Resonance Ultrasonic Vibrations in Cz-Si wafers as a Possible Diagnostic Technique in Ion Implantation

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Abstract. The semiconductor industry does not have effective metrology for well implants. The ability to measure such deep level implants will become increasingly important as we progress along the technology road map. This work explores the possibility of using the acoustic whistle effect on ion implanted silicon wafers. The technique detects the elastic stress and defects in silicon wafers by measuring the sub-harmonic f/2 resonant vibrations on a wafer induced via backside contact to create standing waves, which are measured by a non-contact ultrasonic probe. Preliminary data demonstrates that it is sensitive to implant damage, and there is a direct correlation between this sub-harmonic acoustic mode and some of the implant and anneal conditions. This work presents the results of a feasibility study to assess and quantify the correspondent whistle effect to implant damage, residual damage after annealing and intrinsic defects.

INTRODUCTION

The need for high energy implants increases as the ULSI devices get smaller and the structure becomes more complex, especially in making retrograde wells and buried layers. Due to the limitation of current popular metrology techniques, the industry does not have an effective technique that can measure the variation of the implant energy and dose in this area. For instance, both Thermal wave (TW) and sheet resistance (Rs) do not have the sensitivity with such implants, since the implants are too deep to be probed. We face the challenge to find a technique that has the sensitivity and meets the stringent requirements of a clean room environment.

It has been reported recently that in response to injected ultrasonic waves, silicon wafers generate sub-harmonic resonance that are sensitive to defects and elastic stress.[1,2] By employing the w-mode of sub-harmonic resonance, the whistle effect as it is defined, the characteristics – amplitude dependence, frequency scan and spatial distribution, allow clear distinction versus harmonic vibrations of the same wafer. The origin of the sub-harmonic vibrations observed on 200mm silicon wafers is attributed to a parametric resonance of flexural vibrations in thin silicon circular plates, which is strongly related to defects in the silicon crystalline material.[2] Since ion implantation generates significant damage inside the silicon wafer, it is natural to relate the acoustic wave with its application in ion implantation. Since the measurement is fast, non-contact and nondestructive, it makes this technique a potential candidate for the semiconductor industry.

EXPERIMENT

Application of whistle effect from nonlinear resonance ultrasonic vibrations in silicon wafers is explored in this work.. Ultrasonic vibrations were excited in 200mm wafers using an external ultrasonic transducer. The vibration amplitude was recorded in a non-contact mode using a scanning acoustic probe. Whistle effect(generation of f/2 sub-harmonic mode) was observed in all wafers including control, implanted, and annealed. The measured quantities include whistle amplitude, frequency gate of the whistle excitation (f_{ex}), amplitude threshold (V_{th}) and its dependence versus f_{ex}. According to a general theory of parametric resonance in vibrating systems,[3] the elastic quality of a wafer in terms of whistle damping is higher when the maximum amplitude and width of frequency gate are increased, and opposite,

CP576, *Application of Accelerators in Research and Industry – Sixteenth Int'l. Conf.*, edited by J. L. Duggan and I. L. Morgan

when a threshold and the slope in V_{th} (f_{ex}) dependence are decreased.

Low Dose Implant Experiment

Two sets of 200mm Si wafers were used in this group. Effort was taken to ensure the wafers in the same set came from the same ingot. The implants were with phosphorus at the dose of 1e12/cm^2 at three different energies. In one set of wafers, pre-implant annealing was performed as an attempt to relax any possible initial elastic stress inside the wafers, hereafter referred as "pre-annealed". The other group is referred as "normal". The pre-implant annealing condition was 950 °C for 20 seconds in pure nitrogen ambient. Half of the wafers from the set that was annealed pre-implant and half of the wafers from the set that was not annealed pre-implant were annealed post implant. The post-implant annealing condition was 1000 °C for 10 seconds in pure nitrogen ambient. Control wafers (without implantation) were also included to compare the whistle effect of implantation in the silicon material. The wafers were measured using the W-mode of the applied acoustic wave.

Before the whistle measurement, TW and Rs were measured on the wafers. The control wafers all had ~50 TW units. After pre-implant annealing, the wafers without implantation had about 180 TW unit. This is puzzling, since there was no implant damage introduced in the silicon wafers. Possible oxide growth was first suspected, but the oxide thickness was measured to be 10 – 11Å, which is within the limit of the thickness of native oxide. Although it was not possible to identify the cause of this small variation, it is believed the intrinsic stress in the silicon wafers should have been relaxed due to this thermal treatment. This has been demonstrated in Figure 1, in which one sees the pre-annealed control wafers have higher whistle amplitude and wider windows. Post implant TW readings for the 0.1MeV, 1MeV and 2MeV implants were 630, 580 and 520 respectively. This indicates TW gets less sensitive as the ion energy increases. Sheet resistance was also attempted after post-implantation anneal. However, the four point probe could not pick up sensible signals from all the wafers. This observation demonstrates that neither of these techniques can accurately measure implants in these dose and energy ranges.

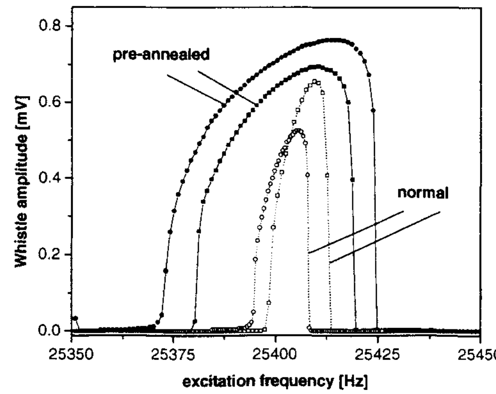

FIGURE 1. Excitation frequency scans of whistle amplitude in four control wafers. It is worth to mention that another control wafer from a different manufacturer exhibits much lower maximum w-amplitude (~0.2mV) and completely off the range of f_{ex}-windows.

Figure 2 shows whistle amplitudes of normal wafers subjected to implantation and post-implant annealing. The whistle amplitude for the as-implanted wafers seems to increase with implant energy. However, the response from the post-annealed wafers does not have a definite trend. The pre-annealed wafers all have similar readings and do not seem to correspond to the variation of the conditions. It is noted that the values of whistle amplitude correspond well to the total energy deposited through nuclear stopping of phosphorus ions in silicon but not to the energy deposited by electronic stopping (See Figure 3). It is reasonable to suggest that the whistle effect is a direct reflection of the lattice damage caused by the energy deposited in the silicon by nuclear stopping.

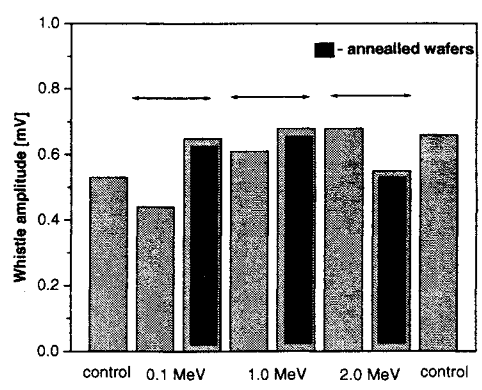

FIGURE 2. Maximum whistle amplitude for the normal wafers. The wafers are paired to check the effect of post-implant annealing. The implantation energies are depicted.

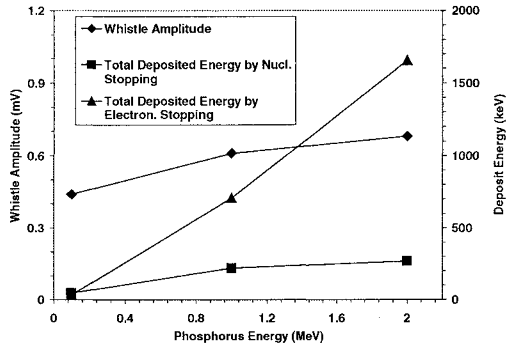

FIGURE 3. The comparison of whistle amplitude and the total energy deposited through nuclear stopping of Phosphorus ions in silicon. The stopping powers were calculated with TRIM95 [4].

A comparison of normal and pre-annealed wafers showed that all pre-annealed wafers have wider gate widths compared to normal wafers. This matches the differences of w-amplitudes of both sets in Figure 2. Table 1 presents the net changes of the frequency gate by comparing to the values of the average of the control wafers. It can be seen that the values are positive except for one, which is 0.1MeV wafer. It suggests that the whistle gate frequency responds to the implant damage and the implanted dopant positively. Although a conclusion is difficult to draw due to the limited set of tested conditions, this will be a direction worth pursuing in future work.

TABLE 1. The net whistle gate change after ion implantation for the two sets of wafers. Values are presented in Hertz.

E (MeV)	Normal as implanted	normal + post anneal	pre-annealed as implanted	pre-annealed + post anneal
0.1	-3	1	10.5	4.5
1	12	13	10.5	18.5
2	12	6	2.5	0.5

Figure 4 shows the V_{th} versus f_{ex} curves in two normal and two pre-annealed wafers. The picture illustrates that normal wafers have higher threshold voltage, ΔV_{pp} = 0.6 to 0.9 mV, compared to pre-annealed ones (at a specific frequency). They also have a slope difference by a factor of ~ 3 (averaged across all normal and pre-annealed wafers). This seems to suggest that normal wafers have larger damping of acoustic vibrations than the pre-annealed wafers. Again, this is consistent with previous data on maximum whistle amplitude and frequency gate.

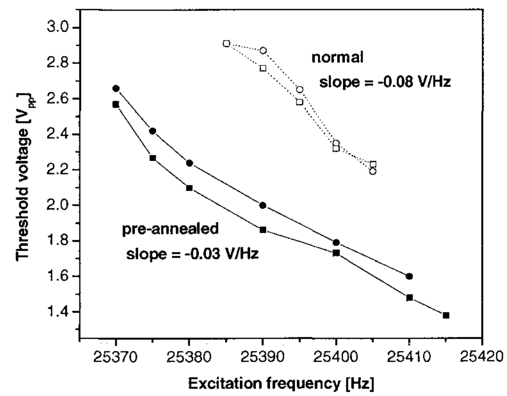

FIGURE 4. Frequency dependencies of threshold voltage for two types of Si wafers. Arrow indicates a decrease of the threshold in pre-annealed wafers.

Whistle Amplitude Response to Implants

A group of six wafers was implanted and annealed to study the whistle amplitude response to ion implantation. The measured whistle amplitudes and the implant conditions are depicted in Figure 5. The whistle amplitude clearly responded to the dose change, but not to annealing. It is interesting that the lower dose implant dramatically damped the amplitude. Although this is in agreement with the observations in Figure 2, it is opposite to the understanding of acoustic resonance mechanism and the observation in Figure 3. The common belief is that acoustic resonance is enhanced when the crystal quality is better. It is expected that the damage to the crystalline quality of the Cz-Si wafers decreases when the implant dose is decreased. This, in turn, should give less damping for the whistle amplitude. However, the observation did not support this argument.

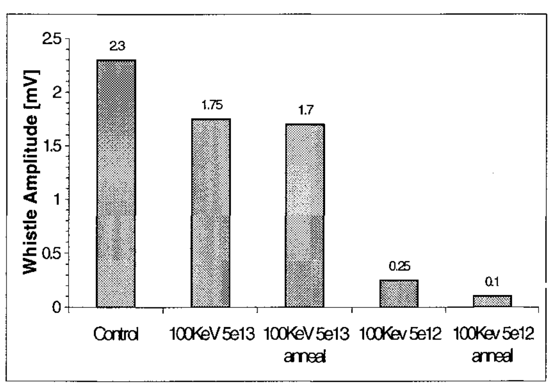

FIGURE 5. Whistle amplitude correspondence to implant dose and annealing. The wafers were not pre-annealed. The post implant anneal condition was 1000 °C for 10 seconds.

Whistle Amplitute Response to Annealing

Figure 6 shows yet another attempt to understand the effect of different annealing conditions on the whistle amplitude. In this case, the implant was 1MeV P^+ at 5e13/cm^2. Two anneals were applied to the implanted wafers. One was a 800 °C 10 second anneal intended to just repair the implant damage. The other went through a typical activation anneal of 1100 °C for 10 seconds in addition to the damage repair annealing. Consistent with the result in Figure 4, this group of wafers also showed strong whistle amplitude damping after thermal annealing,but it seems that the thermal budget of the damage repair annealing is sufficient to get the full scale of amplitude damping. The additional anneal did not contribute more damping.

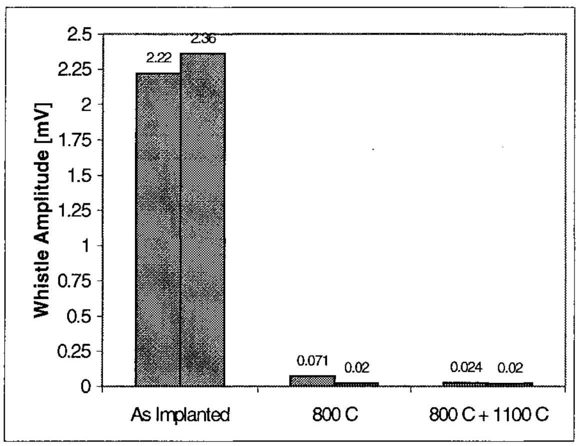

FIGURE 6. Whistle amplitude correspondence to implant and different annealing conditions. The implant was 1MeV P^+ at 5e13/cm^2.

CONCLUSIONS

Based on the data collected in this work, the pre-implant history of the wafer is important for acoustic quality achieved after the implantation and post-implant annealing. The wafers with pre-implant annealing have higher acoustic quality than the wafers without it when they are compared after identical conditions of implantation and annealing. It is possible that the pre-implant annealing relaxes the intrinsic stress in the silicon wafers which causes a higher acoustic response. The 100keV implanted wafers showed the lowest w-amplitude and frequency gate, and highest threshold. This is very clear in normal non-annealed samples before and after implantation. This trend is partially compensated after post-implant annealing, again indicating improvement of quality with post-implant processing. We may suggest that 0.1MeV phosphorus implantation, even at 10^{12} cm^{-2} dose, creates not only near-surface damage due to shallower implant depth (~0.1μm), but also causes a stress effect to a wafer. This is similar to the damping effect on w-mode delivered by SiO_2 layer. [2] The acoustic technique in this study would respond to the integral effect of damage and stress, which can be used for diagnostics. We will follow-up with theoretical analyses of the stress effect to w-mode characteristics.

In some cases, the measured variables showed response to the changes in experimental conditions. However, the data sometimes contradicts the common beliefs of general acoustic resonance theory. Although this is the first step, it is appropriate to suggest that there is much to be explored in the application of the acoustic wave to ion implantation in the semiconductor industry. While the technology progresses rapidly, the search for better metrology techniques must be accelerated as well.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Diffusion/Implant module of Fab25, AMD, for the support they have received in the wafer implantation and annealing process. They also would like to thank their individual employers for granting them this academic experiment.

REFERENCES

1. S. Ostapenko and I. Tarasov, *Appl. Phys. Lett.*, **76** (16), 2217 (2000).

2. A. Belyaev, I. Tarasov, S. Ostapenko, S. Koveshnikov, V. A. Kochelap and A. E. Belyaev, ECS meeting (Phoenix, 2000), in press.

3. L. D. Landau, *Mechanics,* Pergamon Press (1960). P. 80.

4. J. F. Ziegler, Instruction Manual, TRIM version 95.4.