The effects of energy non-monochromaticity of B^{11} ion beams on B^{11} diffusion

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We have shown that energy contamination introduced by ion beam deceleration technology that is used to increase the beam currents available for low energy boron implants, can affect fabricated junctions adversely. A 4 keV B^{11} beam is extracted and retarded by a potential of -3.5 keV for 0.5 keV B^{11} implantation, or by a potential of -3.8 keV for 0.2 keV B^{11} implantation. Intentional energy contamination was introduced by turning off the retarding potential to allow the 4 keV B^{11} ions to irradiate Si wafers directly. The energy contamination levels of 0.1, 0.2, and 0.3% were introduced. Rapid thermal annealing of all the implanted samples was performed under N_2 ambient at 1050ºC for 1s. The dopant tail profiles themselves are not significant if the contamination levels are low. However, the much higher damage level coming from high energy contamination increases the transient enhanced diffusion of B^{11} more than proportionately, resulting in considerable boron diffusion. Energy contamination at a level of 0.1% can extend the profile of 0.5 keV B^{11} implants 10 nm deeper after a 1050°C spike annealing. The study shows a highly monoenergetic beam with energy contamination less than 0.1% is required for sub-micron devices.

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1. Introduction

The fabrication of complimentary metal oxide semiconductor (CMOS) devices beyond the 90 nm node demands a continued reduction of diffusion lengths of dopants in Si [1]. One significant technological barrier has to be overcome is the low beam current in ultra-low energy implantation due to positive space charge effects. One method of achieving adequate boron beam current is the use of post mass analysis ion beam deceleration technology, in which a reverse bias is applied to decelerate the ions down to the final desired energy prior to implanting targets or wafers. However, charge exchanges between beam ions and residual gases after a mass analyzer to form energetic neutrals before and in deceleration optics can give rise to energy-contaminated neutral beams. Methods of controlling energy contamination differ among various implanters. Even with ultra-low energy contamination level while as-implanted dopant profiles almost have no visible differences, the extra radiation damage coming from high energy contamination increases the transient enhanced diffusion of B^{11} more than proportionately, resulting in considerable junction spreading after annealing by interstitial diffusion mechanism [2,3].

In the present study, the effects of energy non-monochromaticity of B^{11} ion beams on both B^{11} diffusion and electrical properties of the fabricated devices are discussed. Energy contamination was internationally introduced by turning off the retarding potential to allow the B^{11} ions, with the energy equal to the extraction energy, to irradiate the Si wafer directly. The study will provide an idea of how important the accuracy of implantation energy control is.

2. Experiments

Bare (100)-oriented n-type Si wafers that were preamorphized with 5 keV Ge ions (R_p~12nm), were implanted with 0.2 keV B^{11} and 0.5 keV B, respectively, at dosages of $5\times10^{14}/cm^2$. Boron implantation was performed at AIBT's high beam current, ultra-low energy prototype ion implanter. The implanter employs special method to remove energy-contaminated neutrals from decel beams. The ion implanter includes an ion source, beam extraction electrodes, a mass analyzer, a deceleration module, a plasma shower, a Faraday cup, a beam profiler, a process batch disk, and a 300mm wafer transfer system. 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, 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.

A 4 keV B^{11} beam is extracted and retarded by a potential of -3.5 keV for 0.5 keV B^{11} implantation, or by a potential of -3.8 keV for 0.2 keV B^{11} implantation. Intentional energy contamination was introduced by turning off the retarding potential to allow the 4 keV boron ions to irradiate a Si wafer directly. The percentage of contamination is defined as the ratio of the 4 keV B^{11} dose to the 0.5 keV or 0.2 keV B^{11} dose. Energy contamination, at levels of 0.1, 0.2, and 0.3% was introduced. Rapid thermal annealing (RTA) of all the implanted samples was performed under N_2 ambient at 1050ºC for 1s. The B^{11} atomic depth distribution profiles were obtained using secondary ion mass spectrometry (SIMS). Oxygen flooding was used to reduce secondary ion transient effects near the surface.

3. Results and discussion

Figure 1 shows calculated depth distribution of Si displacements produced by contaminated B^{11} implantation from 0.1 to 0.3%, which corresponds to 5×10^{11}, 1×10^{12} and

$1.5\times10^{12}/cm^2$ of 4 keV B^{11} bombardments, respectively. The displacements per ion are calculated to be 58 for 4 keV B^{11} and 8 for 0.5 keV B^{11} from transport of ion in matter (TRIM) code [4]. Even for low contamination level, 4 keV B^{11} implants can produce considerable radiation damages. The arrow in Figure 1 indicates the projected range of 5 keV Ge ions. One would expect that, by increasing preamorphization energy, the total displacements caused by contaminated B^{11} implantation can be totally contained within the amorphous region. However, the benefit of deep preamorphization is offset by the detrimental increase in B^{11} TED and B^{11} segregation [5].

Figure 2a shows the B^{11} atomic depth profiles of samples implanted with 0.5 keV B^{11} with energy contamination of 0.1, 0.2, and 0.3%. As-implanted profiles of energy-contaminated samples have visible enhanced tails with buried peaks at around 17 nm deep, which corresponds to the projected range of implanted 4 keV B^{11}. Effects of various percentages of energy contamination on boron diffusion after RTA are surprisingly large. Energy contamination extends the junction depth significantly deeper than that obtained with monoenergetic implants. For the 0.1% contaminated sample, the junction depth measured at $1\times10^{18}/cm^3$ is increased by around 10 nm. Junction depth finally reaches 53 nm at 0.3% energy contamination, corresponding to a diffusion length of almost double that obtained from contamination-free samples. Figure 2b shows annealed B^{11} profile for 0.2 keV B^{11} implants. Energy contamination at 0.2% induces an additional profile shift of 14 nm. Both Figure 2a and 2b show anomalously enhanced boron diffusion with increased percentage of contamination. Figure 3 summarizes the junction shifts as a function of contamination levels. These results clearly show the importance of beam energy monochromaticity on the ultra shallow junction formations.

It has been shown that anomalous B^{11} diffusion persisted even for sub-keV B^{11} implantation.[6]. One proposed mechanism is the so called boride-enhanced diffusion (BED), in which self interstitials injected from a silicon boride phase cause enhanced B^{11} diffusion [6]. Another mechanism is the coupled diffusion of B^{11} [7]. A simple explanation for it is that the flux of B^{11} self-interstitial pairs from Si surface into the bulk drags Si interstitials along, creating a super-saturation of Si self-interstitials. However, both of these two mechanisms are operative dominantly at high B^{11} concentrations, and should not be very sensitive to variation of the low B^{11} concentrations typical of the tail of the B^{11} profiles. The observed additional boron diffusion induced by energy contamination is mainly due to transient enhanced diffusion caused by additional implantation damage from 4 keV B^{11} bombardment.

The energy contaminations can seriously detriment device performance. The well known short-channel effects, as the channel length decreases, the fraction of charge in the channel region controlled by the gate decreases, result in the increase of threshold voltage. Si interstitial super-saturation resulted from the energy contamination increases the lateral as well as the vertical diffusion distances. The short channel effects induced from the enhanced lateral diffusion need increases of gate lengths to keep the same threshold voltages. Experimentally, it has been shown that the junction shifts due to the energy contamination is accompanied with the shifts in gate lengths, e.g. an increase of 9nm in junction depth can shift gate length by 15 nm [8]. Also, the extra damages may increase leakage currents. Studies on this aspect are underway.

We have used the technique of point defect engineering (PDE) to reduce boron diffusion, and then to lower the requirements on energy monochromaticity of B^{11} ion beams. PDE that uses Si MeV Si ion implantation provides a unique method to separate the spatial distribution of vacancies and interstitials [9]. During ion bombardment, the forward momentum imparted to the lattice Si causes the recoiled Si interstitial distributions to be deeper than that of vacancies. Since spatially separated Frenkel pairs recombine in nearby proximity, an excess vacancy rich region is formed close to the surface and excess interstitials are left in the deep range. Reductiosn of B^{11} TED and BED with co-implantation of MeV Si ions have been reported elsewhere [9]. In this study, a subset of the wafers additionally received a “PDE” MeV Si ion implantation with a dosage of $5\times10^{15}/cm^2$ before RTA. Figure 4 shows SIMS profiles of 0.2 keV B^{11} implants after 1050°C RTA, with or without PDE. It shows that the X_j of 0.1 % energy contaminated sample is 5 nm deeper than that of contamination-free sample, while with PDE the increment is reduced to around 1 nm only. The effects of PDE on the X_j are manifested in the data depicted in Figure 5. PDE significantly reduces B diffusion. Junction depth X_j of all contaminated 0.5 keV B^{11} implants is systematically reduced by around 10 nm if PDE was performed. However, PDE is unable to reduce the profile spreading of 0.2% energy contaminated 0.2 keV B^{11} and 0.5 keV B^{11} implants to a depth close to the contamination-free sample. The study shows that even the most effective B^{11}-diffusion-control method such as PDE cannot eliminate the effects of energy non-monochromaticity on B^{11} diffusion. Therefore, a highly monoenergetic beam with energy contamination less than 0.1% is desired.

4. Conclusions

In summary, our studies have shown that energy contamination during decelerated ion implantation can affect adversely the post-annealing diffusion of B^{11} implants. In order to satisfy device requirements, highly monochromatic beams are needed.

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Caption

Fig. 1. TRIM simulation of Si displacements after 4 keV B^{11} implantations with a dosage from 0.1% to 0.3% of $5\times10^{14}/cm^2$.

Fig. 2. SIMS profiles of 0.5 keV B^{11} implants (a) and 0.2 keV B^{11} implants (b) with a dosage of $5\times10^{14}/cm^2$ after 1050°C/1s annealing. Effects of various percentages of energy contaminations on B^{11} diffusions are compared.

Fig. 3. Junction depths measured at $1\times10^{18}/cm^3$ after annealing at 1050 °C for 1s for 0.2 keV and 0.5 keV B^{11} implants, as a function of percentages of energy contaminations.

Fig. 4. SIMS profiles of 0.2 keV B^{11} implants with a dosage of $5\times10^{14}/cm^2$. Effects of various percent of energy contamination on boron diffusion after 1050°C for 1s, with or without 1 MeV, $5\times10^{15}/cm^2$ Si ion implantation, are compared.

Fig. 5. Junction depths measured at $1\times10^{18}/cm^3$ after annealing at 1050 °C for 1s for 0.2 keV and 0.5 keV B implants, with or without MeV Si co-implantation.

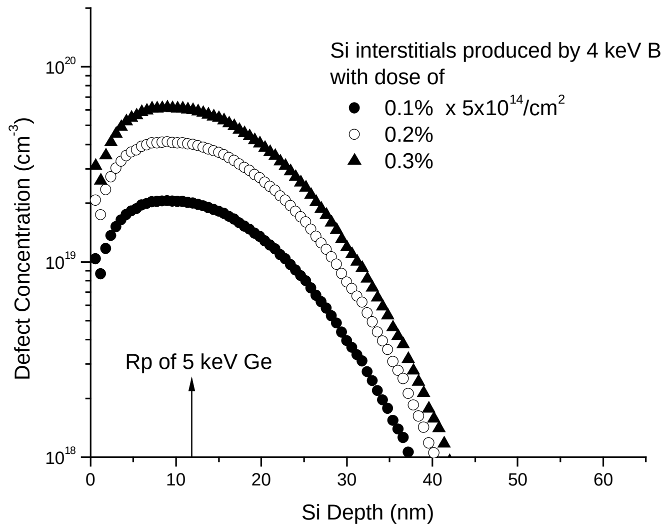
Si interstitials produced by 4 keV B
with dose of
0.1% x 5x10^14/cm^2
0.2%
0.3%
Rp of 5 keV Ge
Defect Concentration (cm^-3)
10^20
10^19
10^18
0
10
20
30
40
50
60
Si Depth (nm)

Figure 1.

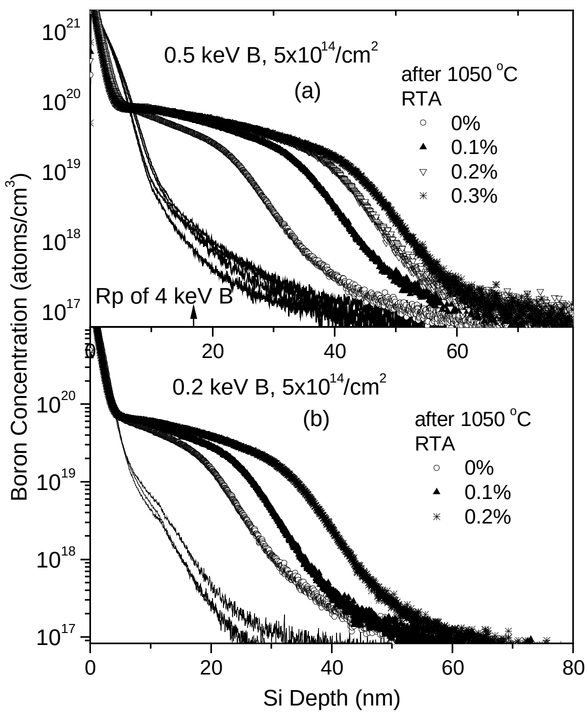
0.5 keV B, 5x10^14/cm^2
(a)
after 1050 °C RTA
0%
0.1%
0.2%
0.3%
Rp of 4 keV B
0.2 keV B, 5x10^14/cm^2
(b)
after 1050 °C RTA
0%
0.1%
0.2%
Boron Concentration (atoms/cm^3)
Si Depth (nm)

Figure 2

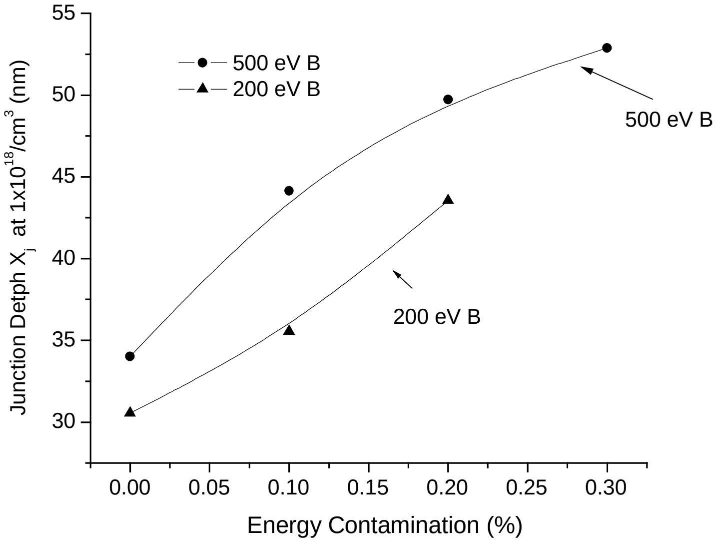
55
50
45
40
35
30
500 eV B
200 eV B
500 eV B
200 eV B
Junction Detph X$_j$ at 1x10^{18}/cm^3 (nm)
0.00
0.05
0.10
0.15
0.20
0.25
0.30
Energy Contamination (%)

Figure 3

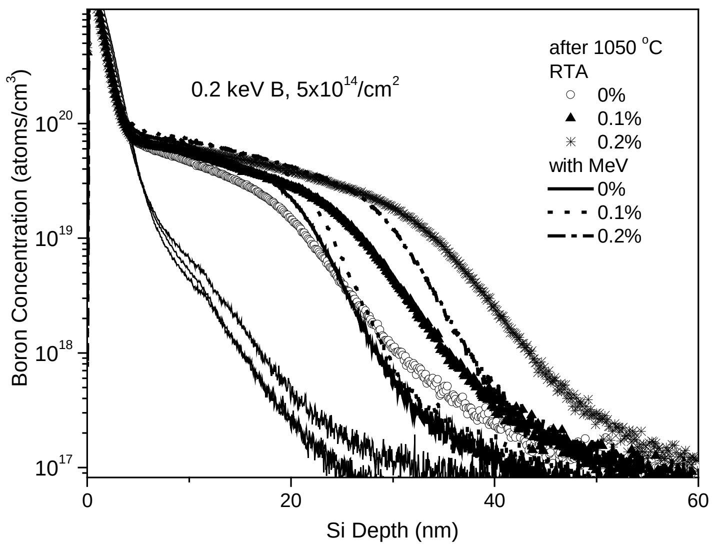
0.2 keV B, 5x10^14/cm^2
after 1050 °C
RTA
0%
0.1%
0.2%
with MeV
0%
0.1%
0.2%
Boron Concentration (atoms/cm^3)
Si Depth (nm)
10^20
10^19
10^18
10^17
0
20
40
60

Figure 4

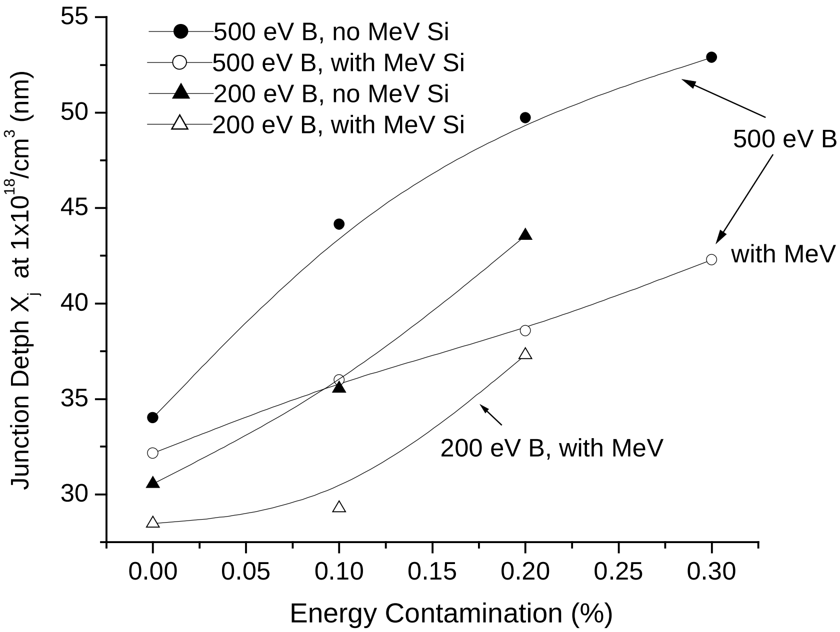
500 eV B, no MeV Si
500 eV B, with MeV Si
200 eV B, no MeV Si
200 eV B, with MeV Si
500 eV B
with MeV
200 eV B, with MeV
Junction Detph X_j at 1x10^18/cm^3 (nm)
Energy Contamination (%)
55
50
45
40
35
30
0.00
0.05
0.10
0.15
0.20
0.25
0.30

Figure 5