Non-Contact Defect Diagnostics in Cz-Si Wafers Using Resonance Ultrasonic Vibrations

A. Belyaev*, V. A. Kochelap+, I. Tarasov*, and S. Ostapenko*

*University of South Florida, 4202 E Fowler Ave., Tampa, FL 33620, USA
+Institute of Semiconductor Physics, Prospekt Nauki 45, Kiev, 03028, Ukraine

Abstract. A new resonance effect of generation of sub-harmonic acoustic vibrations was applied to characterize defects in as-grown and processed Cz-Si wafers. Ultrasonic vibrations were generated into standard 8" wafers using an external ultrasonic transducer and their amplitude recorded in a non-contact mode using a scanning acoustic probe. By tuning the frequency, f, of the transducer we observed generation of intense sub-harmonic acoustic mode ("whistle" or w-mode) with f/2 frequency. The characteristics of the w-mode – amplitude dependence, frequency scans, spatial distribution allow a clear distinction versus harmonic vibrations of the same wafer. The origin of sub-harmonic vibrations observed on 8" Cz-Si wafers is attributed to a parametric resonance of flexural vibrations in thin silicon circular plates. We present evidence that "whistle" effect shows a strong dependence on the wafer's growth and processing history and can be used for quality assurance purposes.

The elastic stress in Czochralski silicon (Cz-Si) wafers and thin films can be caused by point defects and their complexes, like oxygen precipitates, as well as wafer processing such as back-side polishing, oxidation or deposition of polycrystalline or epitaxial Si layer [1]. For instance, thermal oxide on Cz-Si creates a residual stress ~ a few hundreds of MPa in the film due to a difference in thermal expansion of the substrate and oxide, which can be detrimental for gate-oxide integrity and reliability of CMOS devices. Residual elastic stress can also be harmful to silicon substrates, especially, with scaling of wafer diameter up to 12". Another source of stress in Cz-Si is ion implantation into the bulk, which creates lattice damage partially released after thermal annealing. With regard to Cz-Si wafer quality, the elastic stress field creates slip dislocations, which reduce wafers stiffness and can trigger uncontrollable wafer breakage. On the other hand, the stress can be a driving force to various types of defect reactions, such as precipitation of residual impurities deteriorating the electronic quality of material. Therefore, a problem of non-contact and non-destructive monitoring of residual stress/strain in as-grown, oxidized and epitaxial (Cz-Si) wafers is a current issue for microelectronics. Finding a fast and reliable method to control residual stress is strongly motivated. In some cases, this problem is addressed by scanning X-ray diffraction, TEM and micro-Raman spectroscopy [2]. Another possibility is measurement of the change in wafer curvature after thin-film deposition due to stress using laser deflection [3]. We report here a novel approach to the problem of strain/stress control using a new effect of resonance ultrasonic vibrations observed recently in Si-wafers [4].

EXPERIMENTAL

Ultrasonic vibrations were generated into single-side polished Cz-Si wafers of 8" diameter using a circular resonance piezoelectric transducer pressed by vacuum against the backside of the wafer. A typical schematic of the experimental set-up is shown in Figure 1. The wafer is centered with respect to the transducer with an accuracy of ~100 μm. A transducer 70 mm in diameter made of PZT-5H piezoelectric ceramics has a set of acoustic resonance modes. When coupled with the wafer, the transducer's resonance frequencies are slightly shifted and the lowest radial (longitudinal) vibration occurs at about 26kHz. The function generator and power amplifier provide the ac driving voltage to the transducer with tunable frequency (f) and adjustable amplitude. This geometry of acoustic loading of Si wafers offers an express change of samples and is non-harmful to the front polished surface of silicon, which can also carry the oxide or epitaxial film.

Ultrasonic vibrations are propagated in Cz-Si beyond the transducer and form standing waves at specific frequencies. The amplitude of the standing wave is measured using a non-contact ultrasonic probe. The probe is positioned with micrometer accuracy above the front surface of a wafer and can be moved in

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the radial X-direction using a computer-controlled stage with step-motors.

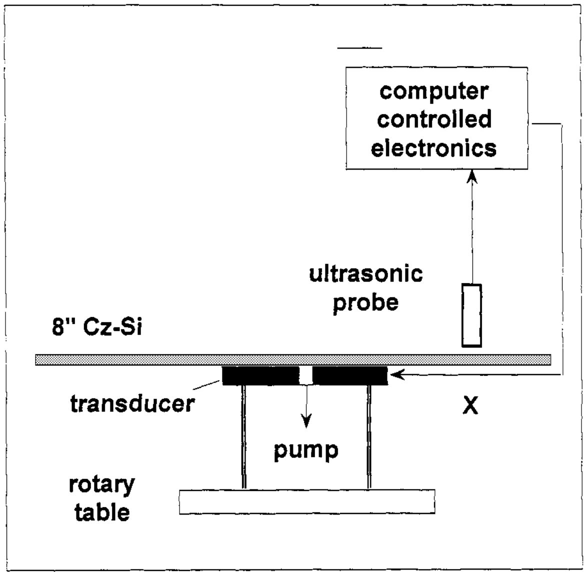

FIGURE 1. A schematic of computer controlled set-up for non-contact monitoring of ultrasonic vibrations in Cz-Si wafers.

Additionally, the transducer and wafer can be rotated using the rotary table. The ac voltage from the probe is recorded using a lock-in amplifier, which is synchronized to the frequency, f, of the driving generator in a case of measuring the harmonic oscillations of the wafer which have the same frequency f. Alternatively, the lock-in can measure sub-harmonic signal at f/2 frequency, which is a special concern in this study.

Single-side polished Cz-Si wafers of 8" diameter both as-grown and carrying the thermally deposited oxide with thickness from 4.2 to 90 nm were investigated. The top active surface of wafers was not affected by mechanical contact with the probe, realizing a non-contact approach. For comparison, we have also applied the ultrasonic diagnostics to polycrystalline 8" Si wafers grown by casting technique.

RESULTS AND DISCUSSIONS

Sub-harmonic vibrations in 8" Cz-Si

In Figure 2, we show resonance frequency curve (f-scan) of the harmonic oscillations of 8" Cz-Si wafer measured at probe elevation of 200-μm above the wafer front surface. Harmonic mode shows a broad maximum at 25.6 kHz with a half-width of 0.9kHz (curve (a)). This curve is very similar to the one of unloaded transducer shifted to lower frequencies by 0.5 kHz. By changing the ac driving voltage we measured an amplitude scan of the acoustic signal (a-scan). It was observed that the amplitude of the harmonic resonance is monotonously increasing with driving voltage with slight non-linearity above 2.5 Vpp. Beyond this voltage the acoustic amplitude starts to saturate due to increasing of losses in the piezoelectric ceramics.

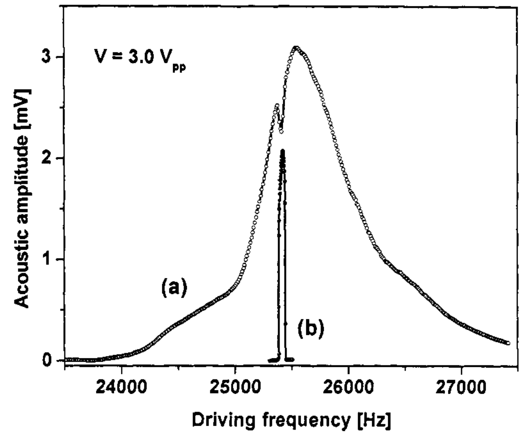

FIGURE 2. Frequency scans of the harmonic (a) and sub-harmonic vibration mode (b). The later is recorded with lock-in tuned to the half of driving frequency.

A new acoustic effect in vibrating Cz-Si wafers was found at relatively high amplitudes of the ac voltage [4]. This effect is exhibiting as a generation of an intense sub-harmonic mode with frequency, f_w, close to half of the driving frequency, f_d. (Note that in harmonic mode these two frequencies are identical). The effect is further referred as a "whistle" and the associated acoustic mode as the w-mode. A picture recorded by digital oscilloscope (Figure 3) shows that the "whistle" mode is a periodic, close to sine function with the frequency ~1/2 of the driving frequency from generator. In Figure 2, the f-scan of the whistle versus f_d is depicted as curve (b). There are two pronounced features of the w-mode. *The first* is that the f-scans of the whistle versus both f_w and f_d are substantially narrowed compared to the harmonic vibrations. This is also shown in detail in Figure 4. Specifically, a half-width of the f_w-curve is Δf_w= 10Hz, and that of the f_d-curve is approximately 50Hz and is changed in Cz-Si wafers with different processing histories (see below). These highly selective f-scans with quality factor $f_w/\Delta f_w \sim 10^3$ offer a sensitive means to monitor defects contributed to elastic properties of Cz-Si. *A second* distinctive feature of the w-mode is the threshold behavior versus driving voltage, which is in a striking contrast to the harmonic mode. Typical a-scans of the w-mode measured in two scan directions are shown in

Figure 5. It was further observed that the threshold voltage is changed between different wafers and shifts toward higher values in wafers with increased concentration of defects, which indicates that this parameter can also serve for Cz-Si quality control.

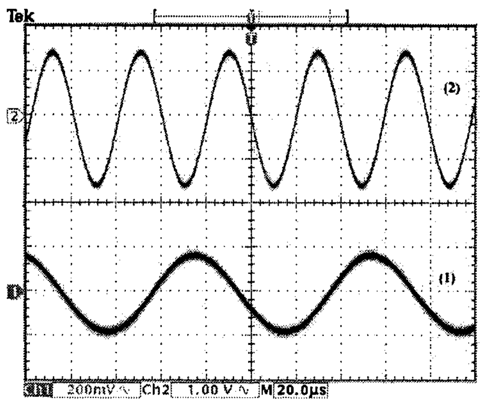

FIGURE 3. Time domain pictures of the resonance sub-harmonic w-mode from high-quality 8" Cz-Si wafer (1) and driving voltage applied to the transducer at 25.4kHz (2).

The following are important features of the sub-harmonic w-mode. (1) The mode shows a strong increase close to wafer's edge as presented by a radial scan distribution at one of the wafers in Figure 6. (2) The direction of vibrations in the w-mode is essentially perpendicular to the wafer plane with amplitude at the wafer edge of ~100μm measured using a laser beam reflected from the polished front surface. Notice that this amplitude is gigantic compared to the 735 μm wafer thickness. (3) The value of f_w is linearly shifted with f_d within the frequency range of whistle generation holding the f/2 ratio. This is shown as insert in Figure 4b. (4) The threshold voltage of the whistle is higher in the upward versus downward amplitude scans by as much as 0.2 Vpp as depicted in Fig.5. A similar effect is observed in upward-downward frequency scans (Fig. 4a).

Defect Control In Cz-Si

As we mentioned, some characteristics of the w-mode show a variation from wafer to wafer indicating that growth defects are contributing to the "whistle", and therefore, the w-mode can be potentially employed for diagnostics of as-grown and process-induced defects in Cz-Si.

A set of 8" Cz-Si wafers was selected and passed through measurements of the "whistle" amplitude, threshold voltage, frequency curve, and radial distribution.

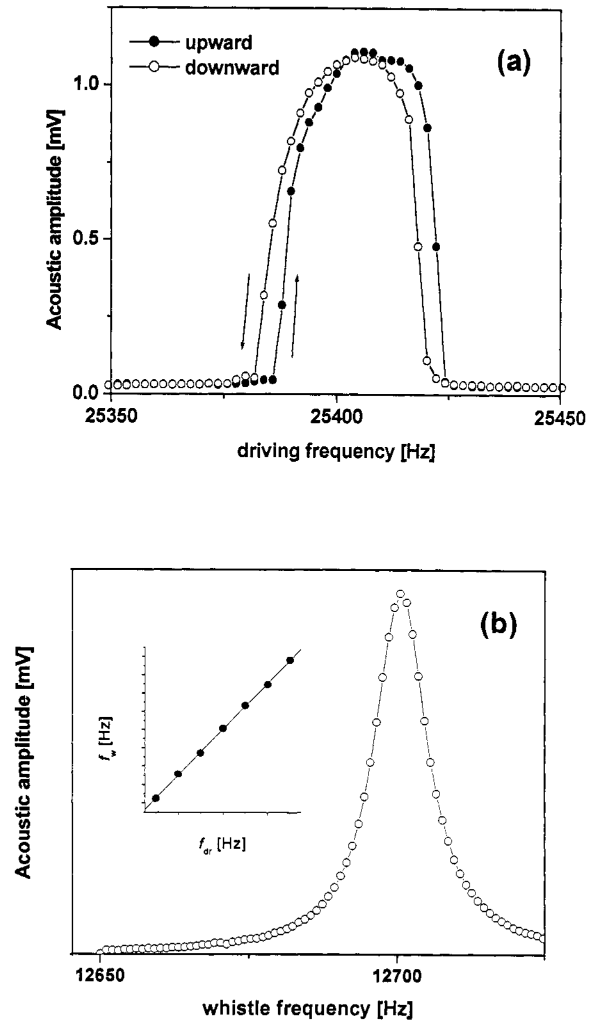

FIGURE 4. Dependence of whistle amplitude versus driving frequency (a) and whistle frequency (b). Notice a shift between upward and downward f_d – scans as indicated by arrows in (a). Insert in (b) shows a linear dependence of the whistle maximum versus driving frequency holding f/2 relation.

Generation of the f/2 sub-harmonic mode with threshold amplitude dependence was clearly observed in all investigated wafers. In terms of the "whistle" characteristics, the wafers could be separated into two different groups assigned as A and B here. Group "A" wafers yield intensive sub-harmonic amplitude, with narrow frequency scan as was described previously and illustrated in Figures 4 to 6.

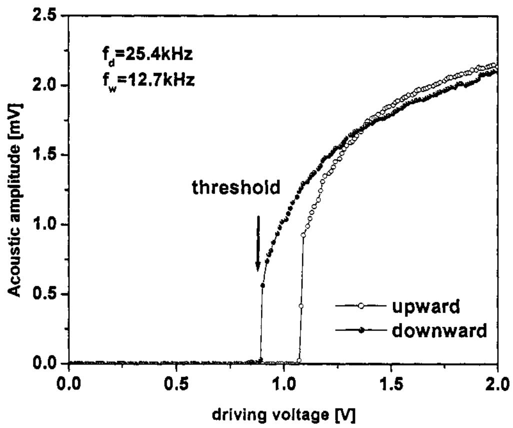

FIGURE 5. Amplitude dependence of the w-mode in two directions of the voltage scans applied to transducer. Shift of the threshold to lower values is observed for the downward scan.

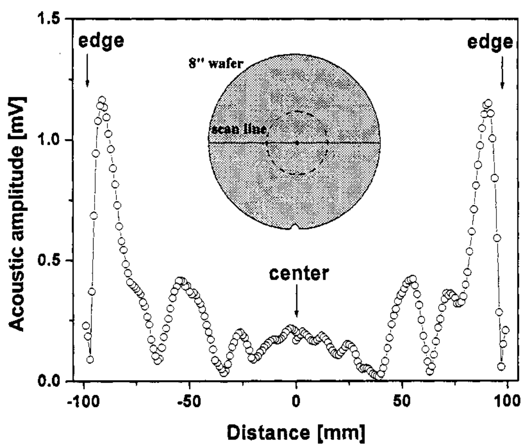

FIGURE 6. . Radial distribution of the w-mode measured as a line-scan across 8" Cz-Si wafer diameter in <110> direction. Insert shows a position of the wafer with respect to underlying transducer (dotted circle).

The wafers of group "B" had maximum amplitude of the w-mode by a factor of *two orders* reduced compared to the group "A". The group "B" exhibited also a shift of the frequency scan toward lower frequencies and broadening as presented in Figure 7. We suggested at this point that B-wafers contained growth defects which provide damping of the "whistle" mode and substantially modify its characteristics. This was challenged by (i) study the effect of thermal oxide to the "whistle" parameter, and (ii) measuring w-mode in 8" polycrystalline Si wafer grown by block casting technique.

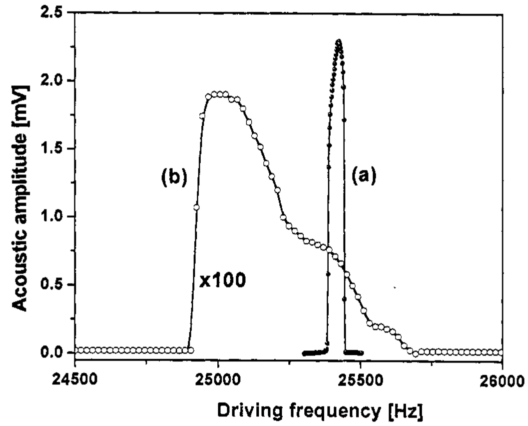

FIGURE 7. Frequency scan of the w-mode in two sets of 8" Cz-Si wafers with high (a) and low (b) electronic quality.

In a case of oxidized wafers with 4.2nm to 90nm SiO_2 layer, the whistle was measured twice at identical driving voltage on the transducer with maintained probe location with respect to the wafer. First time, with the oxide deposited onto the wafer, and second, when the oxide was etched off in diluted HF. A primary result was that oxidized wafers yield lower whistle amplitude, compared to the same wafer immediately after stripping off the oxide. We noticed that even in a thinnest 4.2nm SiO_2 layer, the whistle amplitude is higher by a factor of two when the oxide is removed compared to oxidized wafer. The tendency was also observed on thicker oxides. This experiment shows a high sensitivity of the whistle amplitude to the stress generated by deposited oxide with thickness approaching state-of-the-art gate dielectrics. We believe that measurements of the w-mode parameters can be used for various gate dielectrics, for instance in the gate-oxide-integrity study.

In a case of the polycrystalline Si wafer containing a large amount of cm-size grains separated by grain boundaries, which effectively absorb acoustic vibrations [5], we have only observed w-mode similar on amplitude, f-scan and radial distribution to the group "B" wafers. This experiment can be treated as an additional fact in favor of stress controlled damping of the regular w-mode by crystal defects.

Model of Resonance Effect

The observed features of the excitation of the sub-harmonic w-mode can be consistently explained as non-linear parametric resonance (PR) oscillations of a thin elastic membrane, which is a good model for 8" Cz-Si wafer. An oscillator can exhibit PR when external modulation of its resonance frequency (ω_o) occurs [7]. If such a modulation is a simple harmonic function of frequency γ, the PR in one-dimensional case can be described by applying a standard equation of motion to the vibration amplitude (U) of mechanical system:

$$d^2U/dt^2 + \omega(t)^2 U = 0 \quad (1)$$

$$\omega(t)^2=\omega_o^2 (1+h\sin(\gamma t)) \quad (2)$$

Constant h in Eq.(2) is a small perturbation parameter describing amplitude of the frequency modulation. Important with regards to our experiment, that the most effective PR can be found when the frequency of the modulation γ approaches *double frequency* of the oscillator ω_0. Under these conditions the oscillator becomes unstable and the amplitude of vibrations increases in time exponentially until dissipative processes will be triggered and stabilize the large vibration amplitude. The effect of PR demonstrates essential features inherent to the sub-harmonic w-mode observed in this study: (1) a narrow frequency window for excitation; (2) sharp amplitude threshold; (3) hysteresis of the amplitude as a function of the modulating power, and finally (4) a strong dependence on the damping, which in our case is caused by imperfections of Si wafers.

To extend the PR model to the case of circular Si wafer coupled with transducer, let us recall that among eigenfunctions of a circular membrane there exist two modes of different behavior: (i) the radial vibrations with longitudinal displacement, which directly excited by the transducer; and (ii) flexural vibrations which mostly are represented by the out-plane transverse component of the displacement [8]. The latter have much lower frequencies compared to radial vibrations and are not excited directly by the transducer, however can be coupled with the radial mode by a nonlinear mechanism. One more feature of the flexural modes is their large density of states. If a nonlinear coupling occurs between these two modes of the wafer, then for a selected excited radial vibrations this coupling brings about a periodical in time modulation of the elastic parameters of flexural modes, which, in turn, can give rise to periodical modulation of the frequencies of the flexural modes. In this way the PR mechanism will be realized. The nonlinear coupling between two vibration modes can be provided by the effect of elastic anharmonicity of the crystal. Thus, the observed features of the sub-harmonic vibrations can qualitatively be explained by the non-linear parametric resonance of radial and flexural vibrations of circular membrane. Quantitative analyses of this model applied to Si wafers will be published elsewhere.

CONCLUSIONS

We developed a new ultrasonic diagnostics approach for non-contact and non-destructive monitoring of growth and process-induced defects in full-size Cz-Si. The method offers a quick "snap-shot" recording of the sub-harmonic amplitude of resonance wafer vibrations for in-line/on-line Cz-Si quality assurance. It also can be employed as a sensitive analytical tool for defect characterization by measuring frequency scans, threshold amplitude and "whistle" spatial distribution. It is scalable to Si wafers of the diameter 12" and beyond.

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