>
</tr>
<tr>
<td>14</td>
<td>341</td>
<td>4.37</td>
<td>31.37</td>
<td>48.38</td>
</tr>
<tr>
<td>15</td>
<td>340</td>
<td>4.10</td>
<td>29.46</td>
<td>47.66</td>
</tr>
<tr>
<td>16</td>
<td>366</td>
<td>2.81</td>
<td>25.01</td>
<td>47.60</td>
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<td>17</td>
<td>369</td>
<td>3.33</td>
<td>30.57</td>
<td>47.99</td>
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<td>18</td>
<td>356</td>
<td>4.58</td>
<td>37.78</td>
<td>47.96</td>
</tr>
<tr>
<td>19</td>
<td>343</td>
<td>4.11</td>
<td>29.56</td>
<td>48.98</td>
</tr>
<tr>
<td>20</td>
<td>349</td>
<td>4.93</td>
<td>28.66</td>
<td>49.04</td>
</tr>
<tr>
<td>21</td>
<td>344</td>
<td>5.38</td>
<td>44.77</td>
<td>48.68</td>
</tr>
<tr>
<td>22</td>
<td>346</td>
<td>5.65</td>
<td>29.17</td>
<td>48.78</td>
</tr>
<tr>
<td>23</td>
<td>347</td>
<td>4.36</td>
<td>29.84</td>
<td>48.15</td>
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<tr>
<td>24</td>
<td>344</td>
<td>4.10</td>
<td>29.54</td>
<td>47.80</td>
</tr>
</tbody>
</table>
Figure 35. Experimentally measured frequencies of the resonance longitudinal vibration mode versus average stress in a set of 100mm x 100mm EFG wafers.
Table 6. Average experimental resonance frequencies [Hz] of the three selected longitudinal vibration modes for 100x100mm EFG-Si and 125x125mm cast-Si wafers compared with FEA calculated values. Experimental values show standard deviation of 1% (see Table 5).

<table>
<thead>
<tr>
<th>100x100mm EFG-Si</th>
<th>125x125mm cast-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEA [Hz]</td>
<td>Experiment [Hz]</td>
</tr>
<tr>
<td>48772</td>
<td>48620±510</td>
</tr>
<tr>
<td>60794</td>
<td>62540</td>
</tr>
<tr>
<td>85381</td>
<td>88350</td>
</tr>
</tbody>
</table>
Figure 36. Finite Element Analysis calculations of the first two principal mode shapes at frequency of (a) 48772 Hz and (b) 60794 Hz. The X and Y are scaled in cm.
4.1.2.4. Bending test

Additional evidence of a stress dependent resonance frequency shift is achieved from the following 5-point wafer bending experiment. In this test, a silicon wafer was loaded vertically upward using supporting pins applied to the four corners of the wafer while it was held in its center with a vacuum (Figure 37). Concurrently, the frequency scan was taken at each loading value and the resonance vibration frequency peak location determined (Figure 38). One can see the tendency of the wafer resonance frequency location to shift to higher values with the increasing load. This loading experiment provides additional experimental evidence linking the resonant peak frequency shift to stress, as found for EFG wafers.

Figure 37. Schematics of the four-point bending test.
Figure 38. Frequency curves of the resonance vibration mode at different load values using 5-point bending test. Insert shows the resonance frequency versus loading values.
4.2. Crack detection and analyses using resonance ultrasonic vibrations

4.2.1. Initial measurements

A set of identical 125mm x 125mm pseudo-square shaped (100) oriented Cz-Si wafers were chosen for this study. This shape represents one of the accepted photovoltaic industry standards. The wafers were as-grown with a nominal thickness of 0.035 cm. All wafers were initially screened by SAM for structural integrity. The SAM maps have been measured with 100µm step and no periphery or bulk cracks have been observed within this accuracy. Using the RUV vibrations technique frequency scans of the longitudinal vibrations from 10 to 100 kHz were measured on all wafers. A typical full range acoustic spectrum obtained on wafer #1 is shown in Figure 39. In the frequency spectrum, a set of distinctive resonance modes was observed, which are consistently reproduced from wafer to wafer in terms of the maximum amplitude, frequency position and bandwidth ($BW$). One of these resonance modes, assigned hereafter as an A-mode, is observed at $f=49,930±20$ Hz. Tracking f-scan characteristics of the A-mode as a means of crack detection and control in the wafers was proposed. A primary criterion for the A-mode selection is a noticeable clearance from the neighbor peaks to avoid their overlapping and interference, which would reduce the accuracy of the mode analyses. As seen from Figure 39 (insert), the A-mode is indeed a stand-alone narrow peak with $BW=90±10$ Hz.
Figure 39. Full range ultrasonic frequency spectrum obtained on Cz-Si wafer #1. Insert shows the A-mode experimental data (open circles) and fitting Lorentz approximation (solid line). $BW$ parameter is shown by arrows.

We emphasize that the A-mode frequency scan and shape analyses can be measured with sufficient signal-to-noise ratio in a time range of a few seconds. This obviously makes the RUV approach feasible and attractive for potential implementation as an in-line wafer quality control module. The other important feature of the RUV method is that according to vibration theory, the resonance frequencies of the longitudinal vibration modes are independent of the wafer thickness ($h$), in contrast to the flexural vibrations, which are proportional to $h^{3/2}$ [74]. This is especially beneficial in the multicrystalline ribbon silicon wafers, which may have significant (up to 20%) thickness variations across the wafer, as well as from wafer to wafer. This statement was tested by
varying the Cz-Si wafer’s thickness between 100 and 350 microns. The frequency of the principle vibration modes observed in the RUV scans show slight (1.6%) high-frequency shift with reduced wafer thickness, which can be attributed to stress enhancement as was previously observed in mc-Si ribbon wafers [75]. It should be noted that every resonant peak shown in Figure 39 represents a certain longitudinal vibration mode, both symmetrical and asymmetrical. But for now, only the A-mode was considered. The solid line in the insert in Figure 39 shows the numeric approximation of the experimental frequency sweep for the A-mode. This approximation is obtained with the Lorentz function and the following parameters have been extracted: peak resonance frequency, $f_0$, and bandwidth, $BW$.

**4.2.2. Crack engineering**

To introduce or engineer cracks with different sizes, few wafers were cracked by scribing the wafer edge with a diamond pin. As expected, the crack originates at the spot of the diamond application and are oriented along $<110>$ crystallographic directions. The length of each engineered crack has been measured using SAM in the precision mode with a 10 µm step. The SAM image of one of these cracks is presented in Figure 40a. After careful SAM study, the RUV measurements on the wafers with cracks have been carried out and the frequency spectra of the A-mode recorded. In Figure 40, the A-mode spectra in wafers with different crack sizes was demonstrated. Clearly, the A-mode frequency decreases with increasing crack length (also see $\Delta f$ line in insert in Figure 37).
It was noticed that the vibration spectrum of the wafer with the 28 mm crack is non-symmetrical indicating sufficient asymmetry in wafer elasticity induced by the crack. In addition, the A-mode BW increases with crack length. One was able to clearly detect mm-size cracks by assessing A-mode line shift and broadening. Specifically, a 3mm crack is estimated from a 160Hz shift and an 8% increase in $BW$. Thus the RUV approach offers sub-millimeter crack length sensitivity in Cz-Si wafers.
Figure 40. SAM image of the 125mm x 125mm Cz-Si wafer with introduced 28mm periphery crack (a). Vibration mode at 51052Hz obtained with Finite Element Analysis calculations on the wafer with identical crack (b).
The observed decrease of the A-mode frequency and its dependence on crack length are consistent with finite element analysis (FEA) [76]. The wafer is modeled as a 125x125 mesh, with the size of individual elements being 1.25 mm x 1.25mm. The pseudo-square wafers are modeled with isotropic eight-node planar elements with a Young’s modulus of $1.67 \cdot 10^{12}$ dyn/cm², a Poisson’s coefficient of 0.3 and a density of 2.329 g/cm³. The resonance frequencies up to 100KHz and respective mode shapes of the free edge longitudinal vibrations of the shell were calculated [77]. We concentrated on the frequency shift closest to the experiment vibration mode at $f_0=51,052$Hz. Figure 40b shows a calculated profile of the vibration mode on the wafer with identical geometry as the experimental Cz-Si wafers containing a 28mm periphery crack. The crack size and location are identical to the experimental values. The FEA shows a decrease in frequency shift with increased crack length which supports the experimental values in Figure 41. However, calculated values show a much larger frequency shift than observed experimentally. It was initially thought that one possibility for this difference could be the increase in damping in the test wafers with increased crack length. However, even though the $BW$ is proportional to damping, and the $BW$ and therefore damping increases with crack length by about an order of magnitude in the tests presented, the actual damping levels associated with the longitudinal A-mode are very low for all test wafers. Therefore, the increased damping with crack length does not notably decrease the modal frequency. To clarify this, the damping level can be quantified by the modal damping ratio $\zeta = \frac{BW}{2f_n}$ in terms of $BW$ and modal undamped natural frequency $f_n$. The modal damped natural frequency is related to undamped natural frequency and the damping
ratio as \( f_d = f_n \sqrt{1 - \zeta^2} \). Since the damping ratio for the cracked wafers range from 0.001 to 0.01, the modal damped and undamped natural frequencies are essentially equal. A more likely possibility for the difference between experimental and numerical results is that the FEA models an ideal crack without contact elements and contact forces. Contact forces in a crack are inevitable when the test wafer is subjected to vibratory excitation. Such forces would tend to provide some stiffness and thereby result in the smaller frequency shift observed experimentally compared to the wafer model simulations without contact forces. Contact elements can be introduced in the FEA. Such efforts are currently in progress and are expected to improve the model and therefore estimation capabilities of the method.
Figure 41. The A-mode spectra of (a) non-cracked wafer, and wafers with different crack lengths: (b) 3.0 mm, (c) 18 mm and (d) 28 mm. The insert shows the dependence of resonant frequency shift and also $BW$ of the longitudinal mode spectra versus crack length.
5. Conclusions and recommendations

As the principal goal of this PhD research project, resonance ultrasonic vibration methodology was developed both experimentally and theoretically and applied to the analysis of longitudinal vibrations in full-size single-crystal and multi-crystalline silicon wafers primarily for photovoltaic application.

Theoretical analysis of the longitudinal vibrations in single crystal and multicrystalline silicon wafers was created and used to provide a benchmark reference analysis and validation of the approach. Eigenfrequencies and mode shapes were calculated using analytical and finite element approximation approaches. The calculated frequencies were in a good agreement with RUV data obtained on 300 mm Cz-Si wafers. The finite element approximation data also correlated well with both experimental data and theoretical model.

Specific vibration modes were identified in wafers with different geometric shapes and their resonant frequencies correlated to in-plane residual stress. In multicrystalline silicon EFG wafers, a clear trend of increasing resonance frequency of the longitudinal vibration mode with higher average in-plane stress obtained with scanning IR polariscopy was observed. Additional evidence of a stress dependent
resonance frequency shift is achieved from the 5-point wafer bending experiment. One could see the tendency of the wafer resonance frequency location to shift to higher values with the increasing load. That loading experiment provides additional experimental evidence linking the resonant peak frequency shift to stress, as found in EFG wafers.

The resonance ultrasonic vibrations method is suitable for fast crack detection and its length determination in full-size solar-grade Cz-Si wafers. A gradual downward shift of the resonant frequency and line broadening of the longitudinal vibration mode versus crack length has been shown. On a set of identical crystalline Si wafers with artificially introduced periphery cracks, it was demonstrated that the crack results in a frequency shift of a selected RUV peak to lower frequencies and increases the resonance peak bandwidth. Both characteristics – peak position and bandwidth – are increased with the length of the crack. These dependences demonstrate a direct relation of the extracted parameters on crack length. The probable mechanism of the observed effect is attributed to a decrease in wafer stiffness thus affecting the vibration mode frequency with the mm-length peripheral crack. Therefore, the frequency shift and the bandwidth were found to serve as reliable indicators of the crack appearance in silicon wafers and are suitable for mechanical quality control and fast wafer inspection.

It is suggested that the proposed model needs to be further investigated experimentally, for instance, using wafers with different mechanical parameters (material’s density, Young modulus) and also theoretically. The finite element modeling
of the longitudinal vibrations on wafers with periphery cracks is currently in progress by
other students in the group.

The RUV system, built on the idea of using frequency shift and bandwidth as
indicators of wafer quality, allows fast data acquisition (as short as 3 seconds) and
analyses matching the throughput of solar cell production lines.

The results of this work were published or submitted to the following journals:

   (in press).

ii) A. Belyaev, O. Polupan, W. Dallas, S. Ostapenko, D. Hess, J. Wohlgemuth, Appl.

iii) A. Belyaev, S. Ostapenko, W. Dallas, J. Wohlgemuth, Proc. 31st Photovoltaic


v) A. Belyaev, S. Lulu, I. Tarasov, S. Ostapenko and J. P. Kalejs, Proc. MRS Spring
    Meeting, New Orleans, La, 2002.
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77. O. Polupan, private communication, 2005.


About the Author

Anton Byelyayev received his bachelor degree in Physics with concentration in Solid State Physics at Kiev State University (Ukraine). His bachelor diploma work was dedicated to investigation of niobium nitride alloys as a Schottky contacts for metal-semiconductor diodes.

In February 2000, Anton joined the Master’s program in Defect Engineering Laboratory supervised by Prof. Sergei Ostapenko at the University of South Florida. He successfully defended his thesis in July 2003 and in August of the same year he continued to study the resonance ultrasound technique applied to full-sized silicon wafers as a Ph.D. candidate. His Ph.D. work was accomplished in May 2005 and in July 2005 Anton defended his dissertation.

Now he works for Semiconductor Diagnostics, Inc. located in Tampa, FL.