Energy Contamination Control During Ion Beam Deceleration For Low Energy Ion Implantation

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***Abstract*— Ultra low energy ion implantation with high beam current is required for shallow junction formation. Due to space charge limits in low energy ion beam transport, it is necessary to extract ion beams at higher energy (>1kV) and decelerate them to a target energy as low as 100 eV near the process wafers. Energy contamination due to energetic neutral particles that result from charge exchanges between beam ions and beamline residual gas molecules before and during deceleration, increases proportionally with beamline pressure and is difficult to be prevented without sacrificing beam currents substantially. AIBT has developed a method of energy contamination control. Both electrical and magnetic fields are applied to the deceleration region so that the energetic neutral particles created before and during beam deceleration are guided to neutral beam blockers instead of the wafers. The energy contamination is negligible though the beamline pressure is as high as 1E-4torr. This method maximizes beam current performance at ultra low energy and gives easy implant control since the beamline pressure does not affect energy contamination level in our system.**

I. Introduction

As semiconductor device dimensions continue to shrink, source-drain junction depths are reduced accordingly. Shallow junction formation is, however, quickly becoming one of the major limiting factors in the modern semiconductor fabrication process. In making modern Ultra Large-Scale Integrated (ULSI) circuits conventional ion implantation methods do not provide production worthy solutions to the semiconductor industry.

A technology review on ultra low energy boron implantation presented by Yasunaga, et al. in IIT'98 indicates that sub-keV implants are required for the technology nodes beyond 0.15 µm [1]. The 2001 ITRS (International Technology Roadmap for Semiconductors) [2] presented by SEMATECH indicates that 90nm and 70nm devices will be in production in 2004 and 2006 respectively, which may require 100eV or lower energy boron ion implants.

One of the problems of ultra low energy implantation is that throughput is limited by low beam current because of space-charge beam blow up (i.e. divergence) during beam transport from an ion source to wafers. Deceleration of the ion beams is used to obtain high beam currents for the sub-keV implants. The ions are extracted at higher energies than ultimately desired, followed by a mass analysis, and then decelerated just before they reach the targets [3]. The currently available commercial implanters for low energy applications are all using this method. However, the neutrals with the extraction energies are produced when the ions interact with residual gas molecules in the beam line before the deceleration electrodes. These neutrals will not be decelerated by the deceleration electric fields and therefore reach the wafers at higher than desired energies. This effect is known as energy contamination and leads to a deeper than desired dopant depth profile. Energy contamination is only tolerable to a level of ~0.1%, depending on the energy of the neutral fraction, to provide a sufficient margin against shifts in device performance [4].

More stringent energy contamination control is required for sub-100nm devices. The direct interpretations of the ITRS roadmap on source/drain extension junction depth Xj, give different energy requirements for boron beams with 0.3% energy contamination and zero energy contamination for spike anneal, laser melt anneal, and low temperature SPE [5]. For instance, at 100nm technology node with spike anneal, boron energy requirement for 0.3% contamination is <100eV, while for zero contamination is 300-800eV. For 70nm and sub-70nm technology nodes, zero energy contamination is required. This is because the energy contamination, even just a small amount, can have a big impact on shallow junction depth. Experimental results by Richard Lindsay et al. of Philips [6] using Applied Materials' XR80 Leap on 0.5keV 1E15 atoms/cm2 dose decelerated from 1, 2, 3, and 4keV, show that the junction depth at 1E18 atoms/cm3 increases linearly as 40(nm)×(% energy contamination). Junction depth increase would be 12nm for 0.3% energy contamination. Results from Quantum Leap implanter by Amir Al-Bayati et al. [9] of Applied Materials also showed that the 0.3% energy contamination generated by a 1keV decel $^{11}B^{+}$ beam from 5keV resulted in 22nm junction depth, that is 6nm deeper than the 16nm junction depth by a drift beam. The junction depth increase in a range of 10nm caused by energy contamination is not acceptable for 70nm or below devices, since the junction depth range for 70nm devices is only 12-19nm. Eliminating energy contamination, therefore, becomes a basic requirement in 70nm and sub-70nm devices. The lifetime of ion implantation itself will depend on the ability to maintain high beam currents without significant energy contamination. At the moment, the levels of contamination are generally much less than the dopant diffusion during anneal, but when junctions <30nm are required, energy contamination can be a limiting factor on forming such shallow junctions [6]. To meet the requirements of technology nodes beyond 90 nm, implantation tool manufacturers have to develop technologies that provide 1) low energy contamination, 2) high productivity, 3) precise dose control, especially for low energy implants, 4) energy accuracy, and 5) large angle implant capability [7].

Reducing the beamline pressure can reduce the energy contamination but this approach requires the chamber pressures to be kept below 5.0E-7 torr. However, this level of vacuum is very difficult to maintain under normal operating conditions due to the out-gassing of the photo-resist coating of patterned devices, as well as the contribution from feed gases of plasma flooding sources. Another issue is the variation in the level of contamination. Pressure fluctuations during the implant can cause implant systematic Xj non-uniformity across a wafer. Day-to-day changes in vacuum conditions or photo-resist quality may cause batch-to-batch implant result variations. There is a potential of trashing wafers that could worth millions of dollars due to undetected vacuum problems. Vacuum pressure control according to energy contamination level is required to minimize energy contamination. A method has been invented to detect energy contamination during ion beam deceleration [8].

Lowering injection (initial acceleration) beam energies can further control energy contamination, because the charge exchange cross section between energetic ions and residual gases decreases with ion beam energy. The degree of energy contamination is also a function of deceleration ratio (injection energy/final energy) [9]. As the final energy continuously decreases, the injection energy has to decrease accordingly to maintain constant deceleration ratio. On the other hand, for fixed final energy, reducing the deceleration ratio results in lower injection energy. Lowering injection energy reduces injection current significantly especially below 2keV. According to 2001 ITRS, sub-100eV boron implants are needed for sub-25nm technology node. To keep deceleration ratio at 5, for instance, a 50eV final energy beam requires a 250eV injection beam, which has less than 100uA beam current for existing implanters. Controlling energy contamination to a desired level by reducing injection energy may require a reduction in ion beam current by a factor of 10 [6]. Borland pointed out that the conventional high current implanters could not meet the requirements for the devices beyond the 100 nm technology node because of the energy contamination [5]. New methods and systems are required to resolve these difficulties with the effective control over energy contamination of low energy beams.

II. EXPERIMENTAL SETUP

AIBT has built a prototype ion implanter that employs special method to remove energy contamination from decel beams. The ion implanter includes an ion source, beam extraction electrodes, a mass analyzer, a decel module with a plasma shower, a Faraday, a beam profiler, a process batch disk, and a 300mm wafer transfer system from FOUPs to vacuum. The beam transport optics was designed to deliver narrow and tall beams with higher beam currents to wafers, in both drift mode and decel mode, than the existing commercial implanters, especially at energy range from 5keV to 100eV. The decel module includes a set of decel electrodes and a magnet to prevent high-energy neutral particles from reaching wafers in decel mode operations even when the deceleration ratio is greater than 20 and chamber pressure as high as 1E-4 torr. The implant angle, controlled through the process disk, can change from 0° to 45°. The process disk is water cooled to keep wafer temperature below 80°C during implant.

In our experiments, wafers were implanted at different energies using drift beams, conventional decel beams, and AIBT decel beams. Germanium pre-amorphized and crystalline Si wafers were used to eliminate channeling effect.

III. RESULTS AND ANALYSIS

A. Non-detectable energy contamination in decel mode

Our decel module was designed to eliminate high-energy neutral particles that are generated before the decel region. Fig. 1 shows the SIMS profiles of three B^+ implants of 1000 eV drift, conventional decel, and AIBT decel beams. Both decel beams were decelerated from 4.5keV at the chamber pressure of 5e-5 torr. The junction depths Xj at 1E18 atoms/cm3 are 18nm, 65nm, and 18nm, respectively. The long tail in the profile of the conventional decel beam implant indicates severe energy contamination. However we did not observe any difference between the drift beam and the AIBT decel beam implants.

It is possible that SIMS is not sensitive to a small amount of energy contamination. This small energy contamination may become observable after thermal process for dopant activation. Fig. 2 shows the SIMS profiles for the same implants after flash anneals. The implant by the AIBT decel beam still has the same SIMS profile as the drift beam. Junction depths Xj of both implants are ~26nm at 1E18/cm3 and sheet resistance values are 430 and 414 ohms/sq. The flash anneals drive the Xj 8nm deeper. The energy contamination implant gives the lowest sheet resistance value of 216 ohms/Sq. because of a deep implant range resulting in larger dopant activated depth. The sheet resistance value difference between drift and AIBT decel beam implants are within measurement errors and can be neglected. Therefore, the AIBT decel beam implants have results identical to the drift beams.

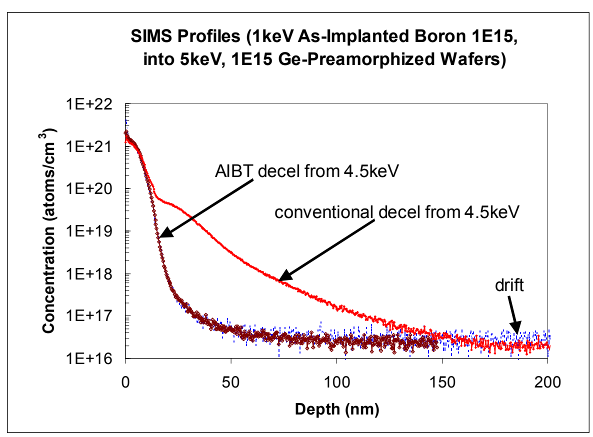


Figure 1. As-implanted SIMS profiles for 1keV B^+, 1E15 atoms/cm^2 implants on pre-amorphized wafers, using drift beam, conventional decel beam, and AIBT decel beam. The decel beams were decelerated from 4.5keV beams at 5E-5 torr pressure in decel region.

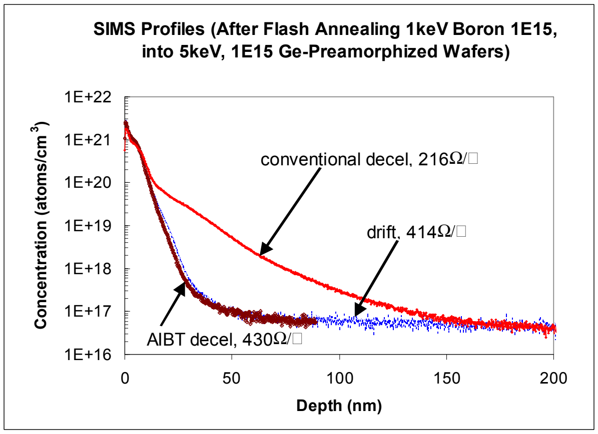


Figure 2. After-anneal SIMS profiles for 1keV B^+, 1E15 atoms/cm^2 implants on pre-amorphized wafers, using drift beam, conventional decel beam, and AIBT decel beam. The decel beams were decelerated from 4.5keV beams at 5E-5 torr pressure in decel region.

B. *More sub-keV Implants demonstrating energy purity using AIBT decel beams*

More sub-keV implants were carried out using conventional decel beams and AIBT decel beams. Fig. 3 shows the SIMS profiles using 500eV B^+ beams decelerated from 2keV. The junction depth Xj of using the AIBT decel beam is 13nm, much smaller than the Xj of 24nm, implanted with the conventional decel beam.

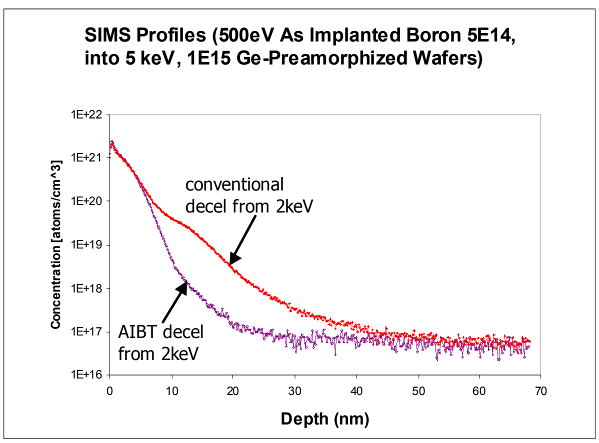
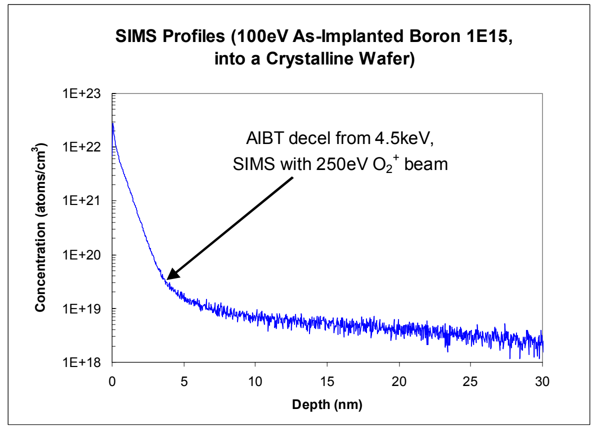
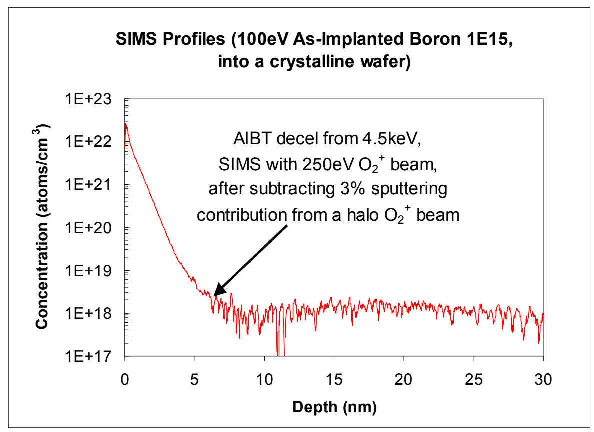


Figure 3. As-implanted SIMS profiles for 500eV B^+, 5E14 atoms/cm^2 implants on pre-amorphized wafers, using conventional decel beam, and AIBT decel beam decelerated from 2keV beams.

Fig.4(a) shows the as-implant SIMS profile using an AIBT decel B^+ beam of 100eV that was decelerated from 4.5keV. The junction depth at 1E19 atoms/cm^3 is ~5nm. The long tail at depth greater than 5nm should not come from the energy contamination of the 4.5keV initial acceleration beam, otherwise there should have been a minor peak around 25 nm as shown in Fig.1. The long tail may be caused by low energy O^+ halo beams that are used in SIMS analysis. The halo part beam has very low beam intensity and sputters Si away at much lower speed. We estimated that only 3% sputtering contribution from a halo O^+ beam could generate the tail as shown in Fig.4(a). By subtracting the 3% sputtering contribution from the original SIMS profile as shown in Fig. 4(a), we can get a revised SIMS depth profile as shown in Fig. 4(b) where the tail disappears and the noise level is much lower. The junction depth Xj at 1E18 atoms/cm^2 is approximately 7nm.



(a)

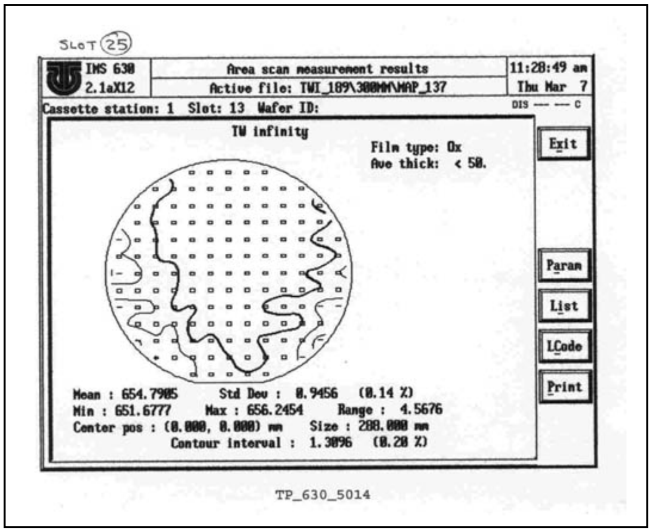


(b)

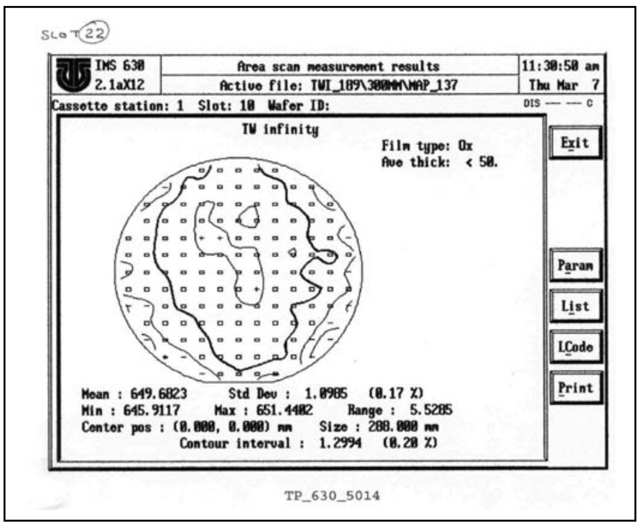
Figure 4. (a) An as-implanted SIMS profile for 100eV B^+, 1E15 atoms/cm^2 implant on a crystalline wafer, using the AIBT decel beam decelerated from 4.5keV; (b) The revised SIMS profile after subtracting 3% sputtering contribution from a halo O_2^+ beam.

C. *Implant Uniformity*

Narrow and tall (>200mm) ion beam has not been used before for implantation in a batch type implanter, especially at ultra low energy. Unstable source operation, improper shower parameters, and inaccurate batch disk control during implant can affect implant uniformity. We implanted 300mm wafers with drift beams and low energy decel beams and found the uniformity was satisfactory with Therma-Wave measurement tool. Fig. 5 shows two Therma-Wave patterns for 200eV B^+ implants at different doses. The 200eV B^+ beam was decelerated from 4.5keV. The uniformities were 0.14% for 1E15 atoms/cm^2 dose and 0.17% for 9E14atoms/cm^2 dose, which are near the measurement error limit and much better than 1% specification of the existing commercial implanters. The excellent uniformity number demonstrates that AIBT's implanter delivers stable low energy beams from ion source to wafers, with accurate implant process control.



(a)



(b)

Figure 5. Therma-Wave mapping for 200eV B^+, 10° tilt implant. B^+ beam was decelerated from 4.5keV. (a) 1E15 atoms/cm^2 dose, standard deviation 0.14%; (b) 9E14 atoms/cm^2 dose, standard deviation 0.17%.

The undetectable difference between drift beams and AIBT decel beams indicates that our decel mechanism provides effective neutral particle filtering during decel giving high advantage over the conventional decel mechanism. The AIBT implanter provides much higher implant yield due to its immunity to high-energy contamination, and easier implant control due to its independence of pressure variation.

IV. CONCLUSION

The implanter designed and built by AIBT provides production worth beam currents from 0.1 to 100keV especially at energy lower than 5keV compared to existing commercial implanters. Its special decel mechanism minimizes energy contamination to an undetectable level, largely independent of beamline pressure. As semiconductor micro-device dimension shrinks down to 90nm and 70nm or even further, AIBT's implanter can enable shallow junction formation with high productivity, reliability, and repeatability.

ACKNOWLEDGMENT

We very much appreciate the support given by Jeffrey Gelpey of Vortek, Prof. Wei-Kan Chu of University of Houston, and Ken Ritz and Heath Pois of Therma-Wave for after-implant wafer process and measurement.

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