Comparison of Production Metrology for High Angle Implantation

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ABSTRACT

The effects of short channel transistor design have been controlled mostly through high angle quad implants. With gate widths shrinking to 65nm and below, the effects of ion channelling at any of the implant tilt/twist combinations in the quad implant can be significant.

We describe SIMS results of high angle implants which assist optimization of implant angle and show how base-line SIMS profiles can be correlated to real-time implant mapping systems commonly used in high volume chip manufacturing; Therma-Probe™ and a novel second generation high resolution surface photo-charge technique.

The ability of these metrology techniques to determine the optimum non-channelling angle consistent with modern transistor design criteria and monitor day-to-day accuracy of angular implant control are compared and contrasted.

PAC Codes: 06.20.-f, 06.60.Mr, 61.85.+p, 68.49.Sf, 68.55.Ln, 78.20.-e, 78.66.Db, 78.66.-w, 79.20.Ap, 79.20.Rf, 81.70.Fy, 81.70.Jb, 85.30.De

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INTRODUCTION

In order to meet the ever-tighter process windows for 65nm transistor technology, it is essential that implant systems exhibit stringent angle constraints to ensure uniform dopant dose and distribution within the silicon wafer. Assessing the uniformity of implants delivered from a specific implant system has traditionally been carried out using SIMS, Therma-Probe™ and transistor short channel parametrics [1-4]. SIMS is an excellent technique for studying implant profiles. It has excellent elemental sensitivity, and in recent years, improvements to the primary ion source have enabled SIMS to probe extremely shallow implants with superior depth resolution [4,5]. Therma-Probe™ techniques have been accepted as the metrology tool of choice for rapidly measuring the characteristics of wafer implants, with most chip fabrication facilities possessing such an instrument. The alternative of four-point probe contact measurements can produce long production cycle times and is well known to be less sensitive to low dose implants. Although SIMS is still essential to fully assess the distribution of any implanted material, alternatives to Therma-

Probe™ techniques are being sought due to the lack of sensitivity of the technique to undesirable angular ion distributions, which can arise from implanter set-up or variations. It is essential to be able to rapidly detect the unwanted dopant distributions that can arise from any unintentional angular changes during implantation and preferably this metrology tool should be in-line.

Surface voltage (SV) and surface photovoltage (SPV) semiconductor characterization techniques lend themselves to such rapid feedback metrology. For this reason, they have become powerful and convenient methods for a variety of material/device parameter measurements [6]. A related method, which can provide rapid, in-line process parameter monitoring, is a high-resolution surface photo-charge technique (QC Solutions™) whereby dynamic charge built up on the wafer following photon irradiation is used to monitor relative changes in the implant [7].

This method is particularly attractive because it is contactless and previous studies have already shown it to be very sensitive to implant dose, energy and beam current [7]. However, it is unknown as to this instruments ability to quantitatively show sensitivity to angular changes in implantation. In this study, we have implemented SIMS, Therma-Probe™ and the QC Solutions™ instrument to assess a carefully selected set of boron implants that have been implanted at specific tilt angles. The effects of implant tilt angle variations have been studied with the three different techniques and from the results we have been able to compare and contrast each ones ability to measure these changes, and therefore consider angular variation sensitivity and practical issues relating to each instruments assessment. From this extensive study we have made conclusions relating to the merits of each instrument in determining optimum non-channelling angle and the ability to monitor day-to-day accuracy of angular implant control.

EXPERIMENTAL

The wafers analysed in this study were supplied by Wacker (bulk Si wafers, Burghausen, Germany). Seven identical 200mm silicon wafers were implanted with 4 x 1e13 atoms.cm^{-2}, 3 keV boron (B^+) dose (1e13 atoms/cm^2 per ¼ rotation) at tilt angles of 30-40º (all angles given are with respect to the normal of the sample) in 2º increments. An additional implant at 35º tilt was included to detect resolution at 1º tilt. The implanter used was an Applied Materials developmental implanter featuring isocentric boustrophedonic wafer-scanning architecture. The 3 keV, 4e13 atoms.cm^{-2} implant protocol was chosen due to its frequent use in the production of 65nm node technology devices. The tilt angle range considered is typically used to test implanter tilt angles due to the fact that, within this range, a maximum in channelling is exhibited. Changing the implant tilt angle from 30º to 40º will obviously decrease the projected range of the implant, but this effect is outweighed by the changes in channelling occurring in this tilt angle range and can effectively be ignored for the purposes of this study.

All SIMS analyses were carried out using a Physical Electronics model Adept 1010 quadrupole based instrument. O_2^+ bombardment analyses were performed using a beam energy of 1 keV at 45º incidence with positive ion detection and oxygen leak (pressure: 1e^{-6} Torr). $^{11}B^+$ ions were detected for the boron profile measurements. $^{30}Si^+$ ions were detected as reference ions. Ion counts were converted to concentration using relative sensitivity factors (RSF) derived from the measurement of a NIST traceable boron reference material presently used by Cascade Scientific for the monitored species.

Depth scale calibrations for SIMS depth profiles were performed using crater depths, which were measured with a Tencor Alpha Step-200 stylus profilometer. The pressure in the sample chamber was <5 x 10^{-9} Torr during analysis.

A second-generation surface photo-charge instrument, known as the QCS ICT300 surface charge profiler [7], developed as a reliable instrument for real-time implant process monitoring (QCS Solutions™, Billerica, Ma, USA) was also used to measure the set of boron-implanted wafers. The technique involves establishing a surface carrier depletion zone with an electric field that can separate photo-generated electron-hole pairs. With chopped light this gives a modulation to the surface charge on the wafer that can be detected by capacitance. The application of the measurement to implants involves quantification of crystal damage associated with the implant process. The loss of surface charge signal to sub-surface electron-hole pair trapping can be used to "calibrate" in relative terms the implant parameters (such as implant tilt angle) to dynamic surface charge.

All wafers were also measured using a Therma-Probe™ TP400XP (Therma-Wave® Inc., Fremont, California, USA). Therma-Probe™ measurements involve the correlation of in-depth defects or implant-induced damage with variations in surface reflectivity.

Computer simulations were performed using the simulation: UT Marlowe 6.0.0 on a COMPAQ laptop with 50,000 ions per calculation.

RESULTS AND DISCUSSION

The experiments performed in this study rely on the fact that, in the tilt angle range used (30 - 40º), implanted material will exhibit a diverse extent of channelling, which is necessary in order to demonstrate each instruments sensitivity to implant tilt angle variation and hence its ability to determine optimum non-channelling angle. These fluctuations in channelling can easily be described with the aid of theoretical calculations, which provide good evidence for the suitability of a particular tilt angle regime to qualify the instruments studied. Figure 1 shows four simulated damage depth profiles, with the plots indicating the percentage of the crystal damaged following implantation with 3e14 atoms.cm^{-2} boron at an energy of 3 keV. It can clearly be seen that, at 35º (figure 3(b)), the damage occurring in the crystal is less in the near surface region than when implantation occurs at 30º or 40º (figure 3(a) and (d), respectively). The simulated damage profile for 36º is almost identical to 35º (figure 3(c)). This is a clear sign that, between 35 and 36º, the ions do not displace as many target nuclei in the crystal, and are channelled along open paths in the lattice more effectively. It is also obvious from the figures that a higher level of damage occurs deeper within the crystal when implantation occurs at 35 and 36º due to this efficient channelling of the ions through the lattice. However, at 30º or 40º, there is little or no damage seen deeper than 0.05 µm due to the lack of channelling paths at these implantation tilt angles.

Following implantation, the samples were primarily analysed with Therma-Probe™. Figure 2 shows the full wafer-averaged Therma-Wave® signal (TW) value plotted as a function of implant tilt angle. In the case of less disordered crystals (greater channelling), the modulated reflectance due to plasma wave effects is higher than that seen in more damaged crystals because the recombination rate of free carriers is low. The magnitude of the effect on reflectivity of the plasma waves is therefore similar to that of the thermal waves produced by the Therma-Probe™ pump laser. As the effects of thermal and plasma waves act in opposite directions, the net reflectivity modulation in less disordered crystals is small. This in turn makes the TW value low (as TW value is defined as "change in reflectivity" / "reflectivity") and explains the evidence of a minimum in figure 2. From the plot it is obvious that the Therma-Probe™ can distinguish between large tilt angle changes and, therefore, significant differences in channelling arising from implanter tilt angle changes. The TW signal shows small, yet distinct, changes across the range of tilt angles, but nevertheless, the angle at which maximum channelling occurs is by no means pinpointed. The broad minimum suggests that the Therma-Probe™ technique is not able to accurately distinguish subtle changes in channelling arising from implanter tilt angle variations when implanting with this particular implant, whilst the instrument is only measuring approximately 0.15 – 0.20 % TW value per degree tilt sensitivity. This may not be the case for implants with different energies or doses, but for this specific and technologically important implant protocol, the TW value (~600) unfortunately lies in one of its most insensitive regions, leading to the result shown.

Figure 3(a) shows an overlay plot of three SIMS depth profiles. The data is obtained from the 30º, 35º and 40º-tilt angle boron implants. According to the theoretical results shown in figure 1, these tilt angles may be considered in order to show the diversity of channelling effects apparent across the tilt angle range used here. The SIMS profiles obtained from implant tilt angles of 30 and 40º are clearly very different from the 35º SIMS profile. The expanded SIMS plot shown in figure 3(b) indicates that the main implant peak height (seen after the surface boron "spike" with R_p ~ 90Å) is lower for the 35º implant. The peak seen at this depth in all the implants studied is due to boron being randomly implanted into the crystal. Conversely, the boron component associated with channelling (seen predominantly after 500Å with R_p ~ 850Å) becomes more prominent at 35º with respect to that seen at 30 and 40º (figure 3(a)). These observations are consistent with increased channelling at 35º. At 35º, more of the boron is found in this channelled component due to less effective nuclear stopping and therefore, due to the implant doses being identical, less boron is expected in shallower regions of the crystal.

As mentioned earlier, changing the implant tilt angle from 30º to 40º will obviously decrease the projected range of the implant, and this effect can be seen in the expanded SIMS plot in figure 3(b). At 40º, the randomly orientated boron component observed in approximately the top 400Å (R_p ~ 90Å) is seen displaced further towards the surface with respect to 30 and 35º. Nevertheless, this angular dependence of projected range is obviously not interfering dramatically with the channelled boron component seen predominantly beyond 500Å (R_p ~ 850Å). Therefore, we have assumed its effect to be inconsequential and essentially independent from any channelling effects being studied here, though as a point of note, it is clear that SIMS is easily able to observe both effects.

The boron dose measured between 500Å and 2000Å (i.e. to detection limits at end of profile) in each of the different implants studied has been plotted as a function of implant tilt angle in figure 4. With the above assumption taken into account, this plot is essentially directly related to the extent of channelling as a function of tilt angle, as the boron beyond 500Å is almost entirely associated with the channelled boron component. SIMS indicates a dramatic variation in boron dose found in the channelled boron component as the tilt angle is varied. There is a clear and relatively sharp maximum in this dose as the tilt angle is varied between 30 and 40°. The technique shows very high sensitivity to small changes in tilt angle (approximately 20% change in dose per degree tilt), as well as an ability to accurately pinpoint the tilt angle at which maximum channelling is occurring. This contrasts dramatically with the Therma-Probes™ inability to accurately pinpoint the optimum channelling tilt angle, whilst the SIMS sensitivity to tilt angle change is approximately 100X greater for this specific implant protocol.

Figure 5 shows the QCS instrument dynamic surface charge measurement, Q_d, (Coulombs.m^{-3}) plotted as a function of implant tilt angle. There is a clear maximum in the dynamic surface charge as the tilt angle is varied between 30 and 40°. In this experiment, the Q_d value is not simply dependant on the total damage apparent in the crystal due to ion implantation, but is sensitive to the depth to which the damage extends in the crystal. Figure 1 clearly shows that more damage is present further into the crystal when more channelling is exhibited (i.e. at 35 or 36°) and it is this phenomenon that the QCS instrument relies upon to show such a sensitivity to change in implant tilt angle. Although the maximum in figure 5 is occurring at 36°, as opposed to 35° in the related SIMS plot shown in figure 4, the theoretical results shown in figure 1 clearly indicate that channelling occurs around 35-36°, and therefore this 1° discrepancy between SIMS and the QCS instrument is easily explained, with both techniques results being essentially well correlated. The QCS instrument is measuring approximately 1.5-2% Q_d per degree tilt sensitivity, a 10-fold improvement on the Therma-Probe™ analysis performed on the same samples.

As an visual indication of each instruments relative sensitivity to the implant tilt angle variations studied here, figure 6 shows the normalised signal intensity measured from the Therma-Probe™, SIMS and QCS instruments plotted as a function of implant tilt angle. This plot clearly indicates the relative performance of each of the analysis techniques in the study of this particular set of samples.

Figure 7 shows a 2-D contour map obtained from the QCS instrument for the wafer implanted at 36°. It is apparent that there are significant differences in the value of Q_d across the wafer. Although not shown, these contours are consistently observed in all seven wafers studied and show very similar patterns for each. We have used SIMS to assess for differences in the boron distribution in the blue region (top right of wafer) and the red region (center of wafer). Although not shown, the SIMS data indicates that the dose and implant profile is identical in these two regions of the sample, suggesting that the implanter is performing uniformly across the wafer. Also, Therma-Probe™ measurements show little or no such contours on this or any of the other wafers. Obviously the QCS instrument is observing variations to the extent of damage in the crystal that are not detectable in either SIMS or Therma-Probe™ measurements. It could be possible that these variations are due to some unknown, yet important implant effect or possibly variations in the crystal damage associated with cooling of the silicon ingot from which the wafer is cut. A more in-depth investigation is necessary to confirm the origin of the QCS instrument contours seen for these samples.

SUMMARY

The results of this study indicate that SIMS is the instrument of choice to fully characterize the effects of tilt angle changes during ion implantation due to its ability to detect very small changes in dopant distribution inside the crystal. SIMS still remains an essential analysis technique to fully test the ion implanters ability to dope a crystal both uniformly and with the desired profile. The results show that SIMS is the most sensitive technique of those studied to tilt angle variations and must always be implemented to ensure total confidence in any implantation process and its long-term control. Furthermore, advances in SIMS have allowed this technique to keep up with the increasingly demanding device technology nodes being introduced, such that implant protocols like the one studied here, and more advanced examples besides, can be easily assessed with high accuracy and precision.

Nevertheless, in the chip manufacturing environment it is still necessary to be able to rapidly measure implant parameters using in-line, real-time, non-destructive metrology. In relation to these requirements, the Therma-Probe™ has been the instrument of choice in recent years. It is well known that the Therma-Probe™ is capable of accurately detecting subtle changes in dopant dose uniformity across the wafer and can be used to monitor ion beam current and energy stability. However, the results of this study indicate that, when considering a particular implant protocol used frequently in the production of 65nm node technology devices, the Therma-Probe™ is not able to accurately distinguish subtle changes in channelling arising from implanter tilt angle variation. The ability to perform implant assessments of this sort is obviously critical to ensure the optimization of non-channelling angle and ensure reliable monitoring of day-to-day accuracy of angular implant control. The results suggest that QCS metrology is a more reliable in-line method than the Therma-Probe™ for performing these operations and tests, along with its already proven ability to assess dose, energy, and beam current variations. The results here also show that the QCS instrument is well correlated with SIMS when considering tilt angle variations and, following further experiments, the QCS instrument may yet show even further uses in the characterization of implant technology.

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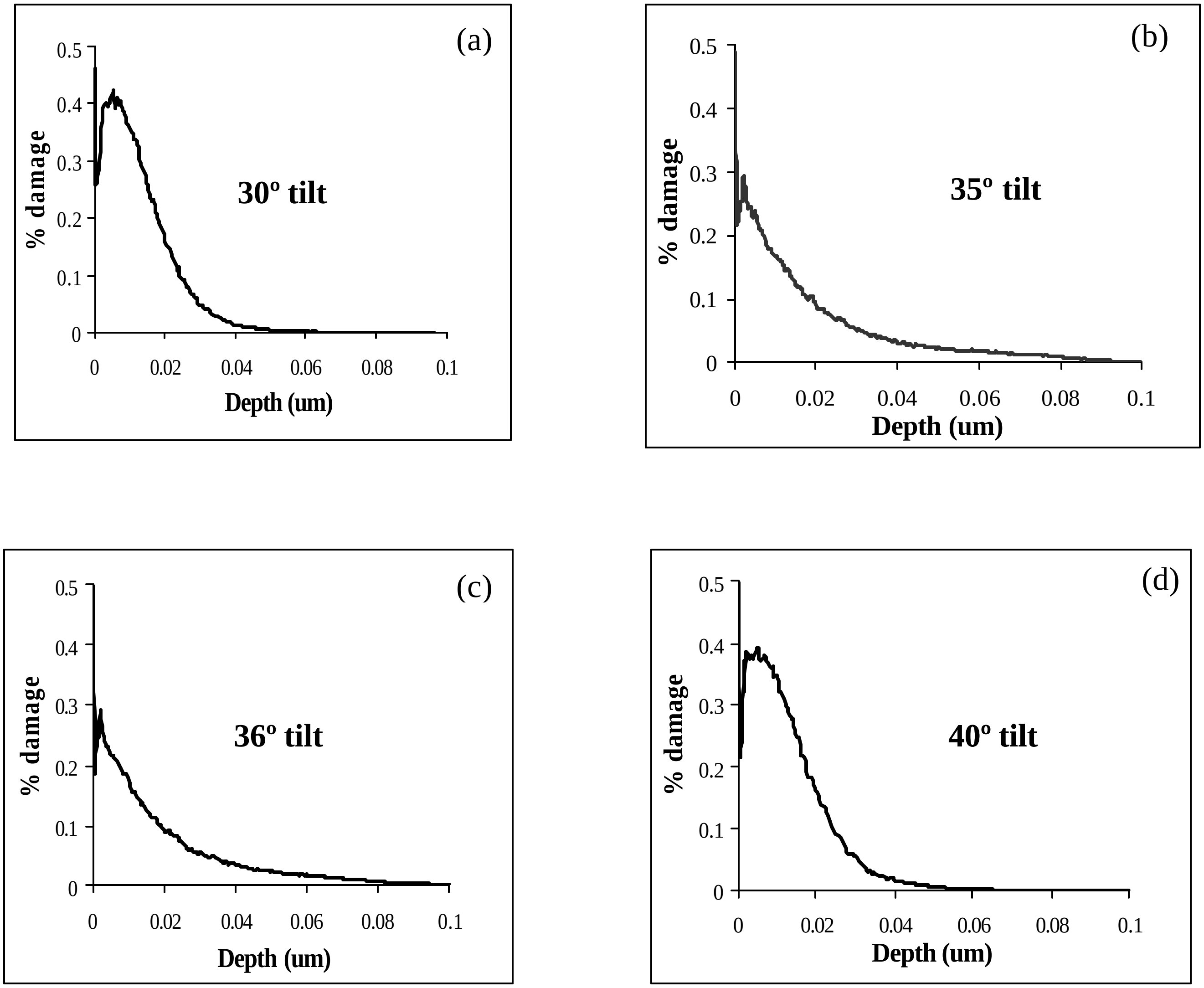

(a)
30º tilt
% damage
0.5
0.4
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
0.1
Depth (um)
(b)
35º tilt
% damage
0.5
0.4
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
0.1
Depth (um)
(c)
36º tilt
% damage
0.5
0.4
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
0.1
Depth (um)
(d)
40º tilt
% damage
0.5
0.4
0.3
0.2
0.1
0
0
0.02
0.04
0.06
0.08
0.1
Depth (um)

Figure 1

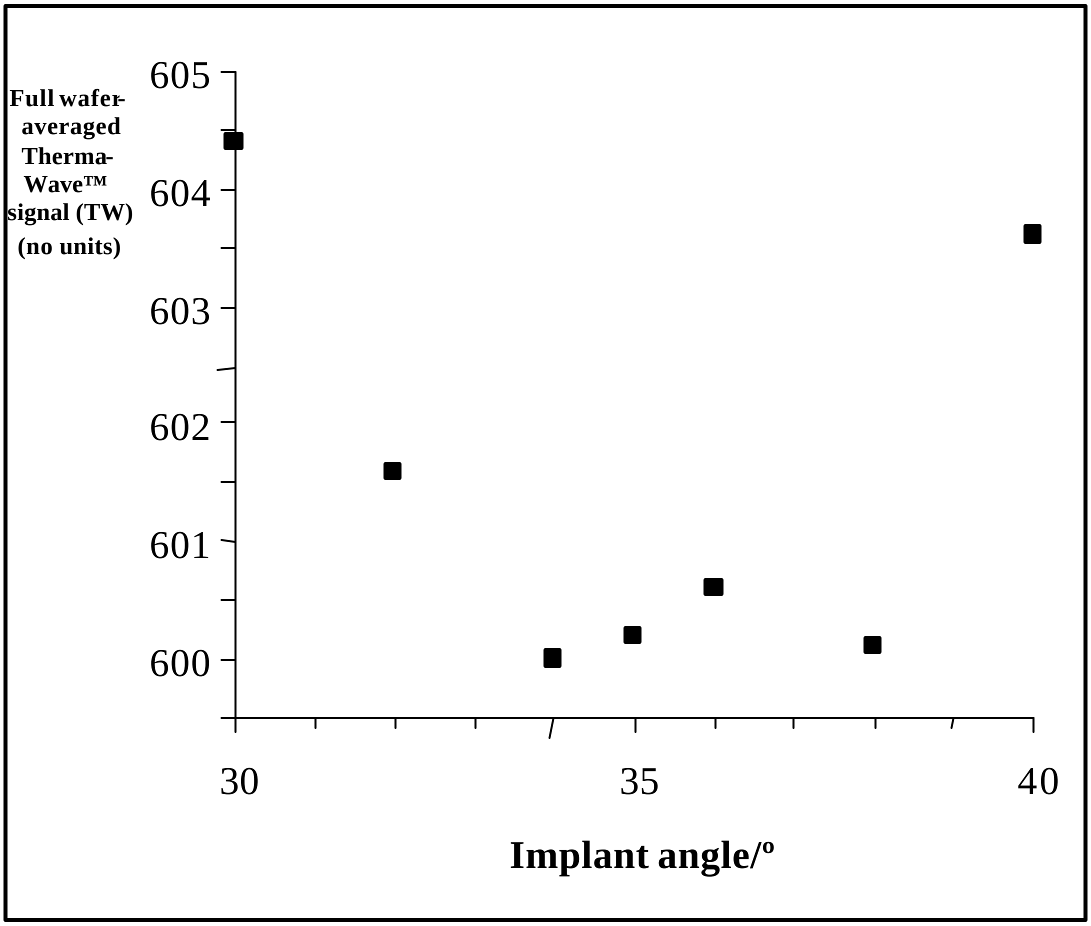

Full wafer-averaged Therma-Wave™ signal (TW) (no units)
605
604
603
602
601
600
30
35
40
Implant angle/º

Figure 3

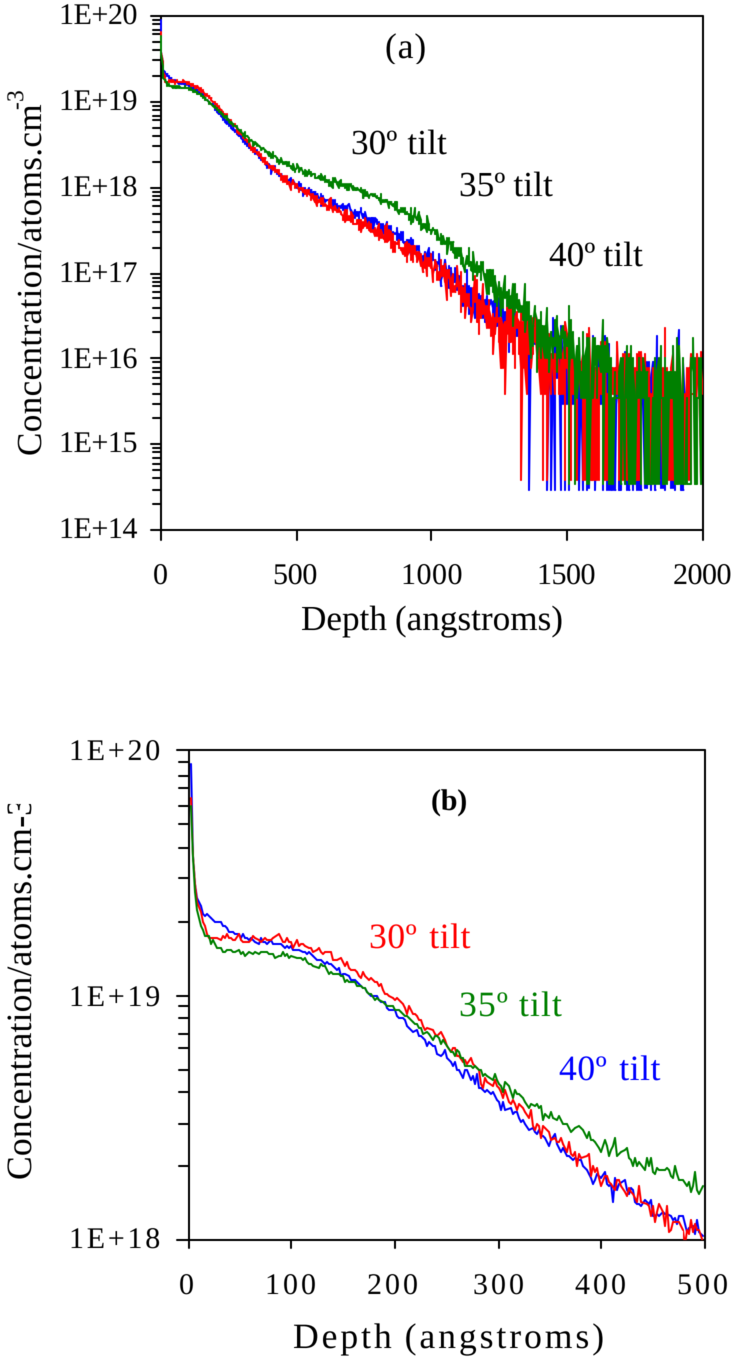

(a)
1E+20
1E+19
1E+18
1E+17
1E+16
1E+15
1E+14
Concentration/atoms.cm^{-3}
30° tilt
35° tilt
40° tilt
0
500
1000
1500
2000
Depth (angstroms)
(b)
1E+20
1E+19
1E+18
Concentration/atoms.cm-3
30° tilt
35° tilt
40° tilt
0
100
200
300
400
500
Depth (angstroms)

Figure 3

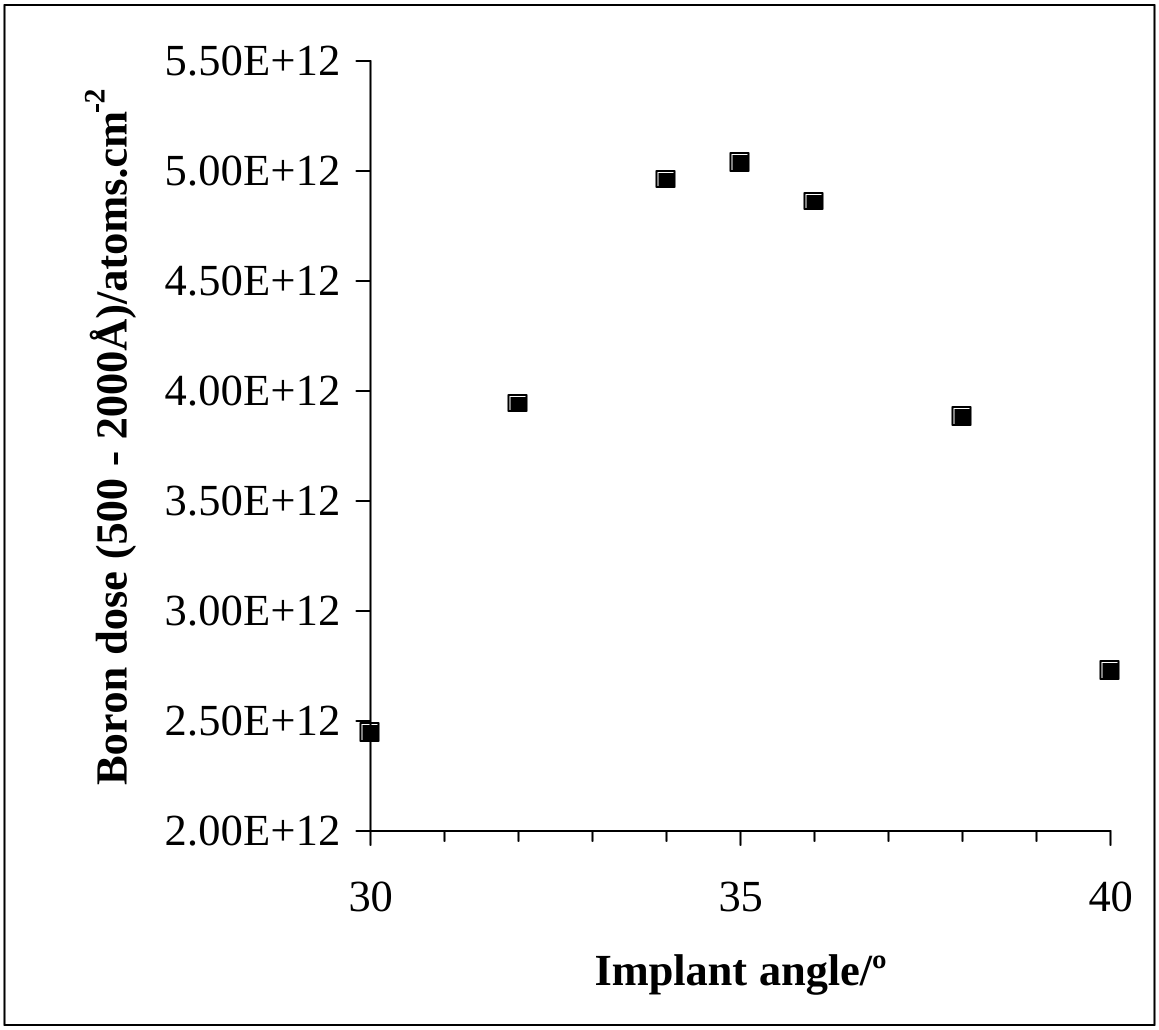
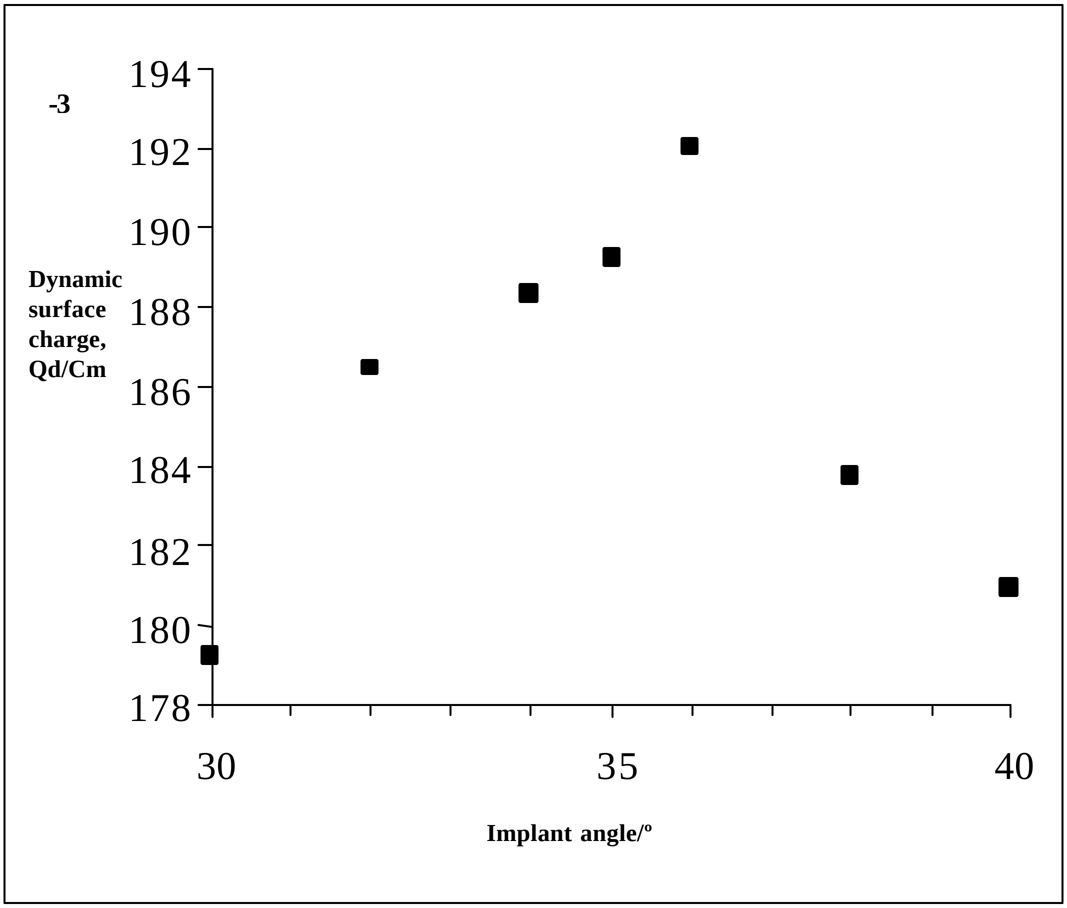

5.50E+12
5.00E+12
4.50E+12
4.00E+12
3.50E+12
3.00E+12
2.50E+12
2.00E+12
Boron dose (500 - 2000Å)/atoms.cm-2
30
35
40
Implant angle/º

Figure 4



-3
194
192
190
188
186
184
182
180
178
Dynamic surface charge, Qd/Cm
30
35
40
Implant angle/º

Figure 5

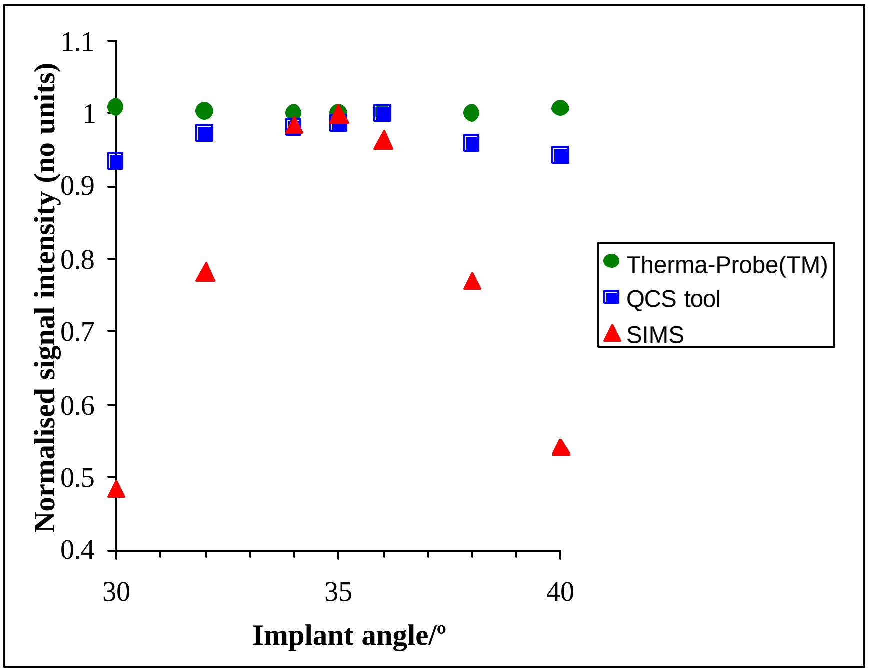
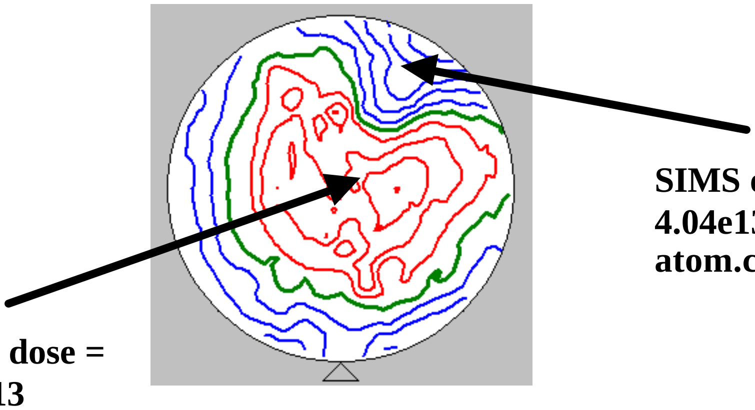

1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
Normalised signal intensity (no units)
30
35
40
Implant angle/º
● Therma-Probe(TM)
■ QCS tool
▲ SIMS

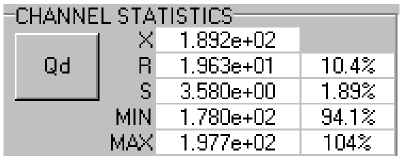
Figure 6

B, 1.0e13 atoms.cm^{-3}, 3keV
35¢ª/quad



SIMS dose = 4.04e13 atom.cm^{-3}

SIMS dose = 4.05e13 atom.cm^{-3}



CHANNEL STATISTICS

X	1.892e+02	
R	1.963e+01	10.4%
S	3.580e+00	1.89%
MIN	1.780e+02	94.1%
MAX	1.977e+02	104%

Contour – 1% Map

Color Index
🟦 Lower than Mean 🟩 Mean 🟥 Higher than Mean

Figure 7

FIGURE CAPTIONS

Figure 1: Comparison of the simulated damage profiles obtained (using the simulation: UT Marlowe 6.0.0) for a 3 keV 4e13 atoms.cm^{-3} B^{+}, quad implant at varying implant tilt angles: (a) 30º, (b) 35º, (c) 36º, (d) 40º.

Figure 2: Dependence of full wafer-averaged Therma-Wave™ signal (TW) measured from boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafers with varying implant tilt angles.

Figure 3: (a) Comparison between the boron SIMS depth profiles obtained from three boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafers with varying implant tilt angles: 30, 35 and 40º. (b) Expanded view of (a)

Figure 4: Dependence of boron dose measured from channelled component (500 – 2000Å) using SIMS in boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafers with varying implant tilt angles.

Figure 5: Dependence of dynamic surface charge, Q_d, measured from the QCS instrument in boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafers with varying implant tilt angles.

Figure 6: Dependence of normalised signal intensity measured from the Therma-Probe™, SIMS and QCS instrument in boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafers with varying implant tilt angles.

Figure 7: 2-D contour map obtained from the QCS instrument for a boron implanted (3 keV 4e13 atoms.cm^{-3} B^{+}, quad) bulk silicon wafer with implant tilt angle of 36°. The boron dose found using SIMS in the regions of extreme Q_d variation are also shown.