Nonlinear resonance ultrasonic vibrations in Czochralski-silicon wafers

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A resonance effect of generation of subharmonic acoustic vibrations is observed in as-grown, oxidized, and epitaxial silicon wafers. Ultrasonic vibrations were generated into a standard 200 mm Czochralski-silicon (Cz-Si) wafer using a circular ultrasound transducer with major frequency of the radial vibrations at about 26 kHz. By tuning frequency (f) of the transducer within a resonance curve, we observed a generation of intense $f/2$ subharmonic acoustic mode assigned as a ''whistle.'' The whistle mode has a threshold amplitude behavior and narrow frequency band. The whistle is attributed to a nonlinear acoustic vibration of a silicon plate. It is demonstrated that characteristics of the whistle mode are sensitive to internal stress and can be used for quality control and in-line diagnostics of oxidized and epitaxial Cz-Si wafers. © *2000 American Institute of Physics.* [S0003-6951(00)02216-6]

The problem of noncontact and nondestructive monitoring of residual strain/stress in as-grown, oxidized, and epitaxial Czochralski silicon (Cz-Si) wafers is a current issue for microelectronics and microelectromechanical systems. The elastic strain in 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 backside polishing, oxidation or deposition of polycrystalline or epitaxial Si layer.[1] Specifically, a thermally grown SiO_2 film typically creates a residual stress of the order of a few hundreds of MPa in the film due to a difference in thermal expansion of the substrate and oxide. Residual elastic strains are harmful for both Si wafers and films. They can cause device failure (curling, buckling, or delamination) as well as uncontrollable wafer breakage. The last problem becomes even more severe as wafer diameter is increased to 300 mm. Therefore, finding a fast and reliable method to control residual strain is strongly motivated. In some cases, this problem is addressed by scanning x-ray diffraction, transmission electron microscopy, 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 a strain/stress control using a new effect of resonance ultrasonic vibrations.

Ultrasonic vibrations were generated into single-side polished Cz-Si wafers of 200 mm diameter using a circular resonance piezoelectric transducer pressed by vacuum against the backside of the wafer. The centers of wafer and transducer coincide with an accuracy of $\sim$100 μm. A transducer 70 mm in diameter made of 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 26 kHz. The function generator and power amplifier provide the ac driving voltage to the transducer with tunable frequency and 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 noncontact acoustic probe. The probe is positioned with micrometer accuracy and can be moved in the X–Y–Z directions above the front surface of a wafer using a computer-controlled stage with step motors. 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. Alternatively, the lock-in can measure subharmonic signal at $f/2$ frequency, which is a special concern in this study.

It was anticipated that the chosen geometry of the experiment would cause the maximum amplitude of the forced harmonic wafer vibrations to occur at the free edge of the wafer. We adopted a well-known equation of longitudinal vibrations of a circular plate with free edge to find the lowest resonance frequency.[4] In the case of 200 mm Si plate this frequency is about 25 kHz, which is close to maximum output of the transducer. Therefore, the transducer coupled with a Si wafer represents an acoustically matched resonance vibrating system.

In Fig. 1, resonance frequency curves (f scans) of harmonic and subharmonic oscillations of the transducer loaded with a 200 mm Cz-Si wafer are presented. All curves are measured at a probe elevation of 200 μm above the wafer. At the center, the f scan shows a broad maximum at 26.0 kHz with a half width of 1.7 kHz [curve (a)]. This curve is very similar to the one of unloaded transducer shifted to lower frequencies by 0.5 kHz. By taking f scan at the wafer's periphery 5 mm from the edge [curve (b)], we observed that the maximum of harmonic mode is shifted to 25.5 kHz and is noticeably narrowed to a half width of 0.9 kHz. This variation of the f scan can be attributed to the generation of a standing wave at a specific frequency of transducer vibrations. In fact, radial distribution of the harmonic mode amplitude shows a gradual increase from the transducer edge to wafer periphery, which proves the concept of standing lon-
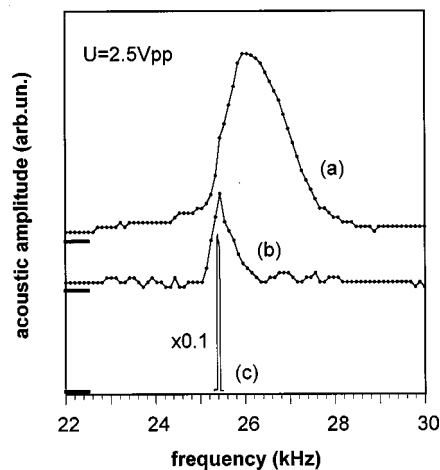
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FIG. 1. Frequency scans of as-grown 200 mm Cz-Si wafer measured in the harmonic mode (a) and (b), and $f/2$ subharmonic mode (c). Curve (a) is measured above the center, curves (b) and (c) at the wafer's periphery.

gitudinal waves generated at ~25.5 kHz in Si plate. We noticed that periphery signal in some wafers contains additional maxima, which are probably due to internal crystal defects and strain inhomogeneity.

By changing the ac driving voltage we could make an amplitude scan of the acoustic signal (a scan). It was observed that the amplitude of the harmonic resonance measured above the center or at the periphery is essentially linear up to a driving voltage of 3.0 V_{p-p} (Fig. 2). Beyond this voltage the acoustic amplitude is saturated due to increasing of losses in the piezoelectric ceramics. A new acoustic effect in vibrating Cz-Si wafers was found at high amplitudes of the ac voltage and frequencies close to the longitudinal resonance of free wafer vibrations. This effect is exhibiting as a generation of an intense subharmonic mode with frequency, f_w, close to half of the driving frequency, f_d. (Note that in harmonic mode these two frequencies are the same). The effect is further referred as a ''whistle'' and the associated acoustic mode as the whistling mode (w mode). In Fig. 1, the f scan of the whistle versus f_d is depicted [curve (c)]. We emphasize that the w-mode amplitude exceeds the harmonic amplitude by as much as one order of magnitude. There are
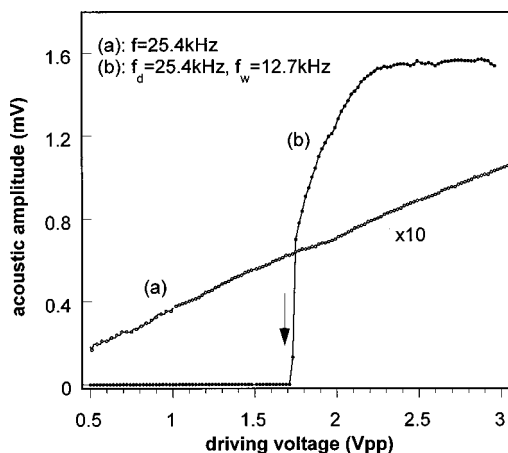

FIG. 2. Amplitude dependence of the harmonic vibration (a) and subharmonic vibration (b). The arrow marks the threshold driving voltage for the whistle effect.
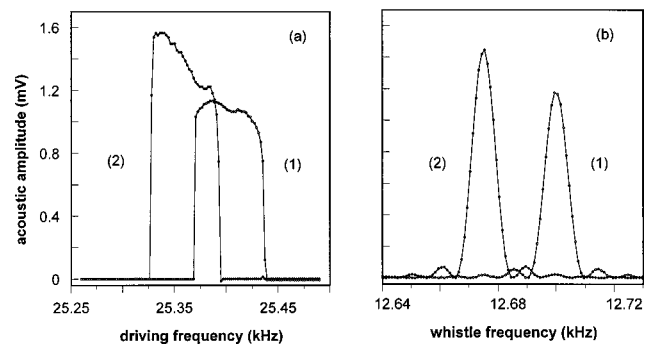

FIG. 3. Dependence of the whistle amplitude vs driving frequency (a) and whistle frequency (b) in as-grown (1) and epitaxial p/p^+ Cz–Si wafers (2). A similar but smaller shift of frequency curves is observed in wafers with thermal oxide after the oxide was etched off.

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 Fig. 3. Specifically, a half width of the f_w curve is 10 Hz, and that of the f_d curve is 50–100 Hz in 200-mm wafers with different processing histories (see below). These highly selective f scans offer a sensitive means to monitor elastic properties of the processed 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. A typical a scan of the whistle is shown in Fig. 2. It was observed that threshold voltage is changed between different wafers (see below) 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.

The following are important features of the subharmonic w mode. (1) The mode is symmetric with respect to the wafer circumference and shows a sharp increase at the wafer edge with a donut shape of about 20 mm at the wafer periphery. This is contrary to a gradual increase of the harmonic mode amplitude from transducer edge to the wafer's periphery. (2) The direction of vibrations in the w mode is essentially perpendicular to the wafer plane with an amplitude of ~100 μm measured at the wafer edge 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. (4) The threshold voltage of the whistle (Fig. 2) is higher in the upward versus downward amplitude scans by as much as 0.2 V_{p-p}.

An interesting property of the w effect is a response of its parameters to crystal growth defects and variation in the processing of commercial 200-mm Cz-Si wafers. In these experiments, each wafer was accurately centered with respect to the transducer, and the probe was located at 200 μm above the surface and 5 mm from the wafer edge in the $\langle 110 \rangle$ direction opposite to the wafer notch. By multiple repositioning of the same wafer we have found that data are very reproducible. We found that (i) the whistle was never observed in wafers with incorporated growth defects, which were identified using scanning surface photovoltage and photoluminescence techniques. It can be suggested that a strong

acoustic absorption at defects leads to a damping of the w mode. (ii) The whistle characteristics were compared in a set of 200 mm as-grown Cz-Si wafers from the same vendor. It was observed that f_d scans measured at the same driving voltage above the threshold are very close but possess different half width from 50 to 100 Hz. Concurrently, the threshold voltage in a scans is shifted by as much as 30% between these wafers. This indicates a sensitivity of the whistle effect to internal stress in Cz-Si. (iii) A comparison of the f_d scans measured in as-grown Cz-Si and epitaxial p/p^+ wafers had shown a strong shift versus driving frequency. This is illustrated in Fig. 3(a). A corresponding shift of the f_w scans is easily resolved as well [Fig. 3(b)] due to a narrow resonance curve of the w mode. In p/p^+ wafers, the interface stress is created between heavily doped substrate (p^+) and lightly doped epitaxial film (p) as a result of the concentration mismatch. This stress can be partially relaxed after annealing due to redistribution of point defects at the interface.[1] We can suggest that consistently observed frequency shift of the w mode between as-grown and epitaxial wafers is attributed to unrelaxed interface stress. A similar but smaller shift in f curves was observed in wafers with ~5000 Å thermal oxide after the oxide was stripped off in HF solution. We applied a laser reflection technique using a FSN-8800 system to the same oxidized wafers before and after the oxide was removed by etching. It was found an average tensile stress in the oxide of 40–60 MPa. These results show a utility of the whistle effect to nondestructive assessing of internal stresses in epitaxial wafers and wafers with deposited dielectrics.

Generation of subharmonic acoustic vibrations is a distinctive property of nonlinear systems, specifically, a thin circular plate, which is a good model of 200 mm Si wafer with 735 μm thickness. Theoretical analysis predicts a generation of the $f/2$ subharmonic mode in a vibrating system with quadratic nonlinearity.[5] Recently a similar nonlinear vibrating effect was studied experimentally in small millimeter size Si multilayer diaphragms utilized in microelectromechanical systems.[6] It was observed that at resonance conditions and high vibration amplitude exceeding 4% of membrane thickness, the $f/2$ subharmonic mode is dominating a harmonic mode by intensity. This is consistent with our results in Cz-Si wafers. Therefore, a fundamental of the whistle effect described in this letter can be attributed to nonlinear subharmonic vibrations of a thin Si plate.

In conclusion, we have observed for the first time a new resonance generation of intense acoustic vibrations in 200 mm Cz-Si wafers. The whistle effect has distinctive threshold amplitude dependence and narrow resonance curves versus driving and whistling frequency. These features allow elaboration of the fast nondestructive method to stress diagnostics applicable to as-grown Cz-Si wafers and wafers with deposited or grown thin dielectric or epitaxial film. The technique is scalable to wafers of 300 mm diameter and beyond.

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