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

Hao Wu[1], Shreyes N. Melkote[1],
Anton Belyaev[2], Igor Tarasov[2], Deven Cruson[2] and Sergei Ostapenko[2]
[1] The George W. Woodruff School of Mechanical Engineering,
Georgia Institute of Technology, Atlanta, Ga, 30332
[2] Ultrasonic Technologies Inc, Tampa, FL 33612

ABSTRACT

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

INTRODUCTION

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

While the Si wafers are gripped by the vacuum wafer holder (or chuck) to ensure firm coupling between the wafer and the transducer in the RUV setup, the handling stresses generated by the vacuum chuck, which to a large extent are determined by the geometrical design of the chuck, may influence the effectiveness of the RUV approach. In this paper, the handling stress produced by different designs of the vacuum wafer holders and their effects on the resonance properties of the ultrasonically excited wafer are studied using Finite Element Analysis (FEA) and confirmed by the RUV tests.

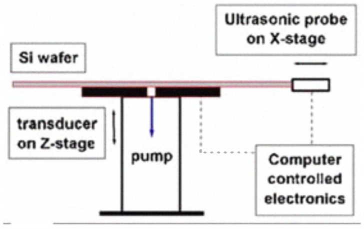


Figure 1 Schematic of the RUV experimental systems [1]

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

ANALYSIS OF HANDLING STRESS GENERATED BY TRANSDUCERS OF DIFFERENT GEOMETRIC DESIGNS

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

The handling stresses generated by the four designs are analyzed in the commercially available FEA software ABAQUS®/Standard. An absolute pressure of 80 kPa is applied to all the designs to simulate actual handling practice. Due to the geometric symmetry of the transducers and wafers, and symmetry of boundary and load conditions as well as material property, only one quarter of the overall model is built to minimize computational costs. The transducers are modeled as rigid bodies while thin shell S4R elements with enhanced hourglass control are applied to model the silicon wafer.

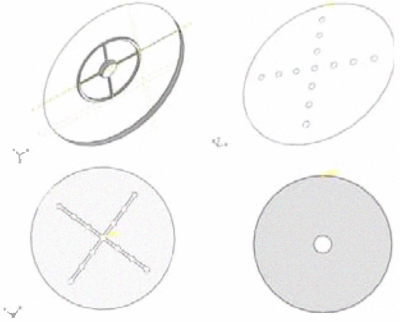


Figure 2 Vacuum chuck/transducer designs analyzed: Design I, II, III and IV, from left to right, top to bottom

Properties of the {100} crystallographic orientation of the single crystal wafer are used, taking [100], [010], [100] orientations as the x, y and z axes. The stiffness matrix capturing the anisotropic behavior of single crystalline silicon is obtained from [3]. The general contact in ABAQUS/CAE is applied to model frictionless hard contact between the transducers and the wafers, since the tangent behavior does not play an important role in determining the out-of-plane motion of the wafer and the stresses generated.

Typical von Mises stress distributions in 200 μm thick single crystal wafers are shown in Figure 3. In Design I, the maximum stresses occur along the edge of the central hole and have a magnitude of 6.2MPa, while for the radial grooves, the stress is less than 0.5MPa, and there is almost no stress (<0.1MPa) in the rest of the wafer. In Design II, III and IV, the maximum stresses, which are ~0.5 MPa, 0.6MPa and 6.1MPa, respectively, also occur along the edge of the holes, while the locations of maximum stresses are along a certain direction. This is caused by the anisotropic mechanical properties of single crystalline silicon.

It is also observed that as the wafer thickness decreases, the stress patterns are unchanged but the magnitudes of the maximum stress increase dramatically for all three designs. The maximum handling stress magnitude versus wafer thickness is shown in Figure 4.

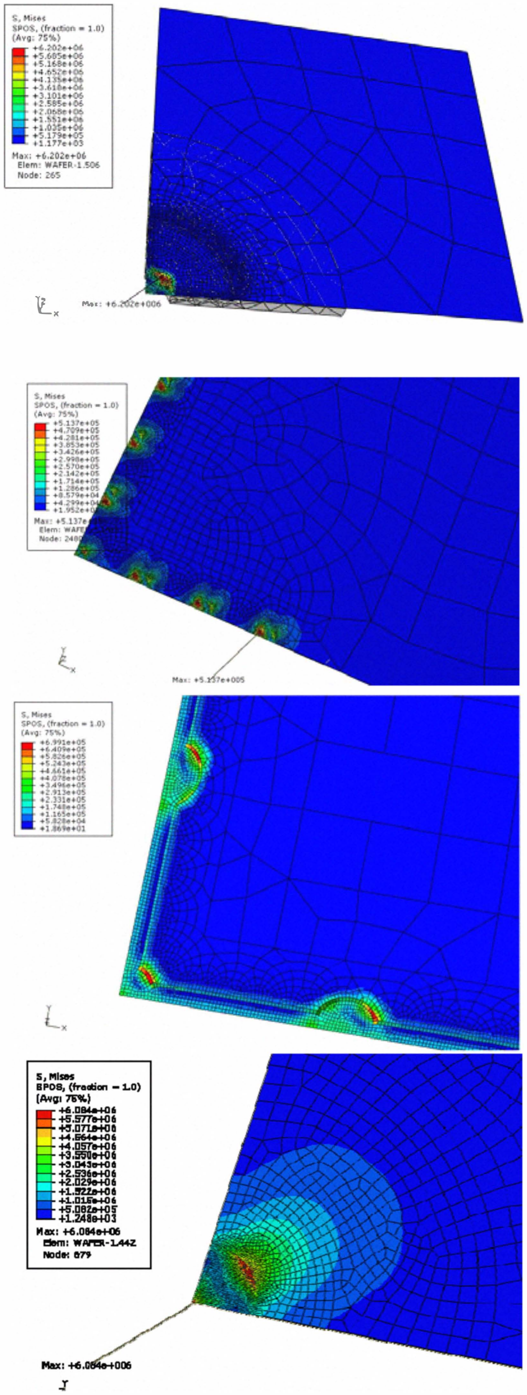


Figure 3 Handling stress (Von Mises) contour maps of Design I to IV (from top to bottom) in the central region

It can be seen in Figure 4 that the maximum handling stress for Design III is barely larger than that obtained in Design II, while still being much smaller than Design I and IV. Note that the maximum stress values are fairly small for normal 200 μm thick single crystal wafers, typically on the order of 1 MPa, which suggests that the likelihood of wafer breakage is low.

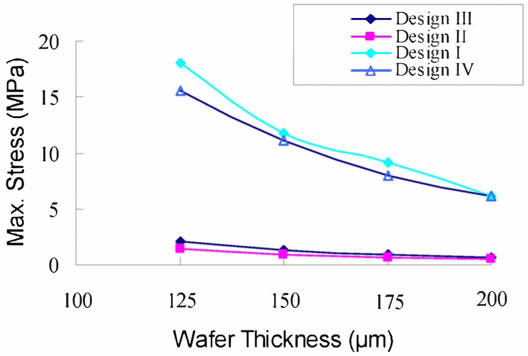


Figure 4 Maximum handling stress (von Mises) vs. wafer thickness for the transducer designs

While both Designs II and III generate small handling stresses, it is observed that the total handling force for Design III is more than twice that of Design II. The total handling force can be calculated as:

$$F_{Total} = \Delta PA \quad (1)$$

Where ΔP is the vacuum gauge pressure, namely the difference between atmospheric pressure and the absolute pressure, and A is the area of the vacuum grooves. The vacuum area in Design I is 132.54 mm^2, in Design II it is 40.85 mm^2, while for Design III it is 94.28 mm^2 and Design IV it is only 33.17 mm^2. It can be seen from the above results that,from a standpoint of maximizing the wafer holding force while minimizing the handling stresses, Design III is superior to the other designs.

IDENTIFICATION OF ULTRASONIC VIBRATION CHARACTERISTICS OF WAFERS HANDLED BY TRANSDUCERS OF DIFFERENT GEOMETRIC DESIGNS

Since the RUV method relies on identifying the shift in the natural frequencies of the wafer for crack detection, it is necessary to determine the modal characteristics of the silicon wafers when they are held in vacuum transducers of different shapes, as different boundary conditions will affect the natural frequencies of the wafers differently.

In previous work [1], the RUV modes were identified through FEA by assuming that the wafer is subjected to free vibration and hence neglecting the effect of transducer coupling. In this work, the determination of the RUV modes is carried out via modal analysis in ABAQUS®/Standard. First, the longitudinal natural frequencies of free vibration of 156 mm x 156 mm square multicrystalline silicon wafers are identified and the results are shown to agree very well with the results presented in [1]. Second, the longitudinal natural frequencies of the multicrystalline silicon wafers handled by the four designs of vacuum chuck/transducer presented earlier are analyzed.

The wafers used for the modal analysis are all 156 mm x 156 mm multicrystalline silicon wafers whose mechanical property data are obtained from [3].

Free vibration analysis

The first two longitudinal natural frequencies and the corresponding mode shapes are determined for free vibration of the wafer. It can be seen from Table 1 that the natural frequency values agree very well with those reported in [1]. The corresponding mode shapes are shown in Figure 5.

	Natural Frequency (Hz)	
	First Mode	Second Mode
[1] Results	31,461	45,980
Free Vibration	31,472	46,087
Design I	31,411	46,156
Design II	31,390	46,154
Design III	31,518	46,105
Design IV	31,497	46145
Experiment	30,005	45,980±140*

Table 1 Summary of longitudinal natural frequency study for a 200μm thick, 156mm x 156mm square multicrystalline silicon wafer.

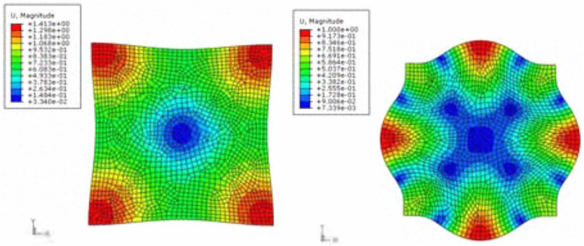


Figure 5 Free vibration mode shapes obtained in the current analysis: Mode 1 and 2

Wafer natural frequency extraction for different transducer geometries

While the free vibration analysis can provide preliminary understanding of the natural frequencies and mode shapes, it is not accurate because it neglects the coupling of the transducer and wafer. In the RUV experiment, the measured natural frequencies of the wafer correspond to the case where the wafer is held against the transducer by vacuum. Since different boundary conditions arising from different vacuum holder designs will result in different stress distributions and thereby different wafer natural frequencies, it is necessary to model and analyze the natural frequencies of the wafers when they are held in the vacumm chuck in order to compare with experimental data obtained from the RUV experiment.

The analysis approach for all four designs is identical. It consists of the following two steps. The first step is the same as in the handling stress analysis where the interactions between the transducer and wafer, loading and boundary conditions are modeled. At the end of the first step, the wafer is subject to the handling stress. The second step is a natural frequency extraction step where the wafer natural frequencies are determined while the wafer is subjected to the handling stress.

Recall that only a quarter model was built in the previous handling stress analysis work for simplicity and computational efficiency. However, in the natural frequency extraction analysis presented here, full models of the transducer and wafer were built in spite of the symmetries in material property and geometry in order to avoid loss of information about any asymmetric mode shapes/natural frequencies.

The first two modes of the longitudinal vibrations are studied for all four transducer designs. The natural frequencies (see Table 1) and the corresponding mode shapes are compared to identify the effects of the different transducer designs. It is observed from Table 1 that the computed natural frequencies for all vacuum holder/transducer designs are very close to the free vibration case, and the longitudinal modal shapes all have the same appearance. The second mode shapes for all four designs are shown in Figure 6. This basically shows that the variation of the transducer geometry and thereby the handling stresses does not change the longitudinal natural frequency valuesor the mode shapes much. Consequently, the RUV method is still applicable for detection of cracks in thinner wafers, which require higher holding force.

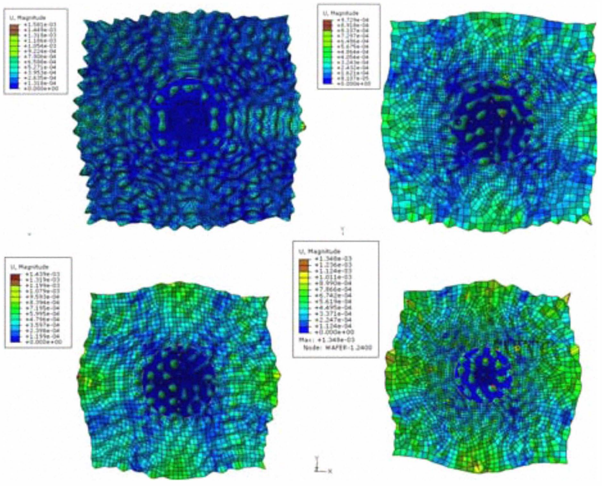
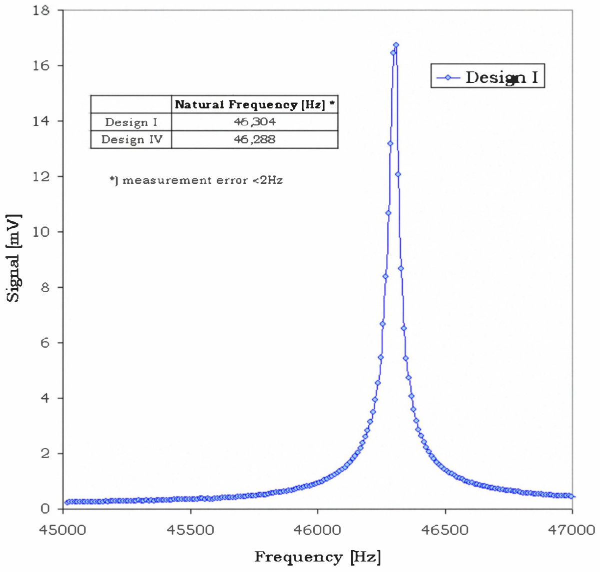


Figure 6 Second mode shapes for Designs I to IV (from top to bottom, left to right)

RUV experiment of wafer natural frequency extraction

A standard RUV setup was used for the measurement of resonant frequencies of the 156mm x 156mm square Si wafers coupled with the piezoelectric transducer. Transducers of two different designs (I and IV) were employed in this experiment. Frequency characteristics of the second resonant mode for Design I is presented in Fig. 7. The average value of the natural frequencies measured for transducer Designs I and IV are presented in the table insert. It is observed that there is only a small difference between the experimental natural frequency values for the two designs. Also,the values are very close to the modeling results given in Table 1. This confirms the FEA results and indicates that the RUV method can be applied effectively for thinner wafers without significant modification to the experimental setup.



	Natural Frequency [Hz] *
Design I	46,304
Design IV	46,288

*) measurement error <2Hz

Figure 7 Experimental frequency scans measured on 156mm x 156mm mono-crystalline Si wafers. Second principal mode is shown.

CONCLUSION

The effects of wafer handling stress on the characteristics of the RUV crack detection method were analyzed in this paper. The use of the RUV method for thinner wafers requires higher handling forces, which could result in wafer breakage during RUV testing. Consequently, four geometric designs of the vacuum wafer holder/transducer employed in the RUV setup were analyzed to determine their potential for providing sufficient wafer holding force while minimizing the wafer stresses. It was shown that Design III of the vacuum holder/transducer is capable of providing sufficient handling force while producing relatively low handling stresses.

The effect of the handling stress on the resonance properties of the ultrasonically excited wafers was also investigated for all the vacuum holder designs. FEA results and RUV experiments show that optimization of the wafer handling stresses obtained by redesigning the wafer holder does not alter the resonance frequencies and mode shapes of the wafer significantly compared to the free vibration case. This indicates that the the wafer holder in the RUV setup can be designed such that sufficient handling force is generated to provide good coupling between the wafer and transducer without compromising the ability of the RUV approach to detect cracks in thin wafers.

REFERENCES

[1] W Dallas,O polupan and S Ostapenko, "Resonance ultrasonic vibrations for crack detection in photovoltaic silicon wafers", *Meas.Sci.Technol.***18,** 2007, pp. 852–858.
[2] Belyaev A, et al., "Crack detection and analyses using resonance ultrasonic vibration in full-size crystalline silicon wafers". *Appl. Phys. Lett.* **88**, 2006,111907
[3] R.Hull, "Properties of Crystalline Silicon", *INSPEC, EMIS Datareviews Series No.20*, London, United Kingdom, 1999.