Resonance Ultrasonic Vibrations for In-line Crack Detection in Silicon Wafers and Solar Cells

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ABSTRACT

The Resonance Ultrasonic Vibrations (RUV) technique was developed for in-line non-destructive crack detection in full-size silicon wafers and solar cells. The RUV methodology relies on deviation of the resonance frequency response curve measured on a wafer with peripheral or bulk millimeter-length crack and on identical non-cracked wafers. Three RUV frequency curve crack detection criteria were identified: (1) shift of the peak position; (2) increase of the bandwidth, and (3) reduction of the amplitude. It was observed that statistical variations of the RUV parameters on a similarly processed silicon wafers/cells with the same geometry lead to “false positive” events reducing accuracy of the RUV method. We proposed a simple statistical approach using three independent RUV crack detection criteria to resolve this issue and demonstrated its validity experimentally. Crack detection using RUV technique was applied to a set of production-grade Cz-Si wafers and finished solar cells from the Isofoton’s production line. Cracked solar cells rejected by the RUV method using the statistical approach were imaged with Scanning Acoustic Microscopy (SAM) and room-temperature photoluminescence (PL) mapping. A comparison of three independent techniques for crack detection, RUV, SAM and PL, was performed on selected samples. A high accuracy and selectivity of the RUV method to identify mm-size cracks in wafers and cells was confirmed.

INTRODUCTION

During times of increasing energy costs, renewable energy sources are considered as a competitive alternative to conventional power sources. To compete with traditional fossil energy sources, the solar or photovoltaic (PV) industry is driven by economic reasons to make solar panels of the highest power conversion efficiency along with high reliability at the lowest possible production cost. Crystalline silicon (c-Si) has taken a dominant role in contributing to over 90% of the entire power module production. It is important to recognize that the silicon wafer is a large contributor, up to 75%, to the overall cost of the solar cell. In addition, the silicon raw material price has roughly doubled in the last two years due to a worldwide shortage of the polycrystalline silicon feedstock. To compensate for the feedstock shortage, solar Si wafers are sliced thinner with thicknesses down to 80-200 microns. Wafer areas have also been increased to reduce overall production costs and larger sizes, up to 210 mm x 210 mm square shaped, wafers are now available. These technological trends make wafer handling in production more challenging and reduce the yield of solar cell lines due to increased wafer and cell breakage. In-line wafer breakage also reduces equipment throughput as a result of down time. Cracked wafers are becoming more common and methods to detect and remove damaged wafers are in great need. Whether the solar cells are based on single crystalline or polycrystalline type silicon, similar manufacturing steps lead to the production of complete cells. Many of these steps induce additional stresses on the already weakened wafers due to ingot and brick sawing and chemical etching. Examples of those steps are the deposition of thin dielectric or metal films, wafer annealing, soldering of contact tabs and lamination of cells into solar panels. Wafer/cell damage in the form of peripheral cracks can be initiated by any of these processes and serves as the starting point for fracture. To improve the economics of cell manufacturing, the PV industry is pushing for the development of a special inspection and quality control tool for integration into the production process. This in-line tool should allow (1) rejection of mechanically unstable Si wafers after ingot cutting before they are introduced into further cell processing, (2) identification of wafers with mechanical defects (such as cracks) during production to avoid their in-line breakage, (3) detection of cracked cells before they will be laminated into modules to avoid panel efficiency reduction and product return from the field. The testing tool must possess the following features at a minimum: (i) high speed data acquisition and analysis, matching the approximately 2 seconds per wafer throughput rate of typical cell lines; (ii) high stability (reliability and duty cycle) of the hardware performance including wafer loading/unloading and parts movement; (iii) easy integration into a belt conveyor configuration or cell testing station, and (iv) user-friendly algorithm for wafer/cell rejection with a minimum number of false positives. Various research groups have presented laboratory results of experimental methods for non-destructive crack detection in Si wafers. The most interesting of them are optical and ultrasonic methods such as, optical transmission [1], photoluminescence [2] and electroluminescence imaging [3], infrared lock-in ultrasound thermography [4], and scanning acoustic microscopy [5, 8]. To our knowledge, none of these techniques completely satisfies all of the specifications listed above for in-line testing and mechanical quality control of Si wafers and solar cells.

In Table 1 we compared different methods for crack inspection currently under investigation and prototyping.

Table 1 Comparison of crack detection methods

Method	Strength	Weakness
Scanning Acoustic Microscopy [8]	High spatial resolution, 10 microns	Wafer must be immersed in water, Slow speed (10 minutes) ;
IR thermography [4]	High spatial resolution (below 1 mm)	Long acquisition time (> 1 min)
Luminescence [2,3]	High throughput, snap-shot imaging	Interference with other defects (scratches, dislocations) , Closed cracks are hidden due to diffraction limit.
Optical transmission [1]	High throughput, high sensitivity	Not applicable in case of closed cracks and final cells with back contacts
Resonance Ultrasonic Vibrations (RUV) [6,7]	High throughput (<2.0 seconds per wafer); Applicable for in-line control; No interference with scratches and other defects	Sensitivity to crack length is limited by wafer statistics; Do not identify crack location, only "reject-accept" protocol (basic model)

We reported recently on an alternative approach for crack detection in solar grade Si wafers and cells using the Resonance Ultrasonic Vibrations (RUV) system [6]. The RUV method enables fast and accurate crack detection with simple criteria for wafer rejection from solar cell production lines. The RUV system relies on variation of modal vibration characteristics due to physical variations in the wafers caused by cracks. In Cz-Si wafers it has been shown that increased crack length leads to a decrease in peak frequency and an increase in peak bandwidth. Minimum crack length sensitivity is related to the uniformity of the RUV parameters from wafer to wafer within a batch. Typically the RUV system is capable of detecting sub-millimeter length cracks.

In this paper we report on developing a statistical algorithm that can be implemented in the RUV systems for in-line crack control. We also performed a cross-correlation study of the cracks and surface scratches using three different techniques: RUV, SAM and PL.

.EXPERIMENTAL SETUP

RUV setup

In Fig. 1 we show a schematic of the RUV system with details published elsewhere [7]. Standing longitudinal vibrations are set up at resonance frequencies with peak positions controlled primarily by the wafer's geometry, size, and material's elastic characteristics. The transducer frequency can be swept in the ultrasonic range from 20 kHz to 100 kHz. The transducer beneath the wafer serves both as a holding stage via the vacuum coupling with the wafer and as an actuator inducing resonance vibrations into the wafer. The vibrations are detected using a broadband ultrasonic probe, which contacts with a sensor-controlled force the edge of the wafer and coupled to a lock-in amplifier. Stepper motors allow synchronized movement and precise positioning of the wafer and probe. The entire system is computer controlled and programming devices are operated by Windows-based original software. The RUV unit may be integrated into an automatic belt-type solar cell production line or used as a stand-alone testing system for mechanical quality control [9].

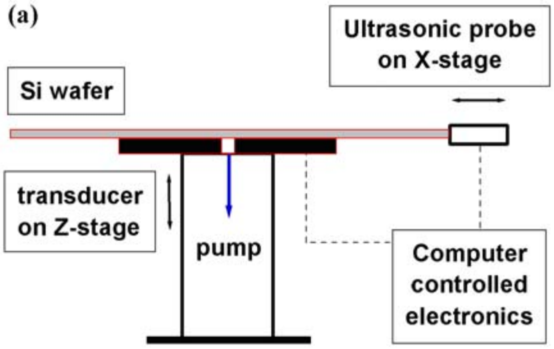

Fig. 1. A schematic of the experimental RUV system

PL system

A schematic of the PL setup for PL measurement is shown on Figure 2. Pulsed AlGaAs 804 nm laser diode with maximum peak power of 150 mW was used as the excitation sources. The laser beam was focused down to

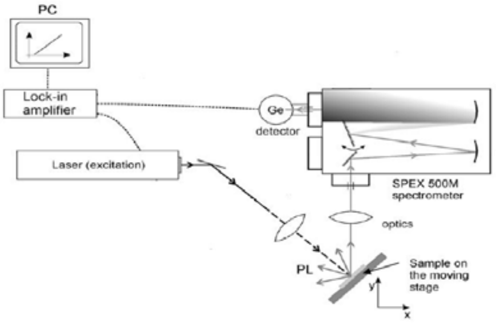

Fig. 2. Photoluminescence setup for room temperature spectroscopic PL mapping of Si wafers and cells

0.25 mm. The PL spectrum in the range of 1,050 – 1,700 nm was dispersed by a 0.5 m SPEX-500M grating spectrometer with a 600 lines/mm diffraction grating yielding a reciprocal dispersion of 3.2 nm/mm.

The PL intensity was registered with a liquid nitrogen cooled Ge detector. AC signal from the detector was fed to lock-in amplifier and analyzed by a computer. The PL mapping experiment was done with the use of a computer controlled X-Y moving stage with 10 µm step precision.

Scanning Acoustic Microscopy (SAM)

SAM principals can be found in detail in numerous sources elsewhere [5]. The SAM operates by emitting high frequency (~ 50 MHz) ultrasonic pulses directed at a sample immersed in the DI water bath. The ultrasonic pulses are emitted by a piezoelectric transducer with a focusing aperture. The focal point of the acoustic beam is set to the desired depth of investigation by moving the transducer in the vertical z direction. We used the SAM system SONIX HS1000 where the emitting transducer also serves as the receiving transducer upon reflection of the ultrasound pulses.

RESULTS

RUV Statistics

A crack introduced into Si wafer alters the RUV peak parameters: amplitude, bandwidth and peak position. This is illustrated in Fig. 3 for two identical 125 mm size Cz-Si wafers. Specifically, the crack in the wafer shows the following features: (1) a frequency shift of the peak position; (2) an increase of the bandwidth, and (3) a reduction of the amplitude. Therefore the RUV approach is essentially based on fast measurement and analyses of a specific resonance peak and rejection of the wafer if peak characteristics deviate from the normal non-cracked wafers.

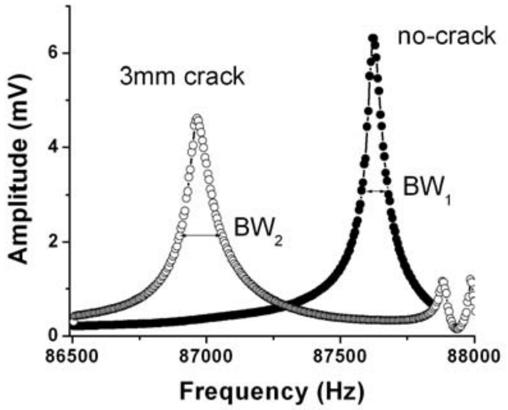

Fig. 3. Si wafer/cell with crack (open marks) can be separated from a regular wafer/cell (closed marks) using one of three rejection criteria: (1) reduced amplitude, (2) increased bandwidth (BW), and (3) resonance downward frequency shift.

One of the technological challenges for using the RUV method as in-line production tool occurred due to the fact that wafers (cells) of even the same size and shape are not identical. They show a statistical variation of the RUV peak characteristics caused by variations of the wafer size, thickness, internal stress, etc. The example of this variation is presented in Fig. 4 on a set of production-grade as-cut 125 mm cast wafers. The histogram represents a statistical distribution of the wafer bandwidth (BW) and a fit by a normal distribution with characteristic mean value and a standard deviation (σ). According to one of the crack rejection features the cracked suspects are located above the 3σ threshold. These suspects, however, can be confused with normal non-cracked wafers, which statistically possess a large BW and may contribute to "false positive" events. The statistical fraction of these false positives is 0.3% for the 3σ threshold, 5% for the 2σ threshold and 32% for the 1σ threshold. To address this issue we suggested using a parallel statistical approach applied to all three independent RUV parameters simultaneously. It was assumed that such a parallel statistics will dramatically reduce percentage of "false positive" events and increase the accuracy of the RUV method. These experiments were performed on a set of 125 mm and 156 mm Cz-Si solar cells, which show a strong statistical scattering of the RUV parameters. As an example the BW standard deviation was 78 Hz compared to 19 Hz in similar size as-cut Cz-Si wafers.

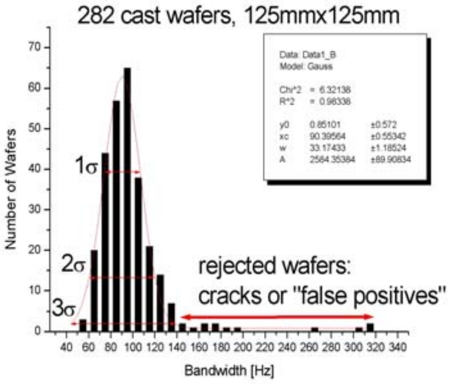

Fig. 4. Statistics of the bandwidth distribution on a set of as-cut cast wafers. Solid curve is an approximation of the histogram with a normal distribution: mean value = 90.4 Hz, standard deviation = 33 Hz. Wafers with potential cracks are located above the 3σ threshold.

In a case of screening multiple wafers or cells with identical geometry, a statistical algorithm has been developed and implemented into the RUV system. In this algorithm, the RUV software generates a mean value (M) and standard deviation (σ) for each of the RUV parameters, i.e. amplitude, BW and peak using initial (reference) set of wafers/cells. By this means, 6 statistical parameters of M and σ are calculated. For each RUV parameter the system calculates three thresholds for accept-or-reject command to pass the wafer as a "good" wafer or to reject it as a crack “suspect”. The threshold represents a minimum or maximum allowable value of the RUV parameter. In the case of 3σ thresholds, they are defined as M – 3σ /2 for amplitude and peak position, and M + 3σ /2 for the BW. In the case of 2σ thresholds, they are M – σ for the amplitude and peak position, and M + σ for the BW (Table 2). Additionally, M and σ values are updated along with the RUV measurement, which further improves an accuracy of the threshold calculations.

Table 2: Definition of thresholds			
	Amplitude	BW	Peak
3 σ case	M – 3 σ /2	M + 3 σ /2	M – 3 σ /2
2 σ case	M – σ	M + σ	M – σ

In the experiment we tested both 3σ and 2σ cases. In Fig. 5 we show a measured RUV parameter on Cz cells. To find wafer with valid statistical deviation we used 3σ rejection threshold in all three parameters. We assigned the cell as a cracked “suspect” when at least two of three parameters fell into the 3σ interval. This condition was satisfied in cells with numbers 2, 26, 43, 54 and 62. All suspects were removed from the batch of cells and measured using Scanning Acoustic Microscopy (SAM). SAM mapping provided a clear confirmation of true positive events revealed by the RUV method.

Table 3: Summary of RUV/SAM comparison on 125 mm x125 mm wafers/cells

Process	**Number of Wafers**	**Number of RUV Rejects**		**Number of True Positives**		**Number of False Positives**	**Number of False Negatives**	
		3 σ	2 σ	3 σ	2 σ		3 σ	2 σ
As-cut	112	1	1	1	1	0	0	0
Texturing	98	5	5	5	5	0	0	0
Diffusion	100	10	10	10	10	0	0	0
AR coating	99	3	3	3	3	0	0	0
Solar cells	110	8	12	7	11	1	5	1
Total	**519**	**27**	**31**	**26**	**30**	**1**	**5**	**1**

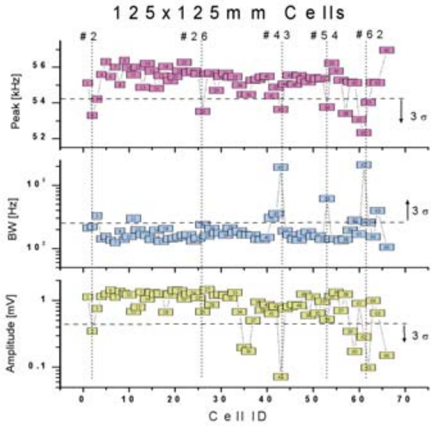

Fig. 5. RUV statistics of the three parameters of the set of 65 cells. Cells with potential cracks are rejected using 3σ criterion.

In Table 3 we summarize the statistical analyses on 125 mm wafers and cells. Note that percentage of errors which is a total of the “false positives” and “false negatives” is greatly reduced when 3σ threshold is changed to 2σ. Concurrently, the number of ‘true positive” events when RUV rejects were confirmed by SAM is increased. We found that the RUV method provided identification of cells with cracks length down to 3 mm.

Based on this study we concluded that the RUV method offers a high probability of crack detection with 91% success rate and 9% of errors as a total of false positive and false negative events. We illustrate in Figure 6 the results of the statistical analysis on both sets of 125 mm and 156 mm wafers and cells. Note that this high success rate of the RUV method will lead to a substantial 10-fold reduction in wafers and cells that contain cracks and interfere with production, reducing line throughput and increasing module cost. We propose that different crack rejection coefficients must be incorporated into RUV system software, allowing a production manager to optimize crack inspection depending on the particular technological step of the cell manufacturing.

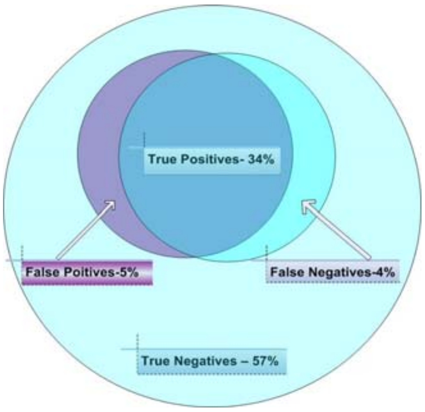

Fig. 6. Diagram illustrating full statistical evaluation of the Cz-Si wafers and cells.

It was further proposed that the larger deviation of the rejected parameter (e.g. BW) from the mean value or corresponding threshold the larger a damage to the wafer cased by cracks. In Figure 7 we present the result of quantitative analyses of the crack length based on the rejected 125 mm cells. We observed a strong correlation of the BW deviation versus crack length. This experiment demonstrates that the RUV method can be also used for estimation of the wafer damage and therefore serve as a crack characterization technique for in-line application.

RUV, SAM and PL correlation

In this section we performed a correlation study of cracks on Si wafers and cells using three independent methods: RUV, SAM, and photoluminescence (PL). The illustrative result of the peripheral crack in Cz-Si as-cut wafer is presented in Fig. 8a-c. All three methods give consistent results in this case. We noticed that the PL map in Fig. 8b contains various artifacts some of which can be attributed to the wafer damage. This is complicate crack identification using PL technique. In one of the cells the RUV method was able to diagnose a partially hidden crack, which was barely seen in the optical technique due to blocking by the busbar. RUV method offered a clear advantage in this case of cracks.

In the next experiment we show how the surface scratch could be misrepresented by the PL method as a crack. Although scratches are one of silicon cell defects, it has only a minor impact on the wafer/cell breakage in PV manufacturing. The scratch was designed by a needle in the direction perpendicular to the cleavage to reliably distinguish from the crack. Fig 9a-c shows all three methods in comparison to each other. A scratch was clearly visualized in the PL map and has also been found by SAM imagine. In SAM the wafer was scanned from both sides and analyzed pulses reflected from the front and rear surface of the wafer. In contrast, there are no changes in the RUV peak parameters caused by the scratch. This experiment justifies high selectivity of the RUV technique to provide diagnostics and characterization of cracks propagated through the wafer thickness.

CONCLUSIONS

The RUV method for in-line application is based on the identification of wafers with cracks in the ensemble of similarly processed wafers by a statistically significant deviation of the RUV curve signatures – amplitude, bandwidth and peak position - from their mean values. The percentage of true positives depends strongly on a σ-threshold selection. The RUV system operator can balance between accuracy of rejection and percentage of “false positive” events by using appropriate number of N as a multiplier to the standard deviation σ. Generally, the smaller N*σ the larger number of wafers with smaller crack length will be detected, however with larger probability to have “false positives”. Conversely, when a larger N*σ is selected only wafers with a large crack length can be identified, but a smaller number of “false positives” will be generated according to the normal distribution statistics. These options offer a flexibility to tune the RUV system to different protocols of crack rejection in wafers and solar cells. We anticipate that second case can be used for solar cells where appearance of false positives is not-acceptable due to high cost of the product, while first case can be used for bare as-cut wafers. The RUV method was confirmed by SAM mapping and passed the acceptance test demanded by Isofoton with success rate of 95% using 3σ-threshold. The RUV method can be used for as-cut and processed wafers including finished solar cells. Our preliminary study (in progress) shows that the method is also applicable to cell soldered in tabs prior to the module lamination step. The RUV method is fast enough with the entire measuring and evaluation cycle below 2 seconds per wafer matching a throughput rate of PV lines. In contrast to optical inspection techniques, the RUV method is not sensitive to surface scratches and therefore provides a firm identification of opened cracks with highest potential to initiate the wafer and cell breakage. The RUV method can serve as an in-line quality control technique to reduce the amount of wafers with internal cracks in multiple places of PV production lines.

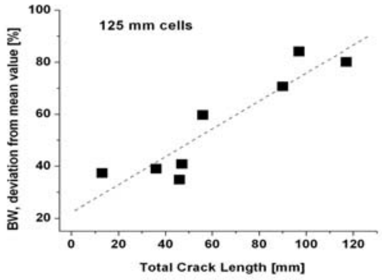

Fig. 7. Deviation of the RUV peak bandwidth from the mean value versus crack length measured by SAM on a set of 125mm Cz-Si cells.

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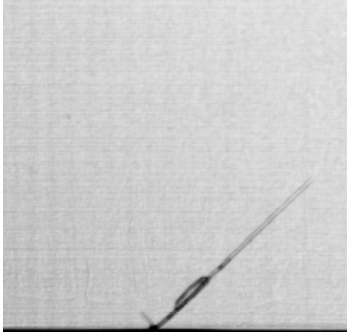

Fig. 8a. SAM image of the cracked Cz-Si wafer. Map size 40 mm x 40 mm, with 10 microns step. Mapping time = 10 minutes.

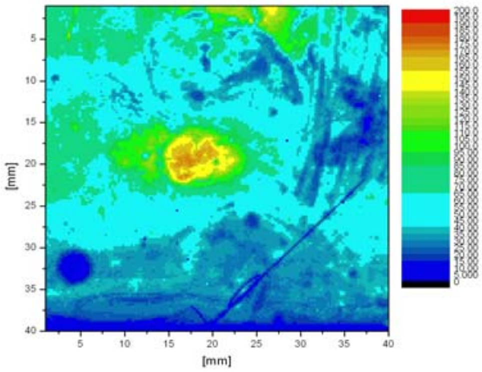

Fig. 8b. PL map of the same cracked area. Map size 40 mm x 40 mm, with step = 0.25 mm. PL wavelength 1146 nm. Mapping time = 2 hours.

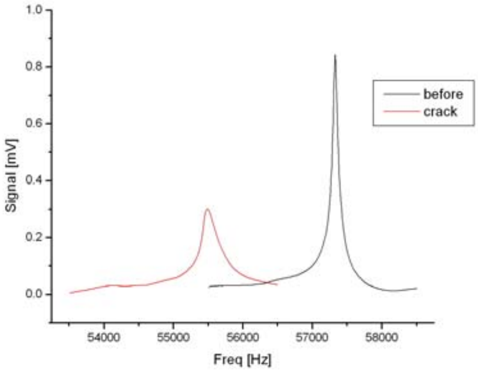

Fig. 8c. RUV scans on the wafer without crack and the one with 25 mm crack. RUV time = 2.5 seconds.

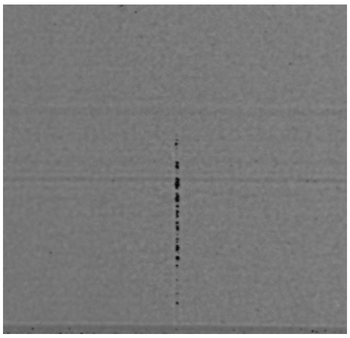

Fig. 9a. SAM image of the scratch area. Mapping size is 20 mm x 20 mm, with 10 microns step.

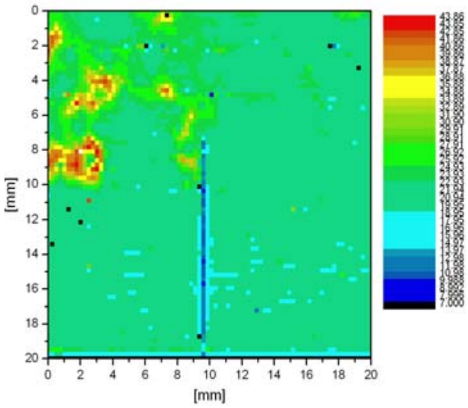

Fig. 9b. PL map of the scratch area. Mapping size is 20 mm x 20 mm, with 0.25 mm step. PL wavelength 1146 nm.

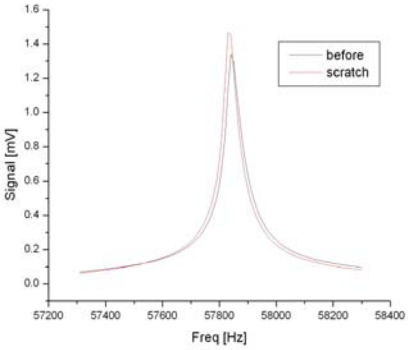

Fig. 9c. RUV scan of the Cz-Si wafer before and after scratch was applied. No change of the RUV peak parameters is observed.