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IMPACT AND EDURANCE TEST ON SINGLE CRYSTALLINE SILICON WAFERS IN SOLAR PHOTOVOLTAIC CELL

Bangarappa. L[1] & Thammaiah Gowda[2]

[1]Research scholar, Department of Mechanical Engineering, Adichunchanagiri Institute of Technology, Chikmagaluru, Karnataka, India

[2]Research supervisor, Department of Mechanical Engineering, Adichunchanagiri Institute of Technology, Chikmagaluru, Karnataka, India

ABSTRACT

The data presented shows a dependence of natural frequencies, peak amplitudes and damping levels of four audio vibration modes in the different frequency range up to 1000 Hz on crack types and crack locations. Data from defective single crystalline wafers exhibit lower natural frequencies, higher damping levels, and lower peak amplitudes. From the results suggest an impact test method may be very useful for solar cell crack detection and quality control in the photovoltaic industry. The aim is to experimentally conduct and detect cracks from vibration measurements introduced by striking the single silicon wafer with an impact hammer. Such a method would reduce costs in the production of solar cells or photovoltaic industry.

KEYWORDS: *Single Crystalline Silicon Wafers, Cracked Silicon Wafers, Audible Detection, Vibration Measuring Instruments*

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INTRODUCTION

Crystalline Silicon is the most common material used in the photovoltaic market with over 98% market share. The reason that the photovoltaic cell is not more widespread is cost, particularly cost of cell production. During crystal growth and processing of silicon wafers, imperfections (such as cracks, residual stresses and sub-surface damage) are introduced. Breakage during production due to defects is currently 6-15%, but the industry wants to get this down to 1%, the method used in this thesis to detect the cracks could help facilitate this goal. There is a need for fast in-line mechanical quality control methods to detect these imperfections during the production of silicon solar cells. This could reduce the further processing of defective products and reduce overall costs. This thesis focuses on vibration impact testing of wafers for crack detection.

The test specimens are single crystalline (100) Czochralski (Cz) silicon wafers. They are pseudo square.’

Specifications

Table 1

Type:	P
Dopant:	Boron
Resistivity:	1.0-3(ohm.cm)
Dimension:	127 x 127±0.5 (mm)
Thickness:	200±20 (µm)
Oxygen Content:	$\leq 1 \times 10^{18}$
Carbon Content:	$\leq 5 \times 10^{16}$
Minority Carrier Lifetime:	≥2 (us)
Microcrystal:	$10/cm^2$
Saw Depth:	<20 (µm)
TTV:	<=30(µm)
Bow:	50 (µm)
Bevel Edge Angle:	90°±0.3
Bevel Edge Length:	1±0.5 (mm)
Rectangular Angle	0.3°
Edge Defect:	No crack, no V-Shape Chip
Surface Quality:	As cut, cleaned, no stain; No water mark, no contamination, no pits on the surface.
Edge Chips:	Length 0.5mm, Depth 0.3mm, 2 per wafer.

Defects in Silicon Wafers

Silicon wafers breakage can occur due to crack defects and also inherent defects which are created during its crystal growth. In the new thin silicon wafers, cracks are one of the most important defects. Cracks can appear in the wafers during wafer sawing or laser cutting. These cracks can propagate in the wafer through the post-processing of the wafers, such as the process of antirefieting coating, front and back contact firing and soldering of contact grid, in case of solar silicon wafers. Crystal originated pits (COPs), surface metals, oxide precipitates, hydrogen-induced defects and process induced defects are some of the most common types of the surface and sub-surface defects in silicon wafers in addition to cracks. Since these defects affect the symmetry of the wafer plane under the loading procedures, they can also cause extra stress on the wafer. Thus, detecting the size and location of these types of defects also help to prevent the use of defective wafers in the processing.

For Impact Test and Endurance Test

- Frequency response
- Test specimens
- Test with large cracks
- Test with small cracks
- Tests of miscellaneous cracks
- Experimental results from frequency response data with four audible modes for vibration parameters,

- Natural frequencies
- Normalized frequencies
- Peak magnitudes
- Damping ratio

To develop an endurance test to investigate how many impacts can be applied on the cracked wafer with a critical length of 1 cm before it breaks. This would represent an endurance test is applicable or not.

Experimental Setup

In the experimental setup and describes the sensors and the analyzer used. The specimens used are single-crystalline Czochralski (Cz) silicon wafers. Since the purpose is to detect cracks in wafers there are different types of specimens tested. In this research, the cracked specimens have been deliberately damaged with a diamond pin. In all, thirty different cracked specimens were made and tested.

Sensors

An impact hammer and a sound level meter are the two sensors used in this experiment. The impact hammer, model PCB 084A17, is made by PCB Piezotronics Inc. The sensitivity of the impact hammer is 22.5 mV/N. The hammer’s weight is 2.9 grams and the aluminum handle is 101.6 mm long, the hammer has a stainless steel head with a diameter of 6.3 mm and a red vinyl tip with a 2.5 mm diameter.

Analyzer

The analyzer is SigLab model 20-42 and is manufactured by DSP Technology Division. The SigLab has 4 input channels and 2 output channels. The impact hammer is connected to input channel 1 and the sound level meter is connected to input channel 3. The analyzer calculates the frequency response with the impact force as the input and the sound pressure as the output.

Experimental Setup

The test setup is shown in figure 3.1.1. The specimen is set on a piece of convoluted foam of dimensions 7 x 33 x 26.5 cm. The sound level meter is attached to a rigid fixture and the microphone is set at 1.2 cm above the specimen. The microphone is set perpendicular to the wafer. The impact hammer is connected to channel 1 of the SigLab analyzer and the sound level meter is connected to channel 3 of the SigLab analyzer.

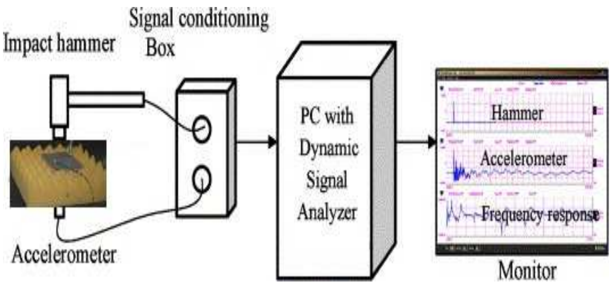


Figure 1: Experimental Setup

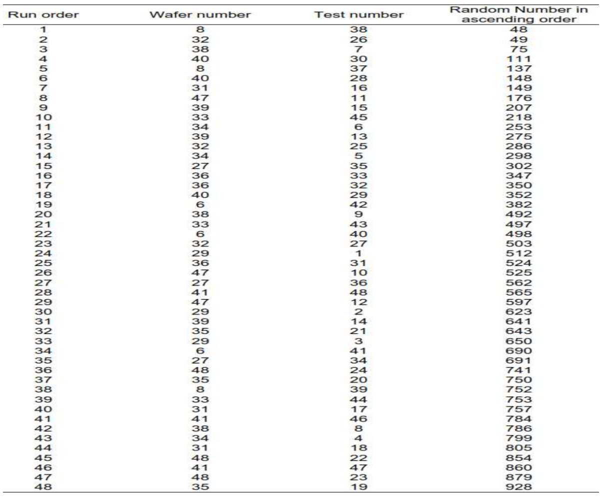
Result Analysis

Here all the wafers that were tested in this study and how the run order were determined. Three different groups of cracked wafers are listed: which are large crack wafer group, small crack wafer group and miscellaneous wafer group. This miscellaneous wafer group was not tested as a set, but is included because it was used to explore larger cracks.

Randomization

The order of the tests was randomized to eliminate bias error. All the wafers were tested three times each (8 impacts per test) and the test order is shown in Table 4.1.1. Three tests per wafer tables with the wafer number and test number is also shown in table. This table was used to define the random run order. The test order was determined by assigning each test a random number and sorting the random numbers.

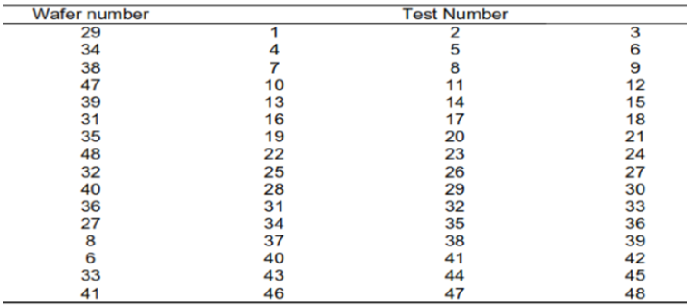
Table 2: Run order for the Large Crack Wafer Set



Run order	Wafer number	Test number	Random Number in ascending order
1	8	38	48
2	32	26	49
3	38	7	75
4	40	30	111
5	8	37	137
6	40	28	148
7	31	16	149
8	47	11	176
9	39	15	207
10	33	45	218
11	34	6	253
12	39	13	275
13	32	25	286
14	34	5	298
15	27	35	302
16	36	33	347
17	36	32	350
18	40	29	352
19	6	42	382
20	38	9	492
21	33	43	497
22	6	40	498
23	32	27	503
24	29	1	512
25	36	31	524
26	47	10	525
27	27	36	562
28	41	48	565
29	47	12	597
30	29	2	623
31	39	14	641
32	35	21	643
33	29	3	650
34	6	41	690
35	27	34	691
36	48	24	741
37	35	20	750
38	8	39	752
39	33	44	753
40	31	17	757
41	41	46	784
42	38	8	786
43	34	4	799
44	31	18	805
45	48	22	854
46	41	47	860
47	48	23	879
48	35	19	928

Test with Large Cracks

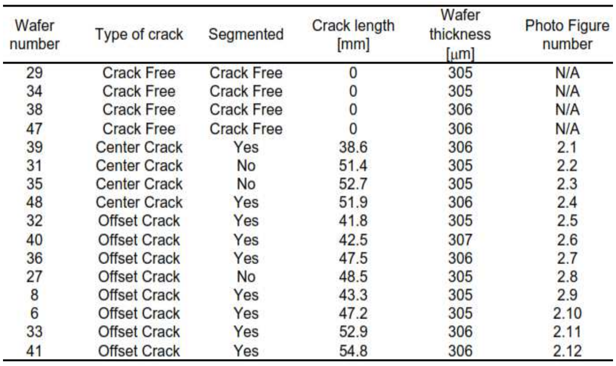
Table 3



Wafer number	Test Number		
29	1	2	3
34	4	5	6
38	7	8	9
47	10	11	12
39	13	14	15
31	16	17	18
35	19	20	21
48	22	23	24
32	25	26	27
40	28	29	30
36	31	32	33
27	34	35	36
8	37	38	39
6	40	41	42
33	43	44	45
41	46	47	48

The large crack test set contains 16 specimens from which 12 specimens are cracked and the other 4 are crack-free. Table 4.3.1 shows the wafer number, type of crack, if segmented or continuous, the length of the crack, the thickness of the wafer and the figure number of the image.

Table 4: Large Crack Wafers

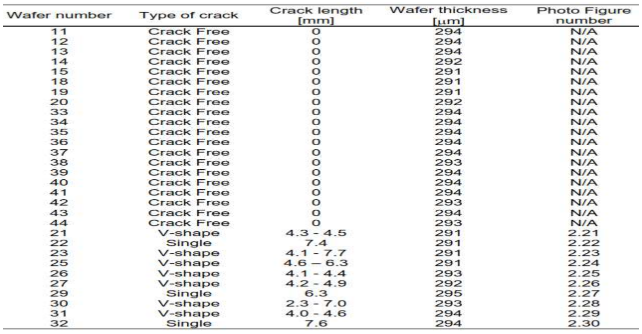


Wafer number	Type of crack	Segmented	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
29	Crack Free	Crack Free	0	305	N/A
34	Crack Free	Crack Free	0	305	N/A
38	Crack Free	Crack Free	0	306	N/A
47	Crack Free	Crack Free	0	306	N/A
39	Center Crack	Yes	38.6	306	2.1
31	Center Crack	No	51.4	305	2.2
35	Center Crack	No	52.7	305	2.3
48	Center Crack	Yes	51.9	306	2.4
32	Offset Crack	Yes	41.8	305	2.5
40	Offset Crack	Yes	42.5	307	2.6
36	Offset Crack	Yes	47.5	306	2.7
27	Offset Crack	No	48.5	305	2.8
8	Offset Crack	Yes	43.3	305	2.9
6	Offset Crack	Yes	47.2	305	2.10
33	Offset Crack	Yes	52.9	306	2.11
41	Offset Crack	Yes	54.8	306	2.12

Test with Small Cracks

Thirty small crack wafers were tested. Twenty wafers were crack-free and ten wafers had cracks introduced to the wafers. Table 4.4.1 shows the wafer number, type of crack, the length of the crack, the thickness of the wafer and the figure number of the image.

Table 5: Small Crack wafers



Wafer number	Type of crack	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
11	Crack Free	0	294	N/A
12	Crack Free	0	294	N/A
13	Crack Free	0	294	N/A
14	Crack Free	0	292	N/A
15	Crack Free	0	291	N/A
18	Crack Free	0	291	N/A
19	Crack Free	0	291	N/A
20	Crack Free	0	292	N/A
33	Crack Free	0	294	N/A
34	Crack Free	0	294	N/A
35	Crack Free	0	294	N/A
36	Crack Free	0	294	N/A
37	Crack Free	0	294	N/A
38	Crack Free	0	293	N/A
39	Crack Free	0	294	N/A
40	Crack Free	0	294	N/A
41	Crack Free	0	294	N/A
42	Crack Free	0	293	N/A
43	Crack Free	0	294	N/A
44	Crack Free	0	293	N/A
21	V-shape	4.3 - 4.5	291	2.21
22	Single	7.4	291	2.22
23	V-shape	4.1 - 7.7	291	2.23
25	V-shape	4.6 – 6.3	291	2.24
26	V-shape	4.1 - 4.4	293	2.25
27	V-shape	4.2 - 4.9	292	2.26
29	Single	6.3	295	2.27
30	V-shape	2.3 - 7.0	293	2.28
31	V-shape	4.0 - 4.6	294	2.29
32	Single	7.6	294	2.30

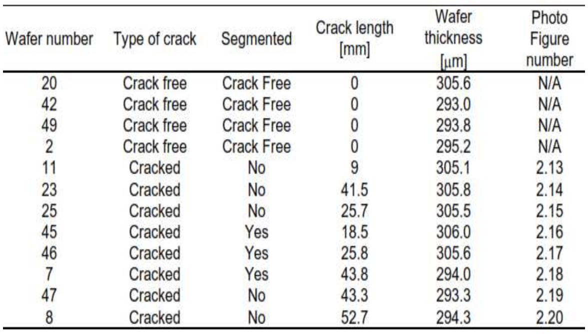
Tests of Miscellaneous Cracks

The tests from the miscellaneous cracks set were not performed in a totally randomized manner. The wafers were tested at different periods of time. However, these tests are grouped put together for presentation. This set includes twelve wafers total: four are crack-free and eight wafers are cracked. Table 4.5.1 shows the wafer number, type of crack, if segmented or continuous, the length of the crack, the thickness of the wafer and the figure number of the image.

Sample Frequency Response Data

Typical frequency response data from a crack-free wafer is shown in Figure 5.2.1. The graph shows a range of frequencies from 0-1000 Hz for coherence, magnitude and phase. Four dominant modes are found at the following frequencies: 420 Hz, 590 Hz, 840 Hz and 960 Hz. By comparing the frequency response data of a non-cracked wafer with a wafer with a large crack, as shown in Figure 5.2.2, one can still see four different modes but the frequencies are lower, the damping is larger (peaks not as sharp) and the peak magnitudes are lower. In the next section, these parameters are extracted from the frequency response data.

Table 6: Test Number for the Large Crack Wafer Set



Wafer number	Type of crack	Segmented	Crack length [mm]	Wafer thickness [μm]	Photo Figure number
20	Crack free	Crack Free	0	305.6	N/A
42	Crack free	Crack Free	0	293.0	N/A
49	Crack free	Crack Free	0	293.8	N/A
2	Crack free	Crack Free	0	295.2	N/A
11	Cracked	No	9	305.1	2.13
23	Cracked	No	41.5	305.8	2.14
25	Cracked	No	25.7	305.5	2.15
45	Cracked	Yes	18.5	306.0	2.16
46	Cracked	Yes	25.8	305.6	2.17
7	Cracked	Yes	43.8	294.0	2.18
47	Cracked	No	43.3	293.3	2.19
8	Cracked	No	52.7	294.3	2.20

Test Results

Introduction

This chapter presents the test data and results. This includes frequency response data with four audible modes. The following parameters are extracted from these 4 modes: natural frequencies, peak magnitudes, damping ratios and coherence.

Sample Frequency Response Data

Typical frequency response data from a crack-free wafer is shown in Figure 5.2.1. The graph shows a range of frequencies from 0-1000 Hz for coherence, magnitude and phase. Four dominant modes are found at the following frequencies: 420 Hz, 590 Hz, 840 Hz and 960 Hz. By comparing the frequency response data of a non-cracked wafer with a wafer with a large crack, as shown in Figure 5.2.2, one can still see four different modes but the frequencies are lower, the damping is larger (peaks not as sharp) and the peak magnitudes are lower. In the next section, these parameters are extracted from the frequency response data.

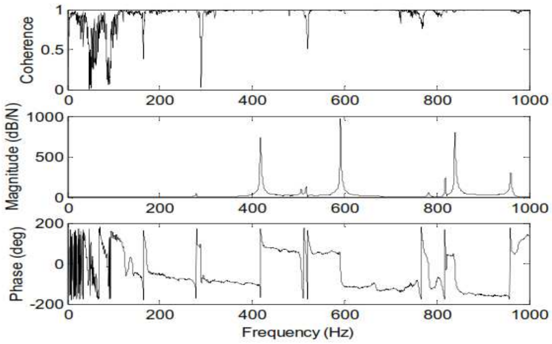


Figure 2: Frequency Response of Crack-Free Wafer Number 29

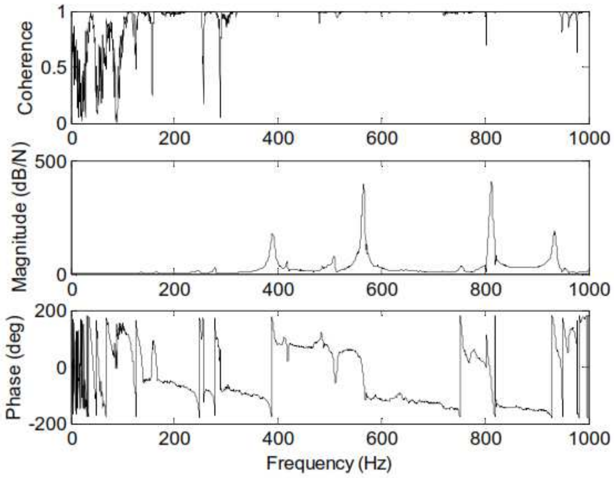


Figure 3: Frequency Response of Large Crack Wafer Number 35

The coherence ranges between 0 and 1, and it measures the amount of output that is caused by the input. A coherence value of 1 means that 100% of the output is caused by the input. In Figure 5.2.1 and Figure 5.2.2 the coherence versus frequency is plotted. From these figures, one can see that the coherence is close to one around the four dominant modes. All the frequency response data from the large crack wafer set are presented in Figures B.1-B.20.

Extracted Parameters

The following parameters are extracted from the four dominant modes in the frequency response data: Natural frequencies, Peak magnitudes and Damping ratio. The data from the large-crack wafer set, the miscellaneous wafer set and the small crack wafer set are shown in the following figures.

Natural Frequencies

Large Crack Wafer Set

The data from the second mode frequencies of the large crack wafer set are most representative and are shown in Table 5.3.1.1.1. The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks as defined in Table 5.3.1.1.1 and shown in Figures 5.3.1.1. In the crack-free wafers, the second mode frequency ranges from 591.6 to 594.1 Hz. For an individual crack-free wafer, the frequency deviation is less than 0.3 Hz, which is the frequency resolution of the measurements. The frequency deviation across all four crack-free wafers is 2.5 Hz.

Table 7: Second Mode Frequency for Large Specimens

Specimen number	Test 1 [Hz]	Test 2 [Hz]	Test 3 [Hz]	Mean [Hz]
29	591.6	591.6	591.6	591.6
34	592.2	592.2	592.2	592.2
38	592.8	593.1	593.1	593.0
47	594.1	594.1	594.1	594.1
39	592.8	592.8	592.8	592.8
31	*571.9*	*571.9*	*569.7*	*571.1*
35	*565.9*	*565.9*	*566.3*	*566.0*
48	*584.4*	*583.4*	*582.8*	*583.5*
32	590.6	590.9	590.6	590.7
40	592.5	592.8	592.8	592.7
36	591.9	591.9	591.9	591.9
27	*587.8*	*587.8*	*570.9*	*582.2*
8	590.3	590.6	590.6	590.5
6	592.2	592.2	592.2	592.2
33	591.9	591.6	591.9	591.8
41	592.8	592.8	592.8	592.8

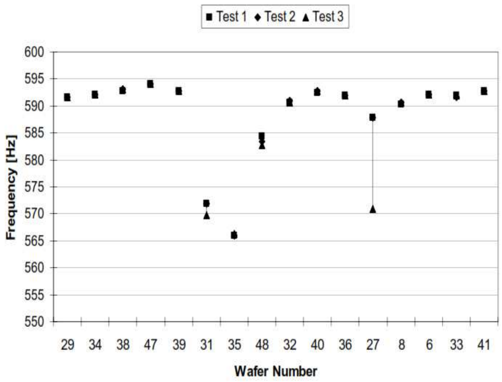


Figure 4: Second Mode Frequencies for Large Specimens

As seen in figure 5.3.1.1, all the specimens have a low frequency deviation (less than 0.3 Hz), except large crack wafer numbers 31, 48, and 27. Cracked wafer 31 has a deviation of 2.2 Hz, wafer number 48 has a deviation of 1.6 Hz, and wafer number 27 has a deviation of 16.9 Hz.

Miscellaneous Wafer Set

The second mode frequency range for the crack-free wafers is from 569.1 to 592.8 Hz. For an individual crack-free wafer the frequency deviation is less than 0.3 Hz. The frequency deviation across all the crack-free wafers is 23.8 Hz. For the 8 cracked wafers the second mode frequency ranges from 554.7 to 593.1 Hz, all cracked wafers are within 38.4 Hz and the deviation within a wafer is less than 2.2 Hz.

The deviation across the crack-free wafers is higher than found for the large crack specimens because these miscellaneous wafers have various thickness 293-306µm.

Small Crack Wafer Set

The crack-free wafers second mode frequencies range from 564.1 to 571.9 Hz. For an individual crack-free wafer the frequency deviation is less than 0.6 Hz, the frequency deviation across all twenty crack-free wafers is 7.8 Hz. For the 10 small crack wafers the second frequency mode ranges from 565 to 572.5 Hz and all are within 7.5 Hz. The deviation in an individual wafer is less than 0.3 Hz. Note that the ranges are very similar to the crack-free wafers and that the cracks are small less than 8 mm.

Normalized Frequencies

Some of the wafers were found to have slightly different thickness. Since natural frequency is directly proportional to the thickness to the three-half power, the frequencies are normalized with respect to the thickness of the wafers by

$$f_{norm} = \frac{f}{h^{3/2}}$$

Where f_{norm} is the normalized frequency, f is the measured natural frequency (in Hz) and h is the thickness of the wafer (in µm). The normalization is necessary for the miscellaneous wafer set since the thickness varied and also to compare the three different types of sets.

Large Crack Wafer Set

The crack-free wafers second mode normalized frequency ranges from 0.0008 to 0.0010 Hz/ µm$^{3/2}$. For an individual crack-free wafer, the frequency deviation is less than 0.0001 Hz/ µm$^{3/2}$. The frequency deviation across all four crack-free wafers is 0.0002 Hz/ µm$^{3/2}$.

Miscellaneous Wafer Set

The miscellaneous wafers second mode frequencies and the normalized second mode frequencies wafer numbers 42, 49, 2, 23, 7, 47, 8 had significantly lower frequencies than the other 5 wafers. The reason that the frequencies are lower is not because of any cracks instead it is because the thickness of the wafers varied from 293-306 µm.

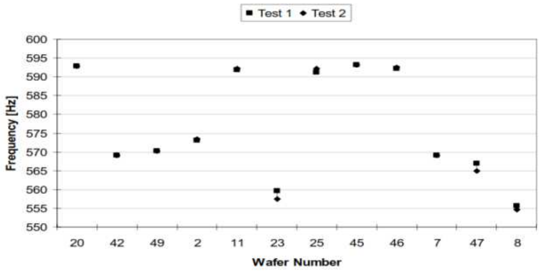


Figure 5: Second Mode Natural Frequencies for Miscellaneous Wafer Set

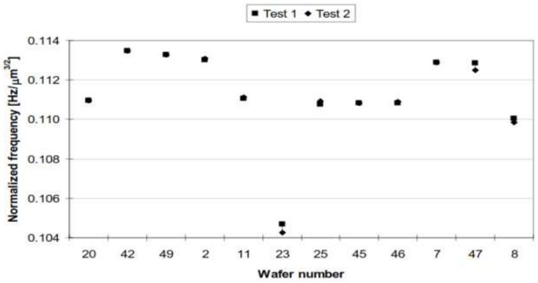


Figure 6: Second Mode Normalized Frequencies for Miscellaneous Wafer Set

Small Crack Wafer Set

Those wafers thickness varies between 291 and 295µm. The twenty crack-free wafers and the ten cracked wafers have the same normalized second mode frequency range from 0.1132 to 0.1138 Hz/ µm$^{3/2}$.The deviation for an individual wafer is less than 0.0001 Hz/ µm$^{3/2}$ and the deviation across all the wafers are 0.0006 Hz/ µm$^{3/2}$. The normalization of the small crack wafer set did improve the second mode frequency data.

Peak Magnitudes

Large Crack Wafer Set

The data from the second mode peak magnitude of the large crack wafer set are shown in Table 5.3.3.1.1**.** The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks as defined in Table 5.3.3.1.1 and shown in Figures 5.3.3.1.2.

Miscellaneous Wafer Set

The crack-free wafers in the second mode peak magnitude range from 927 to 1010 dB/N. For an individual crack-free wafer, the magnitude deviation is less than 50 dB/N. The magnitude deviation across all four crack-free wafers is 83 dB/N.

These 6 cracked specimens are numbered 23, 25, 45, 46, 47 and 8. Again, the magnitude parameter is a better indicator of large crack faults than natural frequency parameter itself.

Small Crack Wafer Set

The 20 crack-free wafers second mode peak magnitudes range from 760 to 1073 dB/N. For an individual crack-free wafer, the magnitude deviation is less than 153 dB/N. The magnitude deviation across all twenty crack-free wafers is 303 dB/N. For the 10 small crack wafers, the second mode peak magnitudes range from 811 to 1087 dB/N. All the wafers are within 276 dB/N. Again the crack-free wafers do not deviate from the cracked wafers when the crack size is small. Therefore, the vibration impact test used in this thesis does not appear to be suitable for detecting small edge cracks.

Damping Ratio

The damping ratio is found by zooming in on each peak and subtracting 3dB on each side of the peak and recording the corresponding frequencies. The damping ratio is then calculated by the following equation,

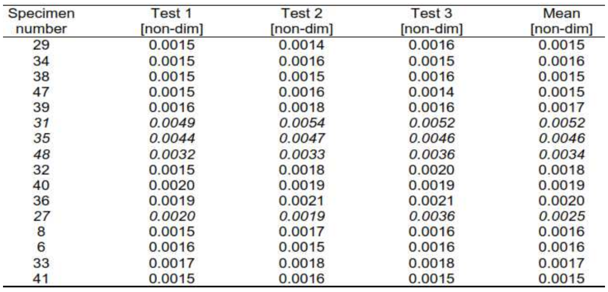
$$\zeta = \frac{(\omega_2 - \omega_1)}{2\omega_n}$$

where ζ is the damping ratio,w_2 is the frequency 3 dB down on the right side of the peak,w_1 is the frequency 3 dB down on the left side of the peak and w_n is the frequency at the peak.

Large Crack Wafer Set

The damping ratio for the second mode frequencies of the large crack wafer set are shown in Table 5.3.4.1.1. The first 4 specimens in the table are the crack-free wafers and the following 12 specimens have cracks.

Table 8: Second Mode Peak Damping Ratio for the Large Crack Wafer Set



Specimen number	Test 1 [non-dim]	Test 2 [non-dim]	Test 3 [non-dim]	Mean [non-dim]
29	0.0015	0.0014	0.0016	0.0015
34	0.0015	0.0016	0.0015	0.0016
38	0.0015	0.0015	0.0016	0.0015
47	0.0015	0.0016	0.0014	0.0015
39	0.0016	0.0018	0.0016	0.0017
31	*0.0049*	*0.0054*	*0.0052*	*0.0052*
35	*0.0044*	*0.0047*	*0.0046*	*0.0046*
48	*0.0032*	*0.0033*	*0.0036*	*0.0034*
32	0.0015	0.0018	0.0020	0.0018
40	0.0020	0.0019	0.0019	0.0019
36	0.0019	0.0021	0.0021	0.0020
27	*0.0020*	*0.0019*	*0.0036*	*0.0025*
8	0.0015	0.0017	0.0016	0.0016
6	0.0016	0.0015	0.0016	0.0016
33	0.0017	0.0018	0.0018	0.0017
41	0.0015	0.0016	0.0015	0.0015

Miscellaneous Wafer Set

The first 4 specimens in the table are the crack-free wafers and the following 8 wafers are cracked. The second mode damping ratio range for the crack-free wafers is from 0.0014-0.0016. For an individual crack-free wafer the damping ratio deviation is less than 0.0001. The damping ratio deviation across all the crack-free wafers is 0.0002.

Small Crack Wafer Set

For the 20 crack-free wafers, the second mode damping ratios range from 0.0013 to 0.0018 and are shown first, followed by 10 cracked wafers whose second mode damping ratios range 0.0014-0.0017. For the crack-free wafers and the wafers with a small crack, the deviation of an individual wafer is less than 0.0004, and the range across all the crack-free wafers is 0.0005 and for the cracked wafers the range is 0.0003.

Discussion

For the large crack wafer set, four wafers (numbered 31, 35, 48, 27) are show significant deviation in the natural frequencies for the four modes. For the magnitude peaks, eight wafers (numbered 39, 31, 35, 48, 32, 40, 36, and 27) show a significant difference. For the damping ratio, four of the wafers (numbered 31, 35, 48, 27) are show a significantly difference. Only four from the twelve large crack wafers set showed significant deviation in frequency, magnitude and damping ratio. These four large crack specimens have continuous cracks as opposed to segmented cracks as in the other 8 large crack specimens.

The damping ratio was higher for number 23, 25, 47 and 8. In other words, 50% of the cracked wafers were different from the crack-free data set considering the damping ratio and the magnitude. The small crack wafer set did not show any notable change in frequency, magnitude or damping ratio. The crack length of the wafers was too small to detect the cracks using the impact method. This would represent an endurance is applicable or not.

Conclusions

The audible vibratory mode data from a set of single crystalline silicon wafers including crack free and cracked conditions has been conducted and presented. The natural frequencies, peak magnitudes, and damping ratios from the first four modes have been extracted. Peak magnitude has been found to be most sensitive to the test wafer cracks. In addition, it is found that all the modal parameters are more sensitive to wafers with continuous cracks than segmented cracks as observed in SAM images.

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