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ORIGINAL PAPER

Single implant damage accumulation and interactions between multiple implants

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Abstract
Device scaling in silicon MOSFET (metal–oxide–semiconductor field-effect transistor) processes continues to drive demand for ultra-shallow junctions. Device manufacturers must simultaneously achieve shallow, well-controlled junction depth while increasing the implanted dose to maintain the desired resistance. As the dose increases at low energy the implanted dose near the projected range (*Rp*) can significantly exceed the activated dose after annealing. In some advanced logic applications device manufacturers are partitioning a single energy implant step into multiple implants with a range of energies with the intent of retaining the required junction depth (*Xj*) and forming a more box-like profile with a lower peak as-implanted dopant concentration. We studied a range of damage engineering knobs to provide control over the damage engineering characteristics of each individual implant. We also studied the impact of controlling order of implants and the queue time between implant steps within a multi-energy implant sequence and their impact to the final damage and concentration profile results. To study this behavior, we invented a method allowing rapid switching between implants of the same species at different energies at a controlled time on the order of seconds to implant entire multi-energy sequences without removing the substrate from the platen. This study reveals that both selection of sequence order and control of the queue time between implant steps influences the results of the entire process with implant order being the stronger effect.

Introduction

When an ion strikes a silicon wafer, and the ion loses its energy through a combination of electronic and nuclear stopping methods. When the energy transferred from the ion to a silicon atom exceeding the displacement energy of approximately 15 eV, the silicon atom will be knocked off its lattice site forming a vacancy and interstitial pair [1]. The damage accumulated over the implant is always a competition between the dynamic accumulation of damage and the rate of vacancy and interstitial recombination [2]. The presence of dopant or silicon interstitials from previous implantation is known to produce de-channeling of subsequent implants [3], this phenomenon is true both for cases when the first implant amorphizes the silicon and when it does not.

Several advanced logic device manufacturers have been exploring partitioning processes from a single energy implant into multiple steps of differing energy to deliver a flatter dopant concentration profile. To match the device performance for a multiple-implant sequence it is critical first to be able to match the damage characteristics of each of the steps and then to understand and control the interactions between steps. This study explores the knobs which may be used to tune the damage accumulated within each implant of a multiple-implant sequence and then explores the potential to influence the final results of a multiple-implant sequence by control of the order of the steps and the queue time between steps.

The first order damage properties are defined by the combination of species, dose, energy, and angle. Under this oversimplification all vacancy/interstitial recombination occurs within the first few picoseconds after implantation so the probability of interaction between damage cascades is negligible however a broad range of second order parameters have been shown to impact the accumulated damage. As the semiconductor industry transitioned from multi-wafer to single-wafer ion implantation equipment it was found that the duty-cycle of beam-on-wafer versus beam-off-wafer time could impact the damage characteristics of the implant [4]. This study extends this observation to test for differences in

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damage properties at the end of multi-implant sequences by control of the queue time between each of the implant steps.

Theoretical

An accepted model for defect generation, accumulation and vacancy/interstitial recombination of ion implanted silicon is well described by Tian et al. [3] The point defects generated by a single cascade are proportional to the ratio of the deposited energy to the displacement energy of the silicon atoms in the lattice. Some proportion of these point defects survive recombination within a single recoil cascade. Subsequent ion trajectories in the solid are altered by collisions with a defect with a probability proportional to the ratio $(\gamma \frac{N}{N_a})$ where gamma is a proportionality constant, N is the local defect density and N_a is the critical defect density for amorphization [3]. In the case of a boron or carbon implantation specie the critical dose for amorphization can be substantial so the final dopant concentration profile will be sensitive to the instantaneous $\frac{N}{N_a}$ ratio throughout the implant.

We hypothesize that implant parameters such as fast scan frequency and slow scan speed adjust the pulse duration within which a unit area of the substrate sees ion flux near the peak current density. Increasing the pulse duration increases the proportion of the dose implanted while the instantaneous defect density is highest producing the most dechanneling and shallowest implant profiles. Since this hypothesis implicitly presumes that the timescale for vacancy/interstitial recombination extends beyond the local "melt" picosecond timescale it is also hypothesized that the local defect density will be sensitive to relatively small variation in the substrate temperature as higher temperature will increase the mobility of defects increasing the recombination probability. The final hypothesis is that in the case of a sequence of multiple implants the highest total damage accumulation and most abrupt concentration profiles will be achieved by building the sequence from lowest energy to highest energy and by minimizing the queue-time between processing steps to minimize the time for vacancy/interstitial recombination.

Apparatus and background

All experimentation was executed on an Axcelis Purion Dragon high current ion implanter. This tool offered beam current up to 70 mA with angle control capabilities on par to those previously described on medium current ion implanters [5] and offers a wide range of knobs for adjusting damage characteristics. The machine was fitted with an optional kit providing control of the platen temperature from 10 to 30 °C. Additional prototype software was developed to leverage the reproducibility of the beamline optics to switch between recipes of different energy within a single species in less than 10 s to enable queue time experiments.

In previous characterization of a Low Temperature Implantation (LTI) system, lower implant temperature for a BF_2^+ 30 keV process has shown to produce a deeper amorphous layer thickness (ALT) as analyzed by secondary ion mass spectroscopy (SIMS) of fluorine clustering at the end of range (EOR) damage after 900 °C anneal. The analysis of the change in secondary peak concentration reveals that the velocity of the beam's motion relative to the beam can modify the characteristics of the implant damage. The sensitivity of the secondary peak concentration to a change of 1 °C is approximately twice the sensitivity to scanning frequency of 1 Hz (Fig. 1a, b). Due to challenges in applying scanning frequency adjustment in manufacturing, this study has focused on adjusting the relative velocity of the beam to the wafer in the vertical as opposed to horizontal direction.

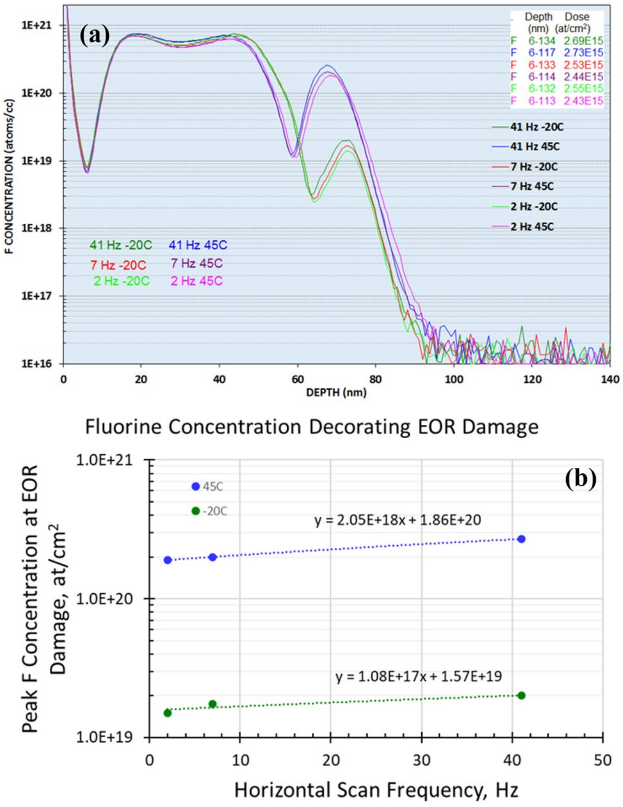

Fig. 1 **a** SIMS for fluorine after BF_2^+ 30 keV after 900 °C anneal as a function of implant temperature and horizontal scanning frequency. **b** Linear fits of secondary fluorine peak concentration to horizontal scan frequency by platen temperature

Experiment and results

The first screening experiment tested the impacts of implant temperature, beam current and vertical scan speed for carbon implants at 12 keV with doses of $5 \times 10^{14}\mathrm{at/cm^2}$ and $2 \times 10^{15}\mathrm{at/cm^2}$ into crystalline silicon on damage as monitored by a Therma-Probe 680XP tool for the purpose of selection of which splits should be analyzed via SIMS. Temperature varied from 12.5 to 27.5 °C, beam current varied over a range from 20 to 100% of the maximum available by energy. Vertical speed varied from ~ 15 to ~ 45 cm/s with the number of passes adjusted accordingly to maintain constant dose. Dose and angle splits were included for references.

The ThermaWave results demonstrated that the platen temperature is generally the strongest effect. Among the remaining parameters, dose has the strongest effect. Beam current and vertical scan speed have similar sensitivities and angle is a negligible factor. The sensitivity to temperatures varied over a 15 °C range shows that small temperature difference has meaningful impact to the rate of vacancy and interstitial recombination between pulses of the beam. The increased vertical scan speed breaks the implanted dose into more vertical pulses of shorter duration so fewer defects are generated within each pulse and there is more time for vacancy/interstitial recombination between pulses. Although most ion implanters use ThermaWave to calibrate the ion beam incidence angle [6,7] these documented procedures use substantially higher energy to maximize the ThermaWave sensitivity to angle. In this lower energy study very little ThermaWave sensitivity to ion beam incidence angle is observed.

When the beam current increases there are two potential factors which may increase the ThermaWave. The increased density of positive charge may cause more blow-up of the beam resulting in higher angle distribution. At higher beam current the mean time for vacancy-interstitial recombination before potential for damage cascade interaction is reduced. In this screening test the presence of ThermaWave sensitivity to beam current on approximately the same scale as vertical scan speed and the lack of angle sensitivity implies that the observed beam current effect is not an angle or angle distribution effect.

In production, dose is generally not a viable knob for matching damage characteristics because of its first order effects on electrical characteristics. Beam current is also not a preferred method for adjusting damage effects because beam current directly impacts the throughput of the process. Selection of implantation temperature and the nominal vertical scan speed do not have similar negative effects and are thus preferable knobs for adjusting the implantation damage, so these two parameters were selected for channeled SIMS comparison with a $\mathrm{C^{+}12keV1} \times 10^{15}\mathrm{at/cm^2}$ process implanted at 0° tilt angle into crystalline silicon. Like the observations in ThermaWave of a larger effect from temperature and smaller but measurable effect from vertical scan speed the SIMS in (Fig. 2a, b) shows only a very slight increase in the concentration in the channeled tail from increasing the vertical scan speed with a more significant increase in the channeled tail concentration from increasing the implant temperature.

Given the stronger sensitivities of ThermaWave and SIMS to platen temperature than to beam current, scanning frequency or scanning velocity we propose that for damage matching or optimization of an individual step the primary knob should be adjustment of the platen temperature to increase or decrease the vacancy/interstitial recombination rate to achieve the target final damage.

The damage, and therefor dopant concentration profiles, can be matched for each individual implant by use

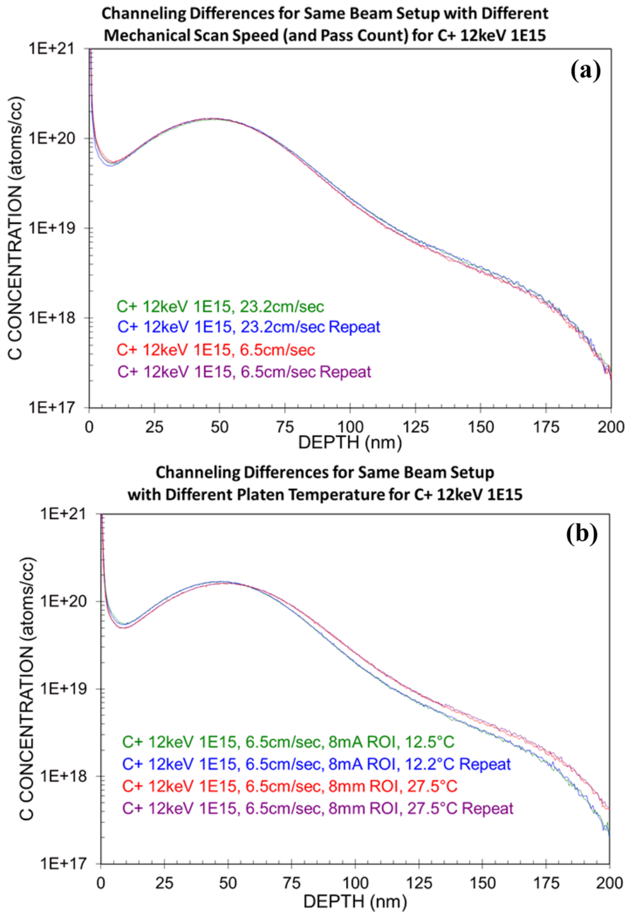

Fig. 2 **a** Small difference in the SIMS tail for $\mathrm{C^{+}12keV1} \times 10^{15}\mathrm{at/cm^2}$ by varying the vertical wafer scanning velocity. **b** Larger difference in the SIMS tail for the same beam conditions by varying the implant temperature

of temperature so to further understand the considerations required to match the process results of a multiple-implant sequence into a single structure a second study was designed to evaluate sequencing and queue times within such a sequence. First a sequence of three boron recipes, each at $5 \times 10^{13}\,\mathrm{at/cm^2}$ with energies at 5 keV, 15 keV and 25 keV were implanted with controlled queue time between each of the implants ranging from 15 min to several days; this test is referred to as the Normal Queue Time test. This experiment was extended by developing software to rapidly change recipes with the wafer on the platen to test queue times between each energy on the order of seconds; this test is referred to as the Rapid Recipe Switch test. The average ThermaWave value from the Rapid Recipe Switch test was predicted within 0.3% by the regression equation fitting the ThermaWave to the log of queue time calculated from the Normal Queue Time test (Fig. 3).

A third test was executed to understand the effects of queue time between implants compared to order of energies implanted within a multi-energy sequence. In this experiment the following conditions were implanted into crystalline silicon to compare the ThermaWave sensitivity to the order of the implants and the amount of time allowed to pass for vacancy-interstitial recombination between implants:

$$\mathrm{B^{+}800\,eV\,2\times10^{15}\,at/cm^{2}0^{\circ}Tilt}$$

$$\mathrm{B^{+}700\,eV\,1\times10^{15}\,at/cm^{2}0^{\circ}Tilt}$$

$$\mathrm{B^{+}600\,eV\,1\times10^{15}\,at/cm^{2}0^{\circ}Tilt}$$

The ThermaWave is sensitive to both the queue time and the implant order factors as illustrated in Fig. 4a. The order of the implant sequence is the stronger factor. There is only weak interaction between the two factors with the ThermaWave sensitivity to queue time only marginally higher when the recipes are implanted from highest to lowest energies as illustrated in Fig. 4b.

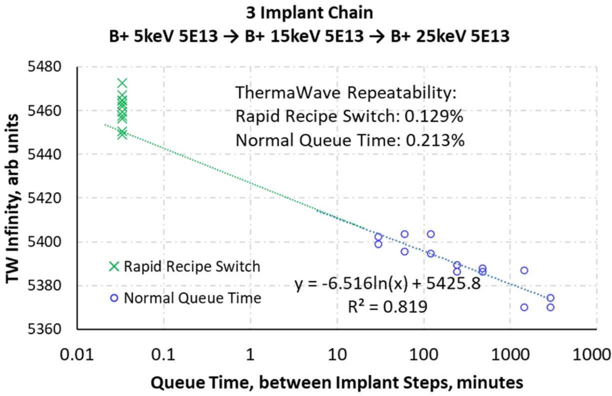

Fig. 3 ThermaWave with Rapid Recipe Switching is well predicted by extrapolation of the relationship between ThemaWave and Queue time from the Normal Queue Time test

The differences observed in the $\mathrm{B^{+}}$ 600 eV to 800 eV implant sequences are not limited to ThermaWave sensitivities. Figure 4c shows a noticeable effect of the order of implants is also observed in the shape of the boron concentration profile near the peak concentration. When the process is executed in the order of highest energy to lowest energy the as-implanted Transmission Electron Microscopy (TEM) appears to show two damage peaks with one at about 15 Å and the other at about 50-60 Å and the annealed SIMS shows boron clustering near these damage locations. When the sequence is implanted in the order of lowest to highest the TEM lacks as clearly defined bands of damage and the annealed SIMS has a smooth concentration profile. This effect is believed to be due to the interaction between the implant steps. The substrate has a perfect crystal lattice when the first implant begins, and the damage accumulation peaks start to develop at the surface and at the projected range (*Rp*) [2]. When each subsequent energy is implanted there is residual damage in the silicon from the previous steps so each of these implants has more nuclear collisions at shallower depth resulting in more build-up of damage close to the surface. If the first implant is the lowest energy, then the higher energy implants accumulate damage closer to the first implant's damage profile smoothing out the final profile. If the first implant is the highest energy its damage profile will be as deep as if it was a single implant process, and the lower energy processes will be dechanneled by the residual damage resulting in larger separation between the damage peaks left at the end of the process. Given this sensitivity, even for ultra-shallow implant sequences (< 1 keV), the selection of implant order can be used to tailor the annealed concentration profile and thus must be considered for device optimization.

Conclusions

There are many factors which can tune the damage accumulation within a single implant. The most effective damage engineering knobs with the smallest negative impacts are the platen temperature which may be rapidly adjusted over the range of up to 20 °C and the vertical scan velocity which may be trivially selected when setting up a recipe. The recipe control of the platen temperature should be the preferred method of damage tuning. When multiple implant processes are present in a single mask layer without an intervening thermal process, the total damage and therefore the final dopant profile will be sensitive to both the order of the implants and the queue time between each of the implant step. The selection of implant order has

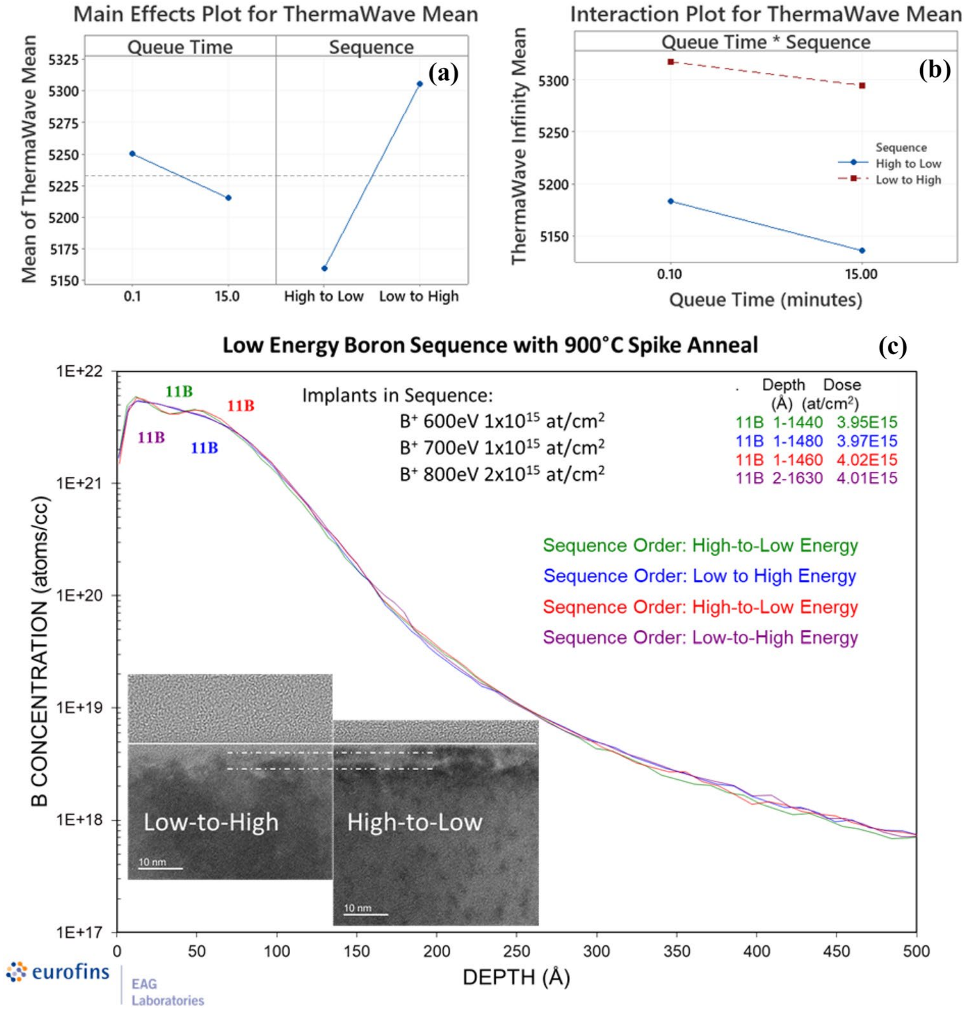

Fig. 4 **a** ThermaWave is sensitive to both implant order and time between implants. **b** Only weak interaction between queue time and implant order observed in ThermaWave. **c** Difference in boron clustering at damage peaks after anneal from difference in implant order

measurable effects on the dopant concentration profile even when all energies in the sequence are < 1 keV.

The degree to which queue time between implants will impact the result will depend on the ratio of the defect density to the defect density necessary for amorphization. The defects in silicon where the lattice has been amorphized will be more stable, recombining more slowly, and there for the final process will be less sensitive to the queue time between steps. For processes where the defect density is slightly below the density necessary for amorphization after one or more of the steps the final dopant profile sensitivity to the queue time will be maximized because of the higher rate of vacancy and interstitial recombination than at higher doses and the higher proportion of interstitials present for collisions resulting in dechanneling than at lower doses.

Data availability All datasets generated and/or analyzed during the current study are available from the corresponding authors upon reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Further reading about thermawave The ThermaWave referenced throughout this work refers to the measurement made by the KLA Thema-Probe 680XP. The Thema-Probe is standard modulated optical reflectance tool for monitoring of damage accumulated during an ion implantation process. A good reference for how Thema-Probe machines work by Pearce et al. [8] is referenced for further reading. A nice study of various ThermaWave sensitivities to factors such as dose and energy is also discussed by by Kamenitsa [9].

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