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Implant Metrology for Bonded SOI Wafers Using a Surface Photo-Voltage Technique

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Small signal Surface Photo-voltage (SPV) measurement techniques have been applied to monitor ion implants typical of those used for layer-transfer SOI processes. This SPV wafer mapping technique was investigated for sensitivity to dose, implant uniformity, and repeatability for hydrogen and helium implants into (100) silicon wafers through a 1450Å surface oxide.

Introduction

With continued CMOS scaling, problems such as active and passive power dissipation, short channel effects and SRAM single event upsets are becoming increasingly intractible. Engineered substrates, in particular SOI wafers, provide an important avenue to managing these problems and enabling further scaling. This is driving the large-scale manufacturing of state-of-the-art, large diameter SOI wafers having very thin top silicon layers with very tightly controlled layer thickness and uniformity. The two dominant methods for producing such SOI wafers, SIMOX and bonded, ion implant-assisted layer transfer, both rely on ion-implantation technology (1). This places increased emphasis on monitoring and process control methods for ion implantation of non-dopant species. This paper presents preliminary results of an implant monitor technology applicable to donor wafers prior to the bond-and-layer-transfer process.

The donor wafers in bonded, layer-transfer SOI manufacture are generally subjected to implantation of H^+ (2) or co-implantation of H^+ with He^+ (3) to define a cleave plane. Prior to ion implantation, a thermal oxidation of the donor wafer is usually performed. Subsequent to implantation, the donor wafer is bonded to the handle wafer and layer transfer is effected. Proper dose, uniformity, and damage level are critical parameters for proper transfer of the layer from the donor wafer.

Historically, SIMS, Hydrogen Forward Scattering (HFS) or Nuclear Reaction Analysis (NRA) have been used to estimate H^+ dose. These techniques give depth profile information about the implant, but have rather low dose resolution, and are inherently single point measurements. They are also destructive tests, and require costly and complex measurement apparatus. Presently, non-destructive, in-line, whole-wafer mapping of layer-transfer implants is not widely used. In some cases, other metrology techniques are performed after layer transfer, or at the End of Line (EOL) on completed SOI wafers to indirectly infer and monitor the implant performance.

Surface Photo-voltage (SPV) measurement of as-implanted wafers is an established technique to produce high-resolution wafer maps of critical dopant implant parameters, without the need to thermally activate the implanted dopant (4). The small signal SPV technique has proven to be highly sensitive to such critical implant parameters as species, dose, and energy (5,6); sensitivity being defined as is typical, percentage change in metrology device signal divided by percentage change in input variable. Such normalized dose and energy sensitivities have been observed for non-activated dopants with values ranging from 1 to 4. Here, we extend this SPV technique to non-destructive, in-line monitoring of ion implants characteristic of those used for layer-transfer bonded SOI processing.

Experimental - SPV Measurement

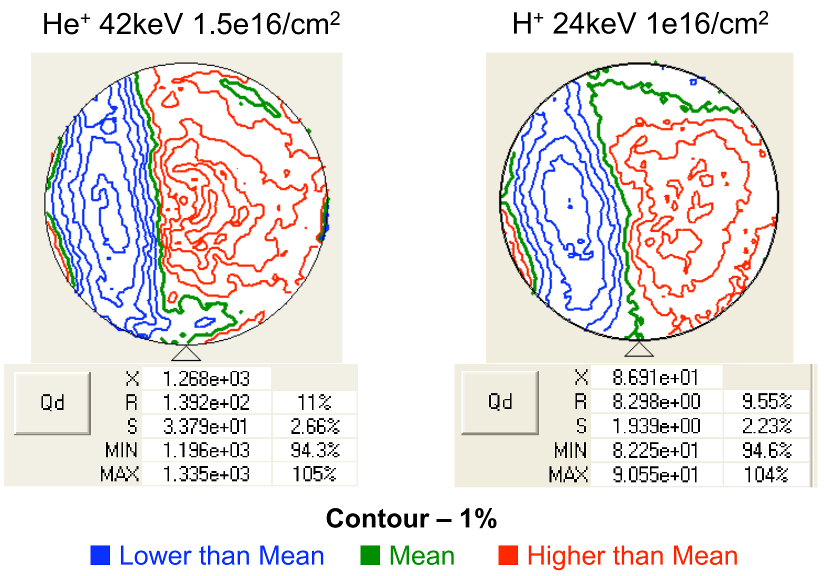
A QC Solutions ICT300 SPV system was used for the measurements in this study. This technique is a low intensity, high modulation frequency, ac-SPV measurement. The light source and sensing probe are capacitively coupled to the wafer, approximately 100μm above the wafer surface. The wafer measurements are non-contact and non-destructive allowing product wafers to be measured, as is currently done in epi wafer applications of the system. A blue light photo source was used for the measurements, and all SPV measurement values are reported as dynamic charge (C/m^3) from the ICT300 system. This above-bandgap, modulated light is strongly absorbed, creating electron hole pairs in the near-surface, Si space charge region. Drift and diffusion of these photo-carriers in the space charge region modulates the surface potential, giving rise to the dynamic charge, Qd. At the modulation frequency used, the induced photo-carriers have sufficient time to recombine, creating a dynamic charge (Qd) that depends on the depletion width and the recombination time in the near surface region. The implanted ions introduce damage that acts as recombination centers, reducing photo-carrier lifetime and thus affecting the SPV-measured dynamic charge (4,5).

The wafer samples tested were ~10 ohm·cm, p-type, (100) crystalline substrates with 1450Å thermal oxide. The wafers were implanted with either hydrogen or helium through the oxide, at doses typical for thin SOI layer transfer processes (2,3). The implanted wafers were measured with the 1450Å thermal oxide intact, representative of a donor wafer immediately after ion implantation. Samples were prepared in both 200mm and 300mm wafer sizes.

Results and Discussion

Wafer Map Uniformity

In Figure 1 300mm medium resolution wafer maps (>4400 points/wafer) are presented for wafers implanted with 42 keV He^+, shown to the left, and with 24 keV H^+, shown on the right. Implanted doses of 1 - $1.5x10^{16}/cm^2$ were used, typical of the co-implantation method (3). Both wafers were measured through a 1450Å oxide on as-implanted donor wafers and show similar map signatures for the He^+ and H^+ implants. These wafer features were observed on all wafers measured from multiple implant lots from this particular implanter, indicating the map is characteristic of the implanter. The dynamic charge statistics for each wafer map are presented in Figure 1; average map value (X), range (R), and standard deviation (S). The dynamic charge value for the He^+ implant is >1 order of magnitude larger which may be attributed in part to the larger damage component and deeper implant profile for this implant. Map uniformity and wafer features are quite similar between the two implanted species that were investigated. In this study helium and hydrogen were investigated individually, and co-implanted wafers were not evaluated.



X	1.268e+03	
R	1.392e+02	11%
S	3.379e+01	2.66%
MIN	1.196e+03	94.3%
MAX	1.335e+03	105%

X	8.691e+01	
R	8.298e+00	9.55%
S	1.939e+00	2.23%
MIN	8.225e+01	94.6%
MAX	9.055e+01	104%

Figure 1. 300mm wafer Map of He^+ 42 keV, 1.5E16/cm^2 and H^+ 24 keV, 1E16/cm^2 with 1450Å surface oxide (contour interval = 1%).

The SPV measurement sensitivity to implantation can be understood with reference to Figure 2. The photo source illumination is absorbed within approximately 2 microns of silicon below the oxide, creating photo-carriers in the Si near surface region. For wafers doped with ~10^{15}/cm^3 boron, the depletion region extends ~8000Å below the oxide. At 24keV H^+ implant energy, the implanted hydrogen depth of ~ 3000Å from the surface produces an extensive damage profile lying within this Si depletion region as well as in the surface oxide. This Si damage directly affects the measured dynamic charge in the near-surface region by creating recombination centers that reduce minority carrier lifetimes, and by creating charged defects that affect the space-charge density, and hence minority carrier drift during illumination. For the 42 keV He^+ implant, the implant depth is slightly deeper at ~3500Å, but the damage density is considerably larger due to the fourfold increase in the ion mass. A higher damage concentration profile from the He+ implant gives and increase in the measured dynamic charge signal compared to the H+ measurement.

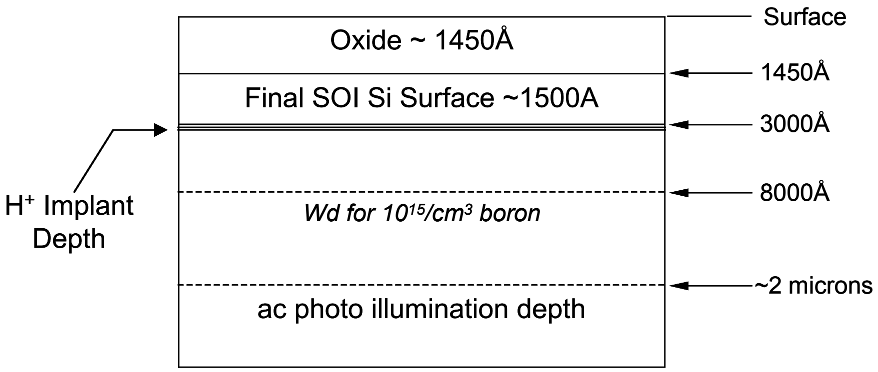
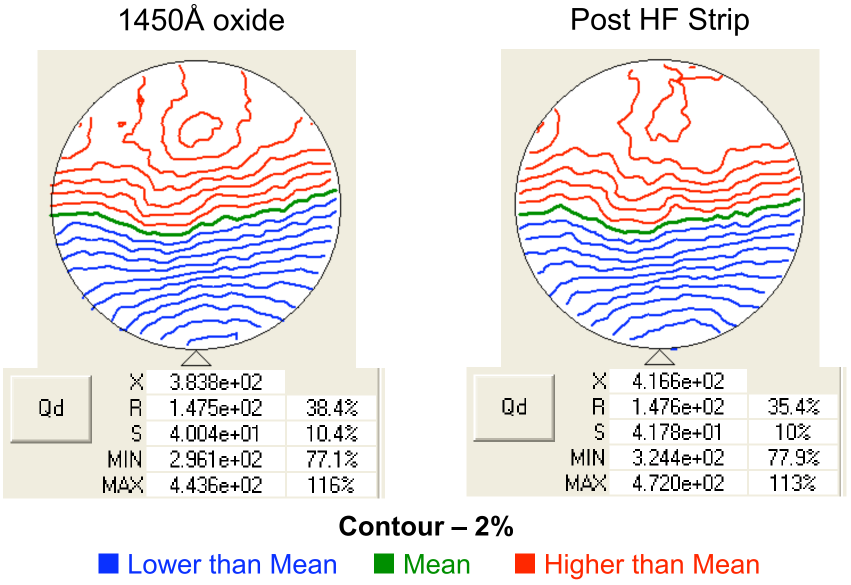


Figure 2. Depth Profile of SOI donor wafer after typical H^+ implant.

Since the SPV technique relies upon light transmission through the SiO_2-Si interface, the thickness and the transmission factor of the oxide need to be accounted for. The ICT300 software incorporates a recipe-specific light transmission algorithm, which corrects for variation in oxide thickness. The impact on the measurement of the implant damage in the oxide and oxide thickness variations within-wafer were investigated.

Wafers with a high H^+ implant dose, $6.6x10^{16}/cm^2$, typical of mono-implant layer transfer (2) were prepared. SPV measurements were initially performed with the thermal oxide intact. After initial measurement, the wafer oxide was removed using a 5% HF:DI strip for 5 minutes, followed by a DI rinse and spin dry. The wafer surface after wet processing was hydrogen terminated. Direct comparison of an implanted wafer with the 1450Å oxide in place and after an HF strip is presented in Figure 3. By removing the oxide, the effect of the surface oxide damage on the SPV measurement can be eliminated and the response from the implant/substrate alone evaluated. The comparison before and after HF strip is presented on a single 200mm wafer. The implant map characteristic is similar before and after HF strip with similar range (R) and std deviation (S) for the wafer map summaries. The map average for the HF stripped wafer is shifted to a larger Qd value, which is attributed to altered light transmission into the Si through the SiO_2. For the data presented the light transmission algorithm was not applied to the measurement in order to directly evaluate the magnitude and wafer map statistics. The impact of the oxide on light transmission through the SiO_2 for the oxide thickness and light wavelength in the present case is fairly small, <10%.

It is important to note that the measured SPV signal is generated from the implanted Si region, and does not show a dependence on the surface oxide or damage within the SiO_2 region, allowing accurate measurement of the implant without removing the 1450 Å oxide.



1450Å oxide

X	3.838e+02	
R	1.475e+02	38.4%
S	4.004e+01	10.4%
MIN	2.961e+02	77.1%
MAX	4.436e+02	116%

Post HF Strip

X	4.166e+02	
R	1.476e+02	35.4%
S	4.178e+01	10%
MIN	3.244e+02	77.9%
MAX	4.720e+02	113%

Figure 3. 200mm SPV wafer maps, H^+ 24keV, $6.6E16/cm^2$, with and without a 1450Å oxide.

Dose Sensitivity

Figure 4 shows dose sensitivity for He^+ 42keV and H^+ 25keV implants into oxidized donor wafers. Implant dose was varied around the reported nominal dose values as reported with a normalized value along the x-axis. The dose ranges investigated are ~1.5x10^{16}/cm^2 for the He^+ implants, typical of the co-implantation method, and ~6x10^{16}/cm^2 for H^+ implants, typical of the mono-implantation method. Average Qd values for full wafer maps were used in the evaluation and were measured through the surface oxide on the as-implanted donor wafers. The measured sensitivity to implanted dose are shown as a normalized Qd sensitivity of ~1.2 for the two cases investigated.

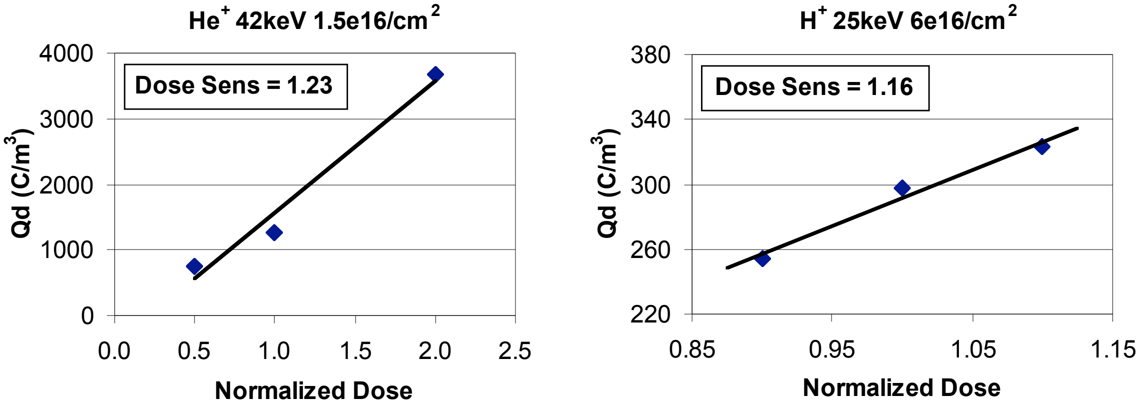


Figure 4. Qd response as a function of normalized dose for He^+ 42 keV 1.5E16/cm^2 and H^+ 25 keV 6E16/cm^2 with 1450Å surface oxide.

Repeatability

Measurement repeatability was evaluated for the H^+ implant with the 1450Å thermal oxide intact. Measurements were collected hourly for the test period of 5 days. The SPV measurements were full wafer maps using the standard wavelength light for the ICT300. Repeatability of the SPV measured technique shows a standard deviation (1-sigma) repeatability of 0.21% for the five day test period. This level of stability within the measurement system, would suggest that a dose variation of 1% can be resolvable using the investigated SPV monitor system with a 2 sigma tolerance level.

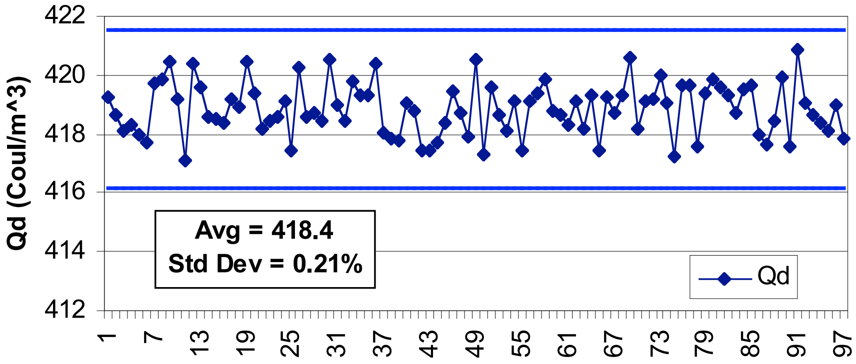


Figure 5. 5 Day Repeatability H^+ 24keV, 6.6E16/cm^2

Summary

The small signal SPV measurement technique presented is a capable high-resolution full wafer map technique for monitoring SOI implants, as implanted through a thick surface oxide. Standard hydrogen and helium layer transfer implants were evaluated for sensitivity to dose with a normalized sensitivity of approximately 1.2 for the investigated cases. A demonstrated repeatability of much less than 0.5% 1-sigma was observed for a multi-day period on hydrogen implanted wafers. This non-destructive technique produces high-resolution wafer maps of as-implanted, oxidized donor wafers. The H^+ and He^+ implants can be monitored non-destructively on standard, oxidized donor wafers without altering the SOI manufacturing process flow, allowing in-line SPC control of this critical step within the SOI layer transfer manufacturing process.

References

1. G.K. Celler and Sorin Cristoloveanu, *J. Appl. Phys*. **93**, 4955 (2003)
2. M. Bruel, *Electron. Lett.* **37**, 1201 (1995)
3. A. Agarwal, T.E. Haynes, V.C. Venezia, O.W. Holland and D.J. Eaglesham, *Appl. Phys. Lett*. **72**, 1086 (1998)
4. Tsidilkovski, E., Crocker, K., Steeples, K. Ion Implant Process Monitoring with a Dynamic Surface Photo-charge Technique. *Advanced Semiconductor Manufacturing Conference*, (2004).
5. K. Steeples, E. Tsidilkovski, Photoelectric Measurment Method for Implanted Silicon: A Phenomenological Approach, CP866, *Ion Implantation Technology*, 558-561 (2006).
6. R.S. Nakmanson, *Solid State Electronics* **18**, 617-626 (1975)