SYMPOSIUM B

Si Front-End Processing–Physics and Technology of Dopant-Defect Interactions II

April 24 – 27, 2000

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* Invited paper

SESSION B1: THE CHALLENGES OF DEVICE SCALING
Chairs: Aditya Agarwal and Hong-Ha Vuong
Monday Morning, April 24, 2000
Salon 3/4 (Marriott)

8:30 AM *B1.1
DOPING REQUIREMENTS OF CMOS NEAR THE LIMITS OF SCALING. Yuan Taur, IBM, T.J. Watson Research Center, Yorktown Heights, NY.

As CMOS channel length is rapidly approaching 0.1 um in manufacturing, this talk focuses on the doping requirements for further scaling and performance gains beyond 0.1 um. A key device challenge is that, while the chip power and reliability issues are driving down the power supply voltage, off-state leakage and dynamic circuit considerations bound the minimum threshold voltage to 0.2 V. To achieve the highest performance gains possible below 0.1 um, an optimized, vertically and laterally non uniform doping profile (SUPER-HALO) is needed to offset the short-channel effect. Another key element is making more abrupt lateral source-drain doping profiles as the channel length is scaled down. Both of these requirements dictate absolutely minimum thermal cycles after low-energy implants. Ultimate control of dopant profiles, especially boron for both the nFET halo and the pFET source-drain, is essential for extending CMOS scaling limits to 25 nm.

9:00 AM *B1.2
JUNCTIONS FOR DEEP SUB-100 NM MOS: HOW FAR WILL ION IMPLANTATION TAKE US? H.-J. Gossmann, Lucent Technologies, Bell Labs, Murray Hill, NJ.

Producing the junctions for transistors with sub-100 nm gatelengths is a significant challenge. For many reasons, such as uniformity, reproducibility, and cleanliness, ion implantation is presently the method of choice for the formation of the source/drain (SD) junctions and the channel. On the other hand, ion implantation does create defects, giving rise to a host of undesirable effects, such as dopant clustering and transient enhanced diffusion. A clear-cut path to a solution that satisfies all constraints is by no means obvious.
In this talk I will analyze the requirements that the International Technology Roadmap for Semiconductors (ITRS) implicitly imposes on the two-dimensional SD dopant profile and translate the results into implant parameters (energy, dose, peak concentration). I will discuss junction depths and the penalty that too deep a junction extracts in terms of achievable gate-length. I will then determine the voltage drop that the SD current develops across the three main (exclusive of the channel) resistive components in the current path: the metal-semiconductor contact; the spreading resistance in the extension region; and the resistance in the link-up region where the SD-region meets the channel. The largest resistance occurs in the link-up region, followed by the resistance of the contact; the extension contribution is the smallest. The extension resistance requirement can be satisfied by ion-implantation for all generations of the ITRS; however, the link-up region requires very abrupt profiles, not demonstrated so far by ion-implantation. The contact eventually necessitates dopant concentrations in excess of solid solubility and for NMOS in excess of the fundamental limit of dopant activation.

SESSION B2: 2D DOPANT CHARACTERIZATION
Chairs: Hong-Ha Vuong and Aditya Agarwal
Monday Morning, April 24, 2000
Salon 3/4 (Marriott)

10:00 AM *B2.1
2D DOPANT AND JUNCTION PROFILING BY SCANNING CAPACITANCE MICROSCOPY. Rafael Kleiman, Lucent Technologies, Bell Labs, Murray Hill, NJ.

Scanning Capacitance Microscopy (SCM) is a powerful technique for characterizing the 2-dimensional properties of fabricated Silicon devices. In its typical application a device is cross-sectioned using conventional techniques leaving a passivating SiO_2 layer. The local C-V characteristics are measured between a very sharp metal or semiconductor probe tip and the semiconductor substrate. A very sensitive high-Q and high frequency capacitance detector is used to measure the small changes in capacitance. For uniformly-doped regions, the C-V characteristics can be used in a straightforward manner to determine the dopant concentration. For regions with rapidly changing dopant concentration, or a change in dopant type as commonly occurs across a device junction, the SCM signature is dramatic. The C-V signal then is dominated by the electrostatics of the junction region in the presence of the perturbation imposed by the potential of the probe tip. Proper quantification requires consideration of the both the 3d Poisson equation and the relevant semiconductor physics. We have developed a simple method for determining the junction position using SCM. Based on this method, SCM can be used to directly determine junction depths and channel lengths in MOSFETs. Determination of the dopant profile in a junction region requires more extensive calculation, and preferably begins with an expected profile from a process model. Due to the perturbing influence of the tip, the question of intrinsic spatial resolution possible with SCM is subtle. Our simulations show that for SIA roadmap scaled devices, SCM always has sufficient spatial resolution to resolve the channel, if the probe tip is sufficiently small. We present a number of illustrative applications of SCM imaging; to conventional MOSFETs in a top down geometry, to aggressively scaled (<60nm) CMOS transistors, and to the newly invented Vertical Replacement-Gate MOSFET.

10:30 AM *B2.2
SSRM AND SCM OBSERVATION OF ENHANCED LATERAL As-DIFFUSION INDUCED BY NITRIDE SPACERS. P. Eyben, N. Duhayon, T. Clarysse, I. De Wolf, G. Badenes and W. Vandervorst, IMEC, Leuven, BELGIUM.

State-of-the-art semiconductor devices require an accurate control of the complete two-dimensional dopant distribution. The routine use of process simulators to predict the envisaged distributions and their resulting accuracy, is strongly linked to the phyiscal models contained in these programs a well as their calibration. Whereas SIMS and SRP have been used extensively for the calibration of 1D-profiles, calibration of 2D-profiles has been very limited. In this work we report on detailed characterization of LDD-profiles for various processing conditions, the role of the nitride spacer used in those experiments and the correlation with simulations. A series of transistors with different nitride spacers (140 vs 200 nm) and different lightly doped source/drain (LDD) have been studied. LDD implant doses varied between 5e13- 5e15 /cm^2 and implant energies between 10, 25 and 40 keV coupled with short time anneals. Two-dimensional carrier profiles have been obtained using Scanning Spreading Resistance Microscopy and Scanning Capacitance Microscopy and predicted using TSUPREM4. Profiles taken with SSRM in large areas (i.e. 1D-profiles) are in complete quantitative agreement with TSUPREM4 process simulations and SRP measurements, whereas the channel profile extracted from the transistor structures reflect the enhanced B-diffusion towards the surface due to the point defect interactions. The lateral LDD profiles and in particular the LDD underdiffusion however, appears to be strongly dependent on the nitride spacer thickness. In fact the experimental effective channel lengths are significantly smaller ($\sim$50 nm) for a thick spacer as compared to the thinner spacers. Such a strong enhanced diffusion can not be related to the small increased thermal budget for the thicker nitride layers as indicated by SUPREM simulations but must, most likely, be correlated with a stress enhanced diffusion of the As under the spacer region. Correlations with Micro-Raman stress measurements will be presented to validate this observation.

11:00 AM *B2.3
DETERMINATION OF PROCESS INDUCED DOPANT RE-DISTRIBUTIONS BY ELECTRON HOLOGRAPHY. A. Orchowski, W.-D. Rau, H. Rücker, P. Schwander, and A. Ourmazd, Institute for Semiconductor Physics (IHP), Frankfurt (Oder), GERMANY.

We show how lateral point defect mediated diffusion can be investigated with nanometer spatial resolution by electron holography in TEM. Using specially designed boron marker layer experiments, we have determined the effect of typical processing steps, such as implants, on lateral boron profile broadening near implant mask edges. From these experiments, the influence of the wafer surface as a sink for point defects can be revealed on a microscopic scale. By matching our results with process simulation, we extract an upper limit of 0.2 μm for the surface recombination length at 950°C, in agreement with published data based on SIMS measurements [1]. We have shown previously, that electron holography can be used to map the two-dimensional electrostatic potential, and hence the 2D dopant distribution in sub-micron MOS transistors [2]. The electrostatic potential maps are deduced from the phase of the electron wave measured by electron holography. From the same holograms, amplitude images corresponding to conventional TEM micrographs can be obtained. This allows an exact correlation of the dopant profile with high resolution geometrical data, such as distances to the surface or other transistor features. Here we exploit this capability by investigating the broadening of steep boron marker layers located several nm below the wafer surface. We have measured the lateral decay length of the broadening near implant mask edges after RTA and determined the surface recombination length of point defects by matching with process simulation. Moreover, from measurements with boron markers layers embedded in SiGe base profiles of heterojunction bipolar transistors, key process margins such as minimum distances of contact implants from active transistor regions can be directly derived [3].

[1] D.R. Kim, C.S. Rafferty and F.P. Klemens, Appl. Phys. Lett. 67, 2302 (1995)
[2] W.-D. Rau et al., Phys. Rev. Lett. 82, 2614 (1999)
[3] B. Heinemann et al., Proc. ESSDERC'97, 544 (1997)

11:30 AM B2.4
INCREASING THE LATERAL RESOLUTION OF SCANNING SPREADING RESISTANCE MICROSCOPY. R. Joe Kline, Phillip E. Russell, NC State Univ, Dept. of Mat. Sci. and Eng., Raleigh, NC; John F. Richards, Intel Corp, Santa Clara, CA.

The miniaturization of semiconductor devices is approaching the limits of present analytical techniques. Two-dimensional dopant profiling has been identified by the NTRS roadmap as an area key to the further development of future process generations. Present two-dimensional dopant profiling techniques do not reach the required lateral resolution of 2nm with a dopant accuracy of 4% for the 130nm technology. In this work, Scanning Spreading Resistance Microscopy (SSRM) is investigated as a possible technique to obtain the required resolution.
The present resolution and accuracy limiter of SSRM is the probe sample contact. Current SSRM probes are CVD diamond coated atomic force microscope probes having as-deposited probe tip radii on the order of 50-100nm. Facets on the end crystallites reduce the contact radius to the order of 5-20nm. Our data indicates that the facets are often unstable during the high loads used in SSRM and the resulting plastic deformation changes the contact area during scanning. The changing contact area alters the relationship between the measured spreading resistance and the resistivity of the underlying silicon, making accurate quantification impossible. The modified contact area also decreases the electrical resolution of the measurement.
Chemically enhanced focused ion beam (FIB) micromachining has been used in the past to sharpen diamond probes for nanoindentation. We have implemented FIB machining of diamond SSRM probes to obtain the desired end probe radius to increase lateral resolution. We are also investigating the degradation in electrical signal which occurs while scanning, and the resulting limitations imposed on the accuracy and repeatability of SSRM measurements. The sequence of measurement degradation has been experimentally observed in measured profiles. High resolution scanning electron microscopy characterization of SSRM probes, before and after the observed electrical degradation appears, reveals no apparent physical changes in the probe.

11:45 AM B2.5
APPLICATIONS OF AFM/SCM IN IMAGING IMPLANT STRUCTURES OF SEMICONDUCTOR DEVICES. Kuo-Jen Chao, Jeffrey R. Kingsley, Robert J. Plano, Xing Lu and Ian Ward, Charles Evans & Associates, Sunnyvale, CA.

Scanning capacitance microscopy (SCM) has been widely used to investigate the two-dimensional carrier profile of semiconductor devices. In this work, SCM was applied in failure analyses. Several different cases were studied. First, one commercially purchased integrated circuit (IC) device was cross-sectioned and polished for the SCM investigation. Implant structures near the gate were clearly resolved. Second, a failed p-channel device was investigated. In the designed p+ region, two different implant concentration regions were found. Third, two semiconductor devices, one good and the other failed, were prepared by cross-sectioning, followed by polishing. Implant profiles of similar structures on both devices were imaged. As compared with the good device, the thickness of the N-well structure was found to be thinner by about 0.4μm for the failed device. Fourth, a GaAs device with Zn thermally diffused through the Si_3N_4 mask was studied. The lateral diffusion length of Zn was determined. Applications in other cases will also be presented at the conference.

SESSION B3: SILICON FRONT-END PROCESSING
Chairs: Hans-Joachim L. Gossmann and Mark E. Law
Monday Afternoon, April 24, 2000
Salon 3/4 (Marriott)

1:30 PM *B3.1
SHALLOW JUNCTION FORMATION AND GATE ACTIVATION IN DEEP-SUBMICRON CMOS. Peter A. Stolk, Philips Research Laboratories, Eindhoven, THE NETHERLANDS.

The semiconductor industry is characterized by an incessant drive for ever smaller electronic devices and circuits. The scaling of CMOS generations to 0.1 um and beyond requires ultimate control of the junctions in the source/drain regions of transistors. Although the international technology roadmap for semiconductors is often used as a reference for research on shallow junctions, the final criterion by which to judge doping strategies lies in the electrical device performance. In this paper, I will discuss shallow junction formation and gate activation in relation to the performance of deep-submicron MOSFETs.
As a first exploration, device simulations were used to investigate how junction profiles affect device performance in terms of the off-state leakage and on-state drive currents. Various approaches to achieving ultrashallow, low-resistance junctions through low-energy As and B implantation were studied, including Ge pre amorphization implants and spike annealing. Experiments using doping marker superlattices were performed to identify the critical physical effects underlying dopant activation and diffusion. In addition, the effect of thin screening oxides on shallow junction formation was studied. The optimized shallow junctions were integrated into a CMOS processing flow, featuring gate lengths down to 50 nm. 2D profiling techniques and electrical measurements were used to characterize the junctions. The implantation and annealing steps for junction formation can also be used to activate the polycrystalline transistor gates. Using electrical measurements, we have investigated how the grain morphology influences the doping efficiency of the gate. In addition, the kinetics of dopant de-activation during further thermal processing have been measured. The simultaneous optimization of junction and gate doping conditions have led to a significant improvement in device performance.

2:00 PM B3.2
THE APPLICATION OF SOLID SOURCE DIFFUSION IN A NOVEL, HIGH-PERFORMANCE 50-NM VERTICAL MOSFET WITH SELF-ALIGNED SOURCE AND DRAIN. Sang-Hyun Oh, J.M. Hergenrother, D. Monroe, T. Nigam, F.P. Klemens, A. Kornblit, G.R. Weber, W.M. Mansfield, C.A. King, R.N. Kleiman, H-H. Vuong, H.J. Gossmann and C.S. Rafferty, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

To continuously shrink MOSFET channel lengths, very shallow source-drain extension (SDEs) with high active dopant concentrations are required to maintain high drive currents and sufficient resistance to short-channel effects. Solid source diffusion (SSD) has emerged as an alternative method to ion implantation for forming ultrashallow junctions with low sheet resistances. SSD avoids the difficulties associated with implant channeling and transient enhanced diffusion, and it has been used successfully by several groups to form self-aligned SDEs in otherwise conventional planar MOSFETs. In this paper, we discuss the first use of SSD to form shallow, self-aligned SDEs in a high-performance vertical MOSFET. This novel device is known as the Vertical Replacement-Gate (VRG) MOSFET. This is the only MOSFET ever built that combines 1) a gate length controlled precisely through a deposited film thickness, independently of lithography and etch, and 2) a high-quality gate oxide grown on a single-crystal Si channel. The use of SSD in this novel geometry allows us to transform the precise gate length control afforded by the VRG process into precise, lithography-independent channel length control. In the VRG-nMOS process, silicon nitride offset spacers separate the phosphosilicate glass (PSG) SSD dopant sources from the polysilicon gate. These offset spacers, whose critical dimensions are also controlled by film thicknesses, allow us to precisely tune the gate-source and gate-drain overlaps in order to optimize the capacitance/series resistance tradeoff. These parasitic overlap capacitances have precluded the high-frequency operation of many previous vertical MOSFETs. In this paper, we will discuss the SIMS and sheet resistance characterization of shallow phosphorus junctions formed in one-dimensional SSD experiments. We will also discuss the scanning capacitance characterization of two-dimensional doping profiles of VRG-nMOSFETs with gate lengths down to 50 nm.

2:15 PM B3.3
ACTIVATION OF IMPLANTED POLY GATES BY SHORT CYCLE TIME ANNEALING. A.T. Fiory, Bell Laboratories, Lucent Technologies, Inc., Murray Hill, NJ; K.K. Bourdelle, Bell Laboratories, Lucent Technologies, Inc., Orlando, FL.

Poly-silicon gate films for use near the 160 nm CMOS technology node were prepared by ion implantation of B, P, and As into amorphous silicon layers and activated by rapid thermal annealing. Gate oxides were grown by furnace oxidation of epitaxial p- on p+ device quality and bulk type wafers. Nominally amorphous undoped silicon gate material was deposited in a furnace for chemical vapor deposition. Annealing cycle times and temperatures were varied and include spike anneal methods that aim for minimum dwell time at the maximum temperatures. Electrical activation was measured by Hall van der Pauw methods for the poly electrode and capacitance-voltage measurements of poly capacitors. Flat-band voltage shifts were used to determine boron diffusion through the gate oxide. Temperature-time relationships are used to compute effective activation energies.

2:30 PM B3.4
EFFECT OF N+ ION IMPLANTATION AND GOX PROCESS ON In AND B CHANNEL PROFILE. G. Curello, R. Rengarajan, J. Faul,

H. Wurzer, J. Amon, M. Schmeide, D. Henke, T. Gaertner, W. Kegel, Infineon Technologies, Memory Products, Technology Development, Dresden, GERMANY.

The use of retrograde channel profiles (RCP) for limiting short channel effect (SCE) in sub quarter micron CMOS technologies is being widely investigated. In addition, lower thermal budget Dual Gox processes employing selective N+ Ion Implantation are also being developed in order to integrate high performance CMOS in eDRAM technologies. In this work we report on the effect of different Gox processes, Well rapid thermal anneal and N+ Ion Implantation on the diffusion / segregation behavior of B and In in the channel of CMOS devices in 0.17um eDRAM technology. Particularly, it will be shown how the N+ dose required to obtain a certain Dual Gox thickness varies with the Gox process used and how the N+ dose affects the In and the B profile due to interstitials injection occurring during N+ implant. The impact of these thickness equivalent Dual Gox processes on SCE and carrier mobility is analysed and guidelines for optimization of device performances will be indicated.

3:15 PM B3.5
DOPANT DIFFUSION IN SILICON SUBSTRATE DURING OXYNITRIDE PROCESS. Nobutoshi Aoki, Toshitake Yaegashi, Yuji Takeuchi, Makoto Fujiwara, Naoki Kusunoki, Tsutomu Sato, Ichiro Mizushima, Yoshitaka Tsunashima, Hiroaki Hazama, Seiichi Aritome and Riichiro Shirota, Microelectronics Engineering Laboratory, Toshiba Corporation, Yokohama, JAPAN; Takashi Shimizu, Manufacturing Engineering Center, Toshiba Corporation, Yokohama, JAPAN.

Oxynitride (SiON) film is indispensable for MOSFET gate insulator, because it blocks dopant penetration from gate to Si substrate. Besides, for the first time, we found an anomalous behavior in dopant diffusion in Si substrate during oxynitride process.In the present paper, the diffusion phenomena and its mechanism are described. B diffusion in Si during NO and N_2O oxynitride process was investigated. Oxynitride films were grown in NO or N_2O ambient on Si wafers. SIMS measurements showed a notable B diffusion during the oxynitride process. Since the growth of oxynitride film causes the oxidation enhanced diffusion (OED) of B in the Si substrate, it is necessary to consider the OED effect in the analysis of B diffusion. We found that the magnitude of the OED effect in the case of the oxynitride condition is larger than that in the corresponding dry O_2 oxidation. The B diffusion increases as N concentration in the oxynitride films increases. The mechanism of the enhanced diffusion was investigated by the observation of B diffusion in nitridation and oxidation processes, making use of NH_3 nitride and re-oxide procedures. Results indicate that largely enhanced diffusion occurs in the re-oxidation process, but not in the nitridation process. FTIR measurements reveal that the re-oxidation process creates a Si-N rich region near the SiON/Si interface. It is considered that the Si-N rich region suppresses the diffusion of interstitial Si from the interface into the SiON film, which leads to the increase of interstitial Si in the substrate and results in the enhanced B diffusion. Finally, the results of simulations for the MOSFETs fabricated under various conditions of oxynitride process are reported and discussed. The simulation results agree well with the experimental ones. The essential issue is the modeling of generation-recombination of interstitial Si at the SiON/Si interface.

3:30 PM B3.6
EFFECTS OF IMPLANTATION OF DECABORANE IONS IN Si. Marek Sosnowski, John M. Poate, Maria A. Albano and Vijay Babaram, New Jersey Institute of Technology, Newark, NJ; Dale C. Jacobson and Hans J. Gossmann, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; Aditya Agarwal, Eaton Corporation, Beverly, MA.

Ions generated by electron impact on decaborane vapor ($B_{10}H_{14}$) were accelerated to energies of 2 - 10 keV. Magnetically analyzed $B_{10}H_x^+$ ions were implanted in Si(100). This work contrasts previously reported experiments in which unanalyzed ions from decaborane were used[1]. The dose of ions measured by current integration was compared with B concentration measured by nuclear reaction analysis using the $^{11}B(p,\alpha)^8Be$ reaction at a proton energy of 650 keV. Samples of the same material were implanted to approximately the same area density of B atoms with B^+ ions of the kinetic energy close to the energy of the B atoms arriving in the decaborane ions. Comparison of the effects of B implantation with the two types of projectiles is presented. They include damage, amorphisation, sputtering, and diffusion. The properties of decaborane ion beams and the prospects of using them for shallow implantation of B into Si are discussed.
[1]A. Agarwal, H.J. Gossmann, D.C. Jacobson, D.J. Eaglesham, M. Sosnowski, J.M. Poate, I. Yamada, J. Matsuo, T.E. Haynes, *Appl.Phys.Letters* **75**, 2015 (1998).

3:45 PM B3.7
ULTRA-SHALLOW p^+/n JUNCTION FORMED BY PLASMA ION IMPLANTATION. S.K. Baek, C.J. Choi, T.-Y. Seong and H. Hwang, Department of Materials Science and Engineering, Kwangju Institute of Science and Technology, Puk-gu, Kwangju, KOREA.

The plasma ion implantation method is considered as a good candidate for achieving ultra-shallow junction profiles because of its ultra-low energy, high throughput and room temperature operation. By using plasma doping at the energy level of 100 eV, we expected negligible transient-enhanced diffusion due to the surface effect which behave as an efficient sink for the removal of point defects. In this study, we have investigated the characteristics of an ultra-shallow junction formed by plasma ion implantation as an alternative of an ion implantation process. Plasma-doping was performed using B_2H_6 (3%) gas diluted with H_2 gas. The wafers were placed in the plasma and a negative DC bias (-350 V) was applied to the substrate for 5 min. The flow rate of B_2H_6 was 5 sccm and pressure was 50 mTorr. For comparison, samples with ultra-low energy implantations of boron at 500eV were also investigated. After doping, rapid thermal annealing was performed in nitrogen ambient at 900°C, 950°C, and 1000°C for 10 s. Compared with ultra-low energy boron ion implantation at 500eV, junction depth and sheet resistance were significantly improved by plasma-doping. The junction depths of the plasma-doped samples were 15 nm and 33 nm after annealing for 10 s at 900°C and 950°C, respectively. In contrast, the junction depths of the low energy ion implanted samples were 28 nm and 55 nm after annealing for 10 s at 900°C and 1000°C, respectively. For the same junction depth, the sheet resistance of the B_2H_6 plasma-doped sample is an order of magnitude less than that of the 500 eV B ion implanted sample. Based on the XTEM analysis, we observed stacking faults after 900°C rapid thermal annealing. With increasing annealing temperature above 950°C, the stacking faults were completely removed and a significant reduction of sheet resistance was obtained. Although the implant damages are very close to the surface, the enhanced diffusion of boron was observed for plasma doped sample which can be explained by the boron enhanced diffusion (BED). In summary, by optimizing plasma-doping and rapid thermal annealing, the high quality p^+/n junction as shallow as 33 nm can be obtained.

4:00 PM B3.8
CRYO-IMPLANTATION TECHNOLOGY FOR CONTROLLING DEFECTS AND IMPURITY OUTDIFFUSION. Atsushi Murakoshi, Kyoichi Suguro, Masao Iwase, Mitsuhiro Tomita and Katsuya Okumura, Process Eng. Lab., Microelectronics Eng. Lab., Semiconductor Company, Toshiba Corporation, Yokohama, JAPAN.

Shallow junction technology is becoming increasingly important for high performance transistors with 0.1-0-15 micron in gate length. With shrinkage of junction depth, acceleration energy of ion implantation decreases and annealing temperature should be lower in order to avoid impurity diffusion. On the other hand, it becomes difficult to recover the defects caused by heavy dose ion implantation. Therefore, the annihilation of defects by annealing with small thermal budget is a key issue for 0.1-0.15 micron regime. In this paper, we propose a novel process module by using cryo-implantation and RTA. Boron ions were implanted into a (100)Si substrate temperature cooled by using liquid nitrogen. The substrate temperature was controlled to be -160° Centigrade during ion implantation. Typical dose and acceleration energy were 1E13-15cm-2 and 3-10keV, respectively. The maximum beam power was controlled to be 20W or below. It was found that an amorphous layer was formed by boron implantation and the damaged layer was completely recovered to a single crystal after annealing at 900°C for 30 sec. No dislocation was observed in the implanted layer by TEM. It was also found that the thermal diffusion of boron was suppressed by cryo-implantation. Pn junction depth was found to be about 10-20% shallower than that of room temperature implantation. This result suggests that suppressing vacancy migration toward the surface during implantation is effective in reducing transient enhanced diffusion of boron. Cryo-implantation was found to be very effective in reducing defects and PN junction leakage was successfully reduced by one order of magnitude as compared with room temperature implantation.

4:15 PM B3.9
POST-OXIDATION ENHANCED DIFFUSION OF LOW-ENERGY IMPLANTED BORON IN ULTRA-SHALLOW P^+/N JUNCTIONS FORMATION. Damien Lenoble, Aomar Halimaoui, Andre Grouillet, France Telecom-CNET, Grenoble, FRANCE.

It is well established that future CMOS technology will require ultra-shallow junctions at Source/Drain extensions. Due to the anomalous high diffusivity of implanted boron in silicon, this challenging objective is particularly difficult to achieve for pMOSFET's. In microelectronics technology, the growth of sacrificial oxide (sacox) prior to implantation is a commonly used process which prevents the contamination of silicon substrate. Here, we report for

the first time the effect of sacox on the boron diffusion in ultra-shallow P^+/N junctions. N-type silicon wafers were implanted at 3, 5 and 10 keV through various sacox thicknesses ranging from native oxide (≈0.8 nm) up to 4 nm, and then annealed at 1050°C for 10 s in an inert ambient (N_2). To investigate the influence of the sacox thickness, we performed SIMS profiling of boron in both as-implanted and annealed samples. It is clearly shown that the use of sacox enhances significantly the boron diffusivity, except for the 10 keV implants. For samples implanted at 5 keV and then annealed, the junctions depth (as measured by SIMS after oxide removal) is found to be 133 nm and 146 nm for native oxide and 4 nm-thick sacox, respectively. Thinner sacox (2.5 nm) does not significantly reduce the diffusion, (junction depth=145 nm). Extented data with thinner oxide (down to 1.5 nm) will detail the oxide thickness influence. Extracted diffusity enhancements of boron in silicon (from SIMS profiles) demonstrate that the sacox enhanced diffusion increases when the implant energy decreases. We emphasize that this Post-Oxidation Enhanced Diffusion (POED) of boron and the well known Oxidation Enhanced Diffusion (OED) are different phenomena. We believe that the overlapping of dopant profile (closer to the surface at low energy) and the residual intersticials injected at the Si/SiO_2 interface during previous thermal oxidation is at the origin of this phenomenon. This paper will point out the benefit to optimize the sacox formation process when using low-energy boron implants, and will detail the mechanisms of the POED.

4:30 PM B3.10
ANALYSIS AND SUPPRESSION OF PROCESS-INDUCED DEFECTS IN MEMORY DEVICES. R. Annunziata, R. Bottini, P. Colpani, C. Cremonesi, G. Ghidini, E. Gomiero, G. Pavia, F. Pio, M.L. Polignano, G. Servalli, ST Microelectronics, Brianza, ITALY.

Dopant decoration of process-induced defects is shown to be responsible for a failure mechanism of memory devices. From the electrical point-of-view, the defect-related failure consists in a source-to-drain resistive path formed by junction piping. This mechanism is made active by the very close spacing which is typical of present device structures. A device-like test structure was used for defect detection. This structure proved to be a very effective tool for studying the impact of various process steps on defect generation, in that it allowed statistical electrical data about the formation of these defects to be collected. TEM analyses were extensively used for studying the evolution of end-of-range defects during subsequent thermal treatments and for measuring the amorphous layer width under various implantation conditions. The role of high dose implantations in the generation of this sort of defects is discussed. Arsenic implantations in the dose range $5 \cdot 10^{14} - 5 \cdot 10^{15} cm^{-2}$ were considered. As expected, a suitable recristallization annealing decreases defect density. However, even if the amorphous layer is completely recovered, residual defects grow and become dopant-decorated during subsequent thermal treatments. Defect density is increased by oxidizing treatments. In this case point defect injection is active both in enhancing dopant diffusion and in growing defects. In addition, substrate-related nuclei play some role in the formation of such defects. Defect formation is suppressed if the amorphous layer is made very shallow by suitable choices of the screen oxide and of the implantation energy. A binary collision code was used to estimate the dependence on energy of the self-interstitial excess outside the amorphous region. The results of these calculations indicate that defect suppression can be tentatively explained by point defect annihilation at the silicon surface.

SESSION B4: ION IMPLANTATION AND SHALLOW JUNCTION TECHNOLOGY

Chairs: Masataka Kase and Tony E. Haynes
Tuesday Morning, April 25, 2000
Salon 3/4 (Marriott)

8:30 AM *B4.1
A HISTORICAL VIEW OF THE ROLE OF ION-IMPLANTATION DEFECTS IN PN JUNCTION FORMATION FOR DEVICES. Richard B. Fair, Duke University, Dept of Electrical and Computer Engineering, Durham, NC.

The early use of ion bombardment of semiconductors for forming doped regions was viewed as a room-temperature process. Many interesting but relatively useless devices were made by implanting species such as Na and Cs ions to form pn junctions from radiation damage or interstitial impurities. The revolutionary idea that one could implant Group III and V dopants into semiconductors and then heat the implanted semiconductor to above 800 C didn't appear until 10 years after Shockley's 1954 patent. And the idea was not well received by the solid state community. However, the key event that propelled ion implantation as an important technology was in adjusting the threshold voltage of enhancement and depletion mode MOSFETs in 1970. Once ion implanters became necessary in the factory, numerous applications proliferated. Ion implantation then became a predeposition technology, and interest in implantation damage disappeared. However, much interest developed around understanding point-defect-assisted thermal diffusion for pn junction formation. With the advent of rapid-thermal-annealing, the emphasis shifted back to ion implantation-induced defects to explain transient-enhanced diffusion (TED) effects when it was established in 1984 that implant-damage annealing caused TED. Today's challenges in forming ultra-shallow pn junctions by ion implantation are in controlling and reproducing the damage structures that dominate junction activation and diffusion. It appears that, in some sense, history has come full circle back to the present preoccupation with implantation damage.

9:00 AM B4.2
JUNCTION DEPTH REDUCTION THROUGH FLUORINE IMPLANTATION AND DIFFUSION IN SILICON. Nell Warnes[1], Kevin S. Jones[1], Dan F. Downey[2], Jinning Liu[2], Scott Falk[2], Mark E. Law[3]. [1]Swamp Center, Dept. of Materials Science and Engineering, University of Florida, Gainesville, FL, [2]Varian Semiconductor Equipment Associates, [3]Swamp Center, Dept. of Electrical Engineering, University of Florida, Gainesville, FL.

Ultra-shallow junction formation is one of many process challenges facing industry today. In order to facilitate this process, BF_2 implants are being used to form p+ source and lightly doped drain [LDD] junctions. It is important that the interaction of boron with fluorine be understood in order to optimize the use of fluorine. Previous studies have shown that F decreases B transient enhanced diffusion but it is unclear whether this is through interaction with the B or the excess Si interstitials. In this study, pre-amorphizing $^{29}Si+$ implants were performed at a dose of $1x10^{15}$ ions/cm^2 at 70keV on Czochralski substrates. B+ was then implanted at a dose of $1x10^{15}$ ions/cm^2 at 1.12keV into the preamorphized Si. Finally F+ has been implanted at a dose of $2x10^{15}$ ions/cm^2 at energies ranging from 2keV to 36 keV into the B implanted preamorphized layers. Si interstitials from the end of range damage enhanced the diffusion of the boron. SIMS analysis performed on these wafers indicate that the fluorine affects the diffusion of the boron through the silicon. As the energy of the F+ implants increases from 1.94 keV to 12 keV, the boron junction depth decreases from 1660 Å to 654 Å. This suggests for the first time that the fluorine traps interstitials from the end of range damage decreasing boron diffusion.

9:15 AM B4.3
A COMPARATIVE STUDY OF DOSE LOSS FOR B AND BF2 IMPLANTS. Reza Kasnavi, Peter B. Griffin and James D. Plummer, Center for Integrated Systems, Stanford University, Stanford, CA.

We performed a comparative study of the differences in dose loss for B and BF2 implants for a wide range of equivalent implant energies. We investigated B implants with energies ranging from 200 eV to 10 keV and BF2 implants with scaled energies to produce similar as-implanted profiles (2 keV to 50 keV). At each energy a lower dose of 2e13/cm2 and a higher dose of 1e15/cm2 were studied. B atoms diffuse differently depending on the source of the implant. B11 implants seem to create deeper junctions with lower levels of activation while maintaining most of the implanted chemical dose. However, BF2 implants with similar as-implanted profiles result in shallower junctions, higher levels of activation and a significant loss of the implanted dose. We have found that B implants show normal segregation to the bulk of the oxide for both low and high doses. BF2 implants on the other hand, diffuse and segregate differently depending on the implant dose. Low dose BF2 implants seem to show no dose loss or segregation. High dose BF2 implants show only segregation to the bulk of the oxide at 50 keV, while at 23 keV and lower energies they show significant dose loss. Lower dose B and BF2 implants produce similar junction depths. At high doses, BF2 implants result in shallower junctions. This effect is more pronounced as we go to lower implant energies. This is in agreement with the dose loss observed for lower energy BF2 implants. We will discuss the physical and chemical origins of the differences in the dose loss for Boron and BF2 implants and discuss how these effects may be modeled.

9:30 AM B4.4
OUT-DIFFUSION MECHANISM OF BORON AND FLUORINE IN IMPLANTED P^+ SILICON. Jung-Ho Lee, Jeong-Youb Lee, In-Seok Yeo, Jae-Sung Roh and Chung-Tae Kim, Hyundai Electronics Industries Co., LTD., Memory R&D Division, Ichon-si, Kyoungki-do, KOREA.

Higher remaining contents of both boron and fluorine in shallow p^+ surface layer are observed in the BF_2/B mixed implanted silicon comparing to conventional BF_2 one. Variation of dopants loss observed with different F doses is explained by introducing the following two types of surface reaction, i.e., (1) recombination of F-Si to make gaseous fluorosilyl/oxyfluorosilyl products and (2) recombination of F-B to form gaseous boron fluorides. A systematic

study on F-Si interactions reveals that Si-F-Si configuration is more stable than interstitial F^- as closer to the surface. The presence of a large amount of F^- at the surface induces upward band bending for hole generation. This implies the reaction of $F^- + Si + h^+ \rightarrow SiF$, and the removal of F atoms out of silicon substrate via the formation of gaseous fluorosilyl (SiF, SiF_2, ...) and oxyfluorosilyl (SiOF, $SiOF_2$) products. This reaction is critically dependent on the doping level and type of silicon. In p^+ type silicon, the amount of band bending is expected to be small because small bending is sufficient for generating holes. As a result of smaller bending extending over a large distances, lower rate etching reaction is expected at the surface, and in turn leads to significant F accumulation close to surface region. Upon the annealing, these F ions accumulated at the surface need to be removed, and may recombine with B atoms to make gaseous boron fluorides like BF_3. Because more F atoms are accumulated at the surface region in BF_2 case, B would be removed more effectively. This leads to the reduced surface p^+ doping level in the BF_2 implant, and produces a stronger band bending. Conclusively, the etching reaction to make gaseous fluorosilyl and oxyfluorosilyl products would be amplified, and results in lesser content of remaining B and F in BF_2 case.

10:15 AM B4.5
ULTRA-SHALLOW JUNCTION FORMATION VIA GeB-IMPLANTATION. X.M. Lu, L. Shao, J.Y. Jin, Q.M. Li, J.R. Liu, Q. Chen, I.A. Rusakova, W.K. Chu, Texas Center for Superconductivity at the University of Houston, Houston, TX; P.C. Ling, Advanced Materials Engineering Research, Inc. Sunnyvale, CA.

Ultra-shallow junction is required for next generation Si micro-electronics. Low energy ion implantation of Boron is an important method in the formation of p type shallow junctions. In this paper, a novel approach uses low energy ion implantation of GeB-ions for the formation of p type shallow junctions. Our study showed that Ge has a deeper profile than B after GeB- ions breaking up entering Si. Ge is effective in implantation damage, so the channeling effect of B is suppressed. Secondary ion mass spectroscopy (SIMS) depth profiles and TEM are used to study the shallow profiles and damage. Two step annealing (550°C pre-annealing plus RTA at high temperatures) produces a much more shallower profile than one step annealing. Sheet resistance measurements show that the sheet resistance is around 200 ohm/sq after RTP.

10:30 AM B4.6
EFFECT OF Ge PRE-AMORPHIZATION ON JUNCTION CHARACTERISTICS FOR LOW ENERGY BORON IMPLANTS. Jinning Liu and Sandeep Mehta, Varian Semiconductor Equipment Associates, Gloucester, MA.

The drive towards developing deep sub-micron CMOS devices places more challenges on semiconductor processing. From the standpoint of doping technology, the challenge is to achieve ultra-shallow p+/n source/drain extension junctions for PMOS. Among the various approaches being pursued to meet this challenge, pre-amorphization was used to curtail channeling of the as-implanted Boron. The effect of pre-amorphization on junction depth and junction sheet resistance in the ultra-low implant energy regime is investigated in this study. Pre-amorphization was achieved with 5keV 1x1015cm^{-2} Ge implant prior to B implants. B was implanted at energies of 250eV to 5keV and at a dose of 1x1015cm^{-2}. Subsequent anneals were performed at 1050°C for 0 second (spike anneal) in nitrogen ambient. In all spike anneal cases, the pre-amorphized wafers exhibit higher sheet resistance and shallower junction depth than crystalline wafers. Another set of anneals were performed at lower temperatures in furnace and RTA and it was observed that at 800°C, shallower junction depth as well as lower sheet resistance can be achieved with pre-amorphized wafers. Microstructures of the wafers are also studied with transmission electron microscopy (TEM).

10:45 AM B4.7
EFFECT OF THERMAL BUDGET ON VARYING IMPLANT CONDITIONS IN ULTRA-SHALLOW JUNCTION FORMATION. Ajay Singhal, Teresa Trowbridge, Dave Lopes, Thermal Processing Organization, Applied Materials, Inc., Santa Clara, CA; Amir Al-Bayati, Implant Product Division, Applied Materials, Inc., Santa Clara, CA.

The ability to fabricate 260-520$\AA$ deep junctions, with <400Ω/sq. sheet resistance (R_s), for the 0.13μm node and below is a driving force for the next-generation devices and processing equipment. Recently, much discussion has been focused on spike anneals, with fast ramp-up rates to achieve ultra-shallow (X_j - 330$\AA$) junctions. It has been argued that *transient-enhanced diffusion* (TED) can be suppressed at high ramp-up rates and shallow junctions can be achieved. However, it is also important to consider the effect of such processing on reduced dopant activation and the resulting higher R_s. Agarwal reported [1] the competing behavior X_j and R_s exhibit. In view of competing behavior of R_s and X_j with changing thermal budget, X_j, R_s, a product of X_j and R_s has been proposed as a figure of merit [2]. We investigated shallow junctions (X_j=260-520$\AA$), with R_s<400Ω/sq. that can be achieved by spike anneals for four shallow implant conditions with 1 keV B^{11}/1x10^{15}, or equivalent 4.5keV $BF_2{}^{49}$/1x10^{15} with and without Ge preamorphization. We examined these properties as a function of implant anneal thermal budget (time (s) at 50°C below the peak target temperature) during a spike anneal. The thermal budget was varied by changing the rapid thermal processing (RTP) spike anneal ramp-up rate (75°C/s, 150°C/s, and 230°C/s) and keeping the peak temperature and ramp-down rate constant. We will discuss R_s, X_j combinations (with X_j = 260-520$\AA$, R_s<400Ω/sq.) obtained for different species (1keV B^{11}, and 4.5keV $BF_2{}^{49}$) subjected to similar spike anneals. Varying dependence of Rs and X_j on the thermal budget will be discussed for the four conditions. We will present the dependence of $X_j.R_s$ on thermal budget for different implant conditions such that a minimum $X_j.R_s$ can be achieved. A minimum in $X_j.R_s$ was observed, for three of the four implant species with a thermal budget of ~2.5s (corresponding to 150°C/s ramp-up rate), revealing sufficient activation without significant diffusion.

[1] Agarwal A., Gossmann H.-J., Fiory A. T., Materials Research Society Symposium Proc. **568**, (1999), in press
[2] Fiory A. T., Camm D. M., Lefrancois M. E., Coy S. M., Agarwal A., *7th International Conference on Advanced Thermal Processing of Semiconductors*, Colorado Springs, CO, Sept. 8-10, 1999, pp. 273-280.

11:00 AM B4.8
UNDERSTANDING AND MODELING RAMP RATE EFFECTS ON SHALLOW JUNCTION FORMATION. Srinivasan Chakravarthi, Boston University, Dept of Manufacturing Engineering, Boston, MA; Alp H. Gencer, Avant! Corporation, TCAD Unit, Wellesley, MA; Scott T. Dunham, Boston University, Dept of Electrical and Computer Engineering, Boston, MA; Daniel F. Downey, Varian Semiconductor Equipment Associates, Gloucester, MA.

Transient enhanced diffusion has been the dominant effect in determining junction depths for the past decade. Because TED effects decrease with T, the use of RTP with fast ramp rates has become an important tool for achieving shallow junctions. The achievement of sub-40nm ultra-shallow source/drain extensions requires low energy implants along with fast spike anneals to minimise diffusion. Although TED effects reduce with implant energy, the achievable reduction in junction depth with increasing ramp-up rate has been found to decrease with increasing implant energy. Sub-1keV implants show a more pronounced decrease in junction depth with increase in ramp rates, while the reduction in junction depth for higher energy implants has been found to saturate for larger ramp rates. The goal of this paper is to understand and model the effect of RTP annealing cycle on junction behavior so that RTP processes can be optimized for shallow, low resistance junctions. Via simulations using moment-based models for extended defects, we find it is possible to predict the extent of diffusion during spike anneals with varying ramp rates by considering the full thermal cycle. We find a reduced effect of ramp rate on x_j (as seen experimentally) and saturation in the junction depth with increasing ramp-up rates. This saturation occurs at larger ramp rates for lower energy implants. Faster ramp-ups retain more of the interstitial clusters and more of the TED occurs during the ramp-down. For higher energy implants, this can not only negate any reduction possible due to the faster rampup, but can even lead to an increase of TED with faster ramp-up. For very fast ramp-up rates, the ramp-up is only a small fraction of the total thermal budget, and hence the cooling rate dominates the total junction movement. Thus, faster ramp-down rates are required to give further reductions in junction depth.

11:15 AM B4.9
FURNACE AND RTA INJECTION OF POINT DEFECTS INTO CVD-GROWN B DOPED Si AND SiGe. Janet M. Bonar, Dept. of Electronics and Computer Science, Univ. of Southampton, Southampton, UNITED KINGDOM; Arthur F.W. Willoughby, Materials Research Group, School of Engineering, Univ. of Southampton, Southampton, UNITED KINGDOM; Barry M. McGregor, Dept. of Engineering, Univ. of Cambridge, Cambridge, UNITED KINGDOM.

The diffusion of B in Si and SiGe under the influence of point defect injection is studied in this work, as understanding dopant movement under the defect injection conditions found in typical device fabrication stages will contribute to being able to make end-of-roadmap size devices. B diffusion is thought to be interstitially mediated in Si, and in $Si_{.8}Ge_{.2}$ in recently published work. However, there is strong motivation to examine B in SiGe at different Ge concentrations. In these experiments, samples consisting of a 30 nm $1\times10^{19}cm^{-3}$ boron doped layer within a 90 nm 10%Ge SiGe layer, topped with a 120 nm Si capping layer, and a 30nm $5\times10^{18}cm^{-3}$

boron doped region in Si were grown by LPCVD. Following growth, Low Temperature Oxide (LTO) and Si_3N_4 layers were deposited and selectively etched to produce samples with bare, Si_3N_4 or Si_3N_4 + LTO covered surfaces. The samples were annealed in an O_2 atmosphere in a furnace at 850°C or by Rapid Thermal Anneal (RTA) at 1000°C. During annealing, bare surfaces will experience interstitial injection, Si_3N_4 surfaces experience vacancy injection, and Si_3N_4 + LTO surfaces experience inert, uninjected diffusion. Profiles were obtained by high resolution Secondary Ion Mass Spectroscopy (SIMS), and compared with simulations to extract the diffusivity. The diffusivity of B was found to be enhanced by interstitial injection in both SiGe and Si samples compared to inert anneals. The enhancement factor for RTA annealing of B in Si is 2.8, while 10 is expected for furnace annealing. This work confirms the overwhelming importance of interstitially mediated diffusion of B in SiGe up to 20% Ge.

11:30 AM B4.10
QUANTITATIVE MEASUREMENT OF INTERSTITIAL FLUX AND SURFACE SUPERSATURATION DURING OXIDATION OF SILICON. M.S. Carroll, J.C. Sturm, Dept. of Electrical Engineering, Princeton University, Princeton, NJ.

The injection of interstitials into silicon during oxidation is of great fundamental and technological interest due to effects such as oxidation enhanced diffusion. While the increase of boron diffusion near the surface in bulk silicon during oxidation is well known, the actual flux of interstitials into the silicon and the surface boundary condition are not well established. In this paper we measure this flux and determine the surface boundary condition during oxidation at temperatures of 750° and 850°. The excess interstitial flux during oxidation is probed using boron markers placed above and below buried SiGe(C) layers located at depths of 45, 300, 600 nm from the surface. The SiGeC layers are well known to be interstitial sinks, and boron markers are used to measure the local interstitial supersaturation given that the boron diffusion depends on the interstitial super- saturation concentration. Samples were grown using rapid thermal vapor deposition at 625°. A process simulator was used to extract interstitial supersaturation levels from the boron profiles. The surface supersaturation of interstitials was varied to fit the experimentally determined profiles. This number was combined with the well established $D_I C_I$ product, which is now relatively well established [1], to determine the interstitial flux. The total number of interstitials injected during oxidation is observed to depend inversely on the depth of the carbon rich layer. The interstitial flux's inverse dependence on depth of the carbon rich layer may be explained by a fixed excess interstitial surface concentration [2], which is independent of the proximity of the carbon rich layer or how many interstitials are injected or trapped. The ratio of excess interstitial concentration to the equilibrium concentration at the surface and the interstitial flux is determined for both 750° and 850°, and compares well to interstitial flux measurements at 850° done with loop defects [3]. This work was supported by DARPA and ARO. [1] H. Bracht, N. A. Stolwijk, H. Mehrer, Physical Review B, Vol 52, Num 23, 16542, 1995. [2] A. Agarwal, S. Dunham, J. Appl. Phys., 78 (9), 1 Nov. 1995, 5313. [3] D. Skarlatas, M. Omri, A. Claverie, D. Tsoukalas, J. of Electrochemical Society, 146, (6) 2276-2283 (1999)

11:45 AM B4.11
WHAT DOES SILICON SELF-DIFFUSION TELL US ABOUT ULTRA SHALLOW JUNCTIONS? Ant Ural, S.H. Koh, P.B. Griffin and J.D. Plummer, Stanford University, Dept. of Electrical Engineering, Stanford, CA.

Understanding the coupling between native point defects and dopants in silicon will be key to ultra shallow junction formation in silicon technology. Other effects, such as transient enhanced diffusion (TED) will become less important. In this talk, we will first describe how thermodynamic properties of the two native point defects in silicon, namely vacancies and self-interstitials, have been obtained by studying self-diffusion in isotopically enriched structures. These experiments have shown that silicon self-diffusion has competing interstitial and vacancy components over a wide temperature range. We will also present results on self-diffusion under extrinsic carrier concentrations where the presence of charged native point defects become important. The diffusion of shallow high concentration dopant profiles is determined by the competition between the flux of mobile dopants and those of the native point defects. These fluxes are proportional to the interstitial or vacancy components of dopant and self-diffusion. This is why understanding the microscopic mechanisms of silicon self-diffusion is impor tant in predicting and modeling the diffusion of ultra-shallow dopant profiles. In particular, we will show how these coupling effects play a role in the annealing of shallow BF_2 ion implantation. It will be seen that relatively low temperature furnace cycles, following high temperature rapid thermal anneals (RTA), have a significant effect on the minimum junction depth that can be achieved.

SESSION B5: GROUP III DOPANT DIFFUSION AND ACTIVATION
Chairs: Ulrich M. Goesele and Peter B. Griffin
Tuesday Afternoon, April 25, 2000
Salon 3/4 (Marriott)

1:30 PM *B5.1
PROBING THE EVOLUTION OF BORON-INTERSTITIAL CLUSTERS IN SILICON. N.E.B. Cowern, G. Mannino*, F. Roozeboom, J.G.M. van Berkum, and L. Pelaz**, Philips Research Labs, Eindhoven, THE NETHERLANDS; *INFM and Dipartimento di Fisica, Univ. di Catania, Catania, ITALY; **Dept. E. y Electronica, ETSIT Campus Miguel Delibes, Valladolid, SPAIN.

Transient enhanced diffusion and the related phenomenon of boron (de)activation are key factors limiting the formation of low-resistivity p-type ultrashallow junctions in advanced IC technology. Both phenomena are strongly influenced by the formation and evolution of boron-interstitial clusters (BICs). We present a novel approach for the experimental investigation of these sub-microscopic defects, based on the interaction between spatially separated bands of BICs and silicon self-interstitial clusters (ICs). Results from the first experiments using this approach are presented. We distinguish at least three phases of BIC evolution. First, BICs are nucleated. This is a homogeneous process and can only occur in the presence of a high concentration of interstitial atoms, generated by ion implantation. We observe directly that BIC nucleation absorbs interstitials from the initial high density of Frenkel pairs present after implantation. Outside the implant damaged region, no boron clusters nucleate. Second, following Frenkel-pair recombination, BICs continue to evolve by capturing interstitials released from "plus-one" damage, which at this stage consists mainly of sub-microscopic ICs. The BICs continue to grow until the ICs have ripened into more stable {113} defects. Third, the stability of the BICs and the {113} defects becomes comparable, and both defect populations lose significant number of interstitials to the environment (the silicon surface or interfaces). The BICs preferentially lose self interstitials, thus becoming boron-rich and increasingly stable. These BICs persist much longer than the time scale of transient enhanced diffusion. In this sense BICs are primarily a buffer for interstitials during TED, and their predominant role is as a suppressor of prompt TED and as a limiting factor for dopant activation. These observations account for a wide range of experimental observations in the literature, and broadly confirm conclusions from recent ab initio and Monte Carlo studies.

2:00 PM B5.2
THE SOURCE OF TRANSIENT ENHANCED DIFFUSION IN SUB-KEV IMPLANTED BORON IN CRYSTALLINE SILICON. E. Napolitani, A. Carnera, INFM and Dept. of Physics, Padova, ITALY; E. Schroer, V. Privitera, CNR-IMETEM, Catania, ITALY; F. Priolo, INFM and Dept. of Physics, Catania, ITALY; S. Moffatt, Applied Materials, Santa Clara, CA.

The transient enhanced diffusion (TED) during activation annealing of ultra low energy implanted boron (0.5 keV & 1 keV, $1x10^{13}/cm^2$ & $1x10^{14}/cm^2$) in silicon is investigated in details. Annealing in the temperature range from 450°C to 750°C is either performed directly after implantation or after the removal of a surface layer before annealing. The kinetics revealed two regimes of enhanced diffusion ruled by different decay constants. The dependence of these two processes on implantation energy and annealing temperature is described and explained from the microscopical point of view. The annealings performed after surface layer removal, revealed that the defects responsible for the faster diffusion are located deeper than the defects responsible for the slower process. The depth dependence of the two types of defects is discussed in terms of the interaction between the ion beam generated I, V and the implanted boron.

2:15 PM B5.3
CLUSTERING AND ELECTRICAL ACTIVATION OF ULTRALOW ENERGY IMPLANTED BORON IN SILICON. E. Schroer, V. Privitera, CNR-IMETEM, Catania, ITALY; F. Priolo, INFM & Universita di Catania, Catania, ITALY; E. Napolitani, A. Carnera, INFM & Universita di Padova, Padova, ITALY; S. Moffatt, Applied Materials, Santa Clara, CA.

The boron clustering and the electrical activation during annealing (750°C-1200°C) of ultralow energy implanted boron (0.25 keV - 1 keV, 10^{14} cm^{-2} & 10^{15} cm^{-2}) in silicon are investigated. The depth profiles of the electrical activation are measured by means of spreading resistance profiling (SRP) and the chemical boron profiles are measured by secondary ion mass spectroscopy (SIMS). While for the higher dose the direct comparison of SRP and SIMS profiles evidences the correlation of boron clustering and electrical activation, this direct correlation is not possilbe for the lower dose. The dynamics of the total electrical activation in the latter case is characterized by an initial fast activation and a subsequent increase which can be

described by the complementary of an exponential decay. The electrical activation in this case is interpreted as the result of the release of boron from clusters. The temperature dependence of the time constants of electrical activation indicates an activation energy in the range of 2 to 3 eV for the ultralow energy implanted boron.

2:30 PM B5.4
A STUDY OF BORON CLUSTERING PROCESSES UTILIZING X-RAY DIFFRACTION TECHNIQUE. Aaron D. Lilak, Viswanath Krishnamoorthy, Dave Vieira, Mark Law and Kevin Jones, University of Florida, SWAMP Center, Gainesville, FL.

An xray diffraction (XRD) study of boron clustering processes in silicon has been conducted in order to gain an understanding of the processes leading to boron deactivation and the formation of immobile boron interstitial clusters (BIC's). This XRD technique can determine the characteristic strains exhibited by the BIC clusters and presents a means to monitor both the development and time dependencies associated with their formation processes.
In this study a novel CVD process has been employed to grow approximately .4um of boron-doped silicon atop a p-type epi wafer. The doping concentrations were varied from undoped to 5e19cm^{-3}. A silicon implant is utilized to introduce damage to the material and further low temperature anneals are then conducted in order to grow and nucleate a population of BIC type clusters. The material is then analyzed with both the XRD technique to check for strain variations and plan view transmission electron microscopy to check for any extended defects.
Preliminary results from this study indicate the emergence of a new tensile strain peak in the XRD rocking curve with a well delineated strain field following formation and annealing of these BIC type clusters for times of up to 30 minutes at 740C. The strain from this complex has been computed to be approximately 6e-4, and potentially may be utilized to identify the cluster. The thermal stability of this cluster is consistent with SIMS studies of boron diffusion which indicates a significant immobile boron peak to similar processing conditions.
Through this XRD study of boron clustering processes, we plan to demonstrate a means of monitoring the boron clustering processes which occur in highly-doped silicon. Results will be presented for a time and temperature sequence for boron clustering in substrates with varying boron doping concentrations. This study has significant implications for the development of processing conditions leading to highly-doped ultra-shallow p+ regions in silicon.

2:45 PM B5.5
POINT DEFECTS, DEFECT CLUSTERS & PLANAR DEFECTS IN IMPLANTED SILICON: THEIR RELATION TO TED IN SILICON. I. Kegel, T.H. Metzger, Sektion Physik & CENS at Ludwig Maximilians, Universitaet Muenchen, Muenchen, GERMANY; D. Luebbert, J.R. Patel, SSRL/SLAC, Stanford University, Stanford CA, and (JRP) ALS/LBL Berkeley CA.

The problem of the enhanced diffusion of implanted impurities in silicon is intimately related to defects produced in the implantation process and their behavior on annealing. Experimentally much has been learned through excellent TEM and marker studies after implants and anneals. Simulations have also shed much light on the formation and behavior of point defects and clusters.What has been lacking is direct experimental information on point defects and clusters. In this study we report x-ray diffuse scattering results on annealed Boron Implanted silicon. In grazing incidence diffuse scattering we observe narrow diffuse streaks of intensity along $< 111 >$ directions. The streaks arise from stacking faults formed in the early stages of Boron implanted silicon annealed in the range 900-1100 C. From the width of the streaks the average stacking fault size is 70nm in good agreement with TEM observations. These rods of intensity are quite distinct from point defect or point defect cluster scattering in the tails of Bragg peaks (Huang Scattering).From the q dependence of scattering in the Huang region we find clear evidence for defect clusters 4nm in size and remarkably independent of annealing temperature. Preliminary work on the kinetics of stacking fault growth will be presented and these new observations and their relation to TED will be discussed.

3:30 PM B5.6
IMPLANTATION DAMAGE ENHANCED BORON ACTIVATION DURING LOW TEMPERATURES ANNEALING. Jian-Yue Jin*, Qingmian Li, Jiarui Liu and Wei-Kan Chu*, Texas Center for Superconductivity, University of Houston, Houston, TX; *Also Physics Department, University of Houston, Houston, TX.

We have used channeling nuclear reaction analysis (NRA) and four-point probe measurements to study boron activation and deactivation behaviors with different amounts of implantation damage during post-implant thermal annealing. The implantation damage were produced either by different doses of pre-doping Si implantation or same atomic energy and dose of B_n^- (n=1, 2, 3) implantation (e.g.,1 keV B^- 1×10^{15} ions/cm^2, 2 keV B_2^- 5×10^{14} ions/cm^2, and 3 keV B_3^- 3.3×10^{14} ions/cm^2). Channeling NRA is able to measure the number of substituted boron (or the total number of hole carriers), while the four-point probe gives the sheet conductivity, hence an average of carrier mobility can also be determined. The results indicate that during low temperatures annealing, the number of substituted boron greatly increases with increasing implantation damage. And it decreases with increasing annealing temperatures from room temperature until to a certain temperature (T_a. This T_a is dependent on the amount of implantation damage and could be up to 850°C. The average carrier mobility shows to be correlated to the amount of defects left after annealing, which were measured by channeling Rutherford backscattering spectrometry (RBS). The mechanism of boron activation and deactivation will be discussed in detail.

3:45 PM B5.7
BORON IMPLANTATION IN SILICON SUBJECT TO HYDROGEN PLASMA. Sanjay Rangan, M. Horn, S. Ashok, Dept. of Engineering Science and Electronic Materials and Processing Research Laboratory, The Pennsylvania State University, University Park, PA.

A critical Si VLSI scaling issue pertains to boron ion implantation for forming shallower junctions at increasing concentrations. Known problems include ion damage-induced transient enhanced diffusion (TED), segregation of B to extended defects, clustering of ultra-low-energy (<1 keV) implanted B during anneal, and B deactivation by ion damage. Among the techniques proposed to offset the principal problem of TED are use of carbon-rich Si, silicidation-induced vacancy injecion, local-oxidation induced stress, and plasma treatment of Si surface. Hydrogen-decorated Si vacancies have been shown to reduce dopant activation energy, thus potentially lowering the thermal budget for implantation anneal. In addition, atomic hydrogen incorporated in Si at large concentrations from of a high-flux source such as ECR (Electron Cyclotron Resonance) plasma may play a role in B diffusion and possibly in cluster formation. Hence we have carried out a study of ECR hydrogen plasma on the activation and junction formation of B introduced by ion implantation. 33 keV B^+ at doses of 10^{14} cm^{-3} and 10^{15} cm^{-3} was implanted into 20 Ω·cm n-type Si, and subsequently the wafers were hydrogenated at an ECR plasma power of 700 W, with a 20 W RF bias. The substrates were held at 250°C during the 30 min. hydrogenation step. The (B-implanted) samples, with and without hydrogenation, were then subjected to rapid thermal anneal (RTA) at varying temperatures (250 - 1050°C). In the hydrogenated sample (10^{14} cm^{-3} B dose), significant activation of B is found for RTA temperatures as low as 450°C, with the B surface concentration reaching $> 10^{18}$ cm^{-3} at just 800°C. More interestingly, spreading resistance profiles reveal sharp transitions, with a junction depth of 0.3 μm for the latter case. Samples without hydrogen tend to result in deeper junctions. We will present detailed results, including B depth distribution and junction electrical properties.

4:00 PM B5.8
THE EFFECT OF IMPURITIES ON THE DIFFUSION AND ACTIVATION OF ION IMPLANTED BORON IN SILICON. L.S. Robertson, R. Brindos, K.S. Jones, Univ. of Florida, Dept. of Materials Science and Engineering, Gainesville, FL; M.E. Law, Univ. of Florida, Dept. of Electrical and Computer Engineering, Gainesville, FL; J. Liu, S. Falk, Varian Ion Implant Systems, Gloucester, MA.

The interaction between boron and silicon interstitials caused by ion implant damage is a physical process which hinders the formation of ultra-shallow, low resistivity junctions. The possibility of mitigating the effective interstitial point defect population in ion implanted silicon has been investigated. Amorphization of a n-type Czochralski wafer was achieved using a series of Si^+ implants of 40 keV and 150 keV, each at a dose of 1x10^{15}/cm^2. The Si^+ implants produced a 3000 Å deep amorphous layer, which was then implanted with 8 keV 1x10^{14}/cm^2 B^+. The samples were then implanted with high doses of either carbon, oxygen, sulfur, chlorine, selenium, or bromine. The implant energies of the impurities were chosen such that the damage and ion profiles of the impurity were contained within the amorphous layer. This allowed for the chemical species effect to be studied independent of the implant damage caused by the impurity implant. Post-implantation anneals were performed in a tube furnace at 750°C and in a rapid thermal annealing furnace at 1000°C. Secondary ion mass spectrometry was used to monitor the dopant diffusion after annealing. Hall effect measurements were used to study the dopant activation. Transmission electron microscopy was used to study the end-of-range defect evolution. The addition of carbon, sulfur, and selenium each appear to reduce the boron diffusion enhancement to approximately one-fourth that of the boron control. Results of further analysis on the effect of the different impurities on boron diffusion, boron activation, and extended defect formation will be presented.

4:15 PM B5.9
THE EFFECT OF NITROGEN IMPLANTS ON BORON TRANSIENT ENHANCED DIFFUSION. Omer Dokumaci, Suri Hegde, Paul Ronsheim, IBM SRDC, Hopewell Junction, NY.

The effect of nitrogen implants on boron transient enhanced diffusion was studied for various nitrogen and boron doses. A buried layer of boron was formed by implanting boron into CZ silicon and growing an epi layer on top of silicon. The buried layer is used as a detector for interstitial supersaturation in the structure. Then, boron was implanted at doses ranging from 1e14 to 1e15 cm^{-2} at 14 keV. Nitrogen (N2) was subsequently implanted such that nitrogen peak matched boron's. Nitrogen dose varied between 5e13 to 5e14 cm^{-2}. Some of the samples received no nitrogen implants to serve as control samples. RTA and low-temperature furnace anneals were carried out on all the samples. Nitrogen and boron profiles were obtained by SIMS. The enhancements in the diffusivity of the buried boron layers were extracted for each condition. From these enhancements, the effect of nitrogen implants on interstitial supersaturation was characterized. The direct interaction of nitrogen with boron was investigated from the nitrogen-boron co-diffusion profiles.

4:30 PM B5.10
BORON DIFFUSION IN SILICON AND THE PREDICTIVE POWER OF AB-INITIO CALCULATIONS. Wolfgang Windl[a], Michael F. Morris[a], Murray S. Daw[a], Xiang-Yang Liu[b], Computational Materials Group, Motorola, Inc., [a]Austin, TX, [b]Los Alamos, NM.

First-principles calculations of diffusivities and reaction constants of dopant atoms and native defects in semiconductors can be a very useful input to improve semiconductor process simulations. However, it is not granted that such calculations find automatically the "right" result: Instead of the kick-out mechanism, which has been believed for a long time to be the relevant one for B diffusion, supported by *ab-initio* calculations, other, very recent *ab-initio* calculations suggest now a one-step diffusion of the B-interstitial pair.[1] In this work, we examine the predictive power of such ab-initio calculations by a discussion of their capabilities and possible sources of error in light of the progressing advances within the field. We perform a critical comparison of the ab-initio values to experiment (where possible), and discuss the predictive capabilities of a diffusion model built from these values. We will focus on the accuracy of the recently proposed values for B diffusion; also, on predictions for the stress dependence of these quantities, which becomes more and more important with shrinking device dimensions.
[1]W. Windl *et al.*, *Proc. of the 2nd International Conference on Modeling and Simulations of Microsystems, 1999* (Computational Publications, Cambridge, MA 1999), p. 369; MRS Symposia Proceedings No. 568 (MRS, Pittsburgh, 1999), p. 91; Phys. Rev. Lett. **83** (1999); B. Sadigh *et al.*, *ibid.*

4:45 PM B5.11
BORON DIFFUSION MECHANISM IN SILICON OXIDE USING AB INITIO METHODS. Vladimir Zubkov, Sheldon Aronowitz, Valeriy Sukharev, LSI Logic Corp, Santa Clara, CA; Juan Senosiain, Stanford Univ., Dept. of Chemical Engineering, Stanford, CA.

Ab initio quantum chemical methods have been employed to gaininsight into the mechanisms of boron diffusion in silicon oxide. The silicon oxide has been modeled by clusters of various sizes. It has been found that there are three highly stable structures resulting from B insertion into the silicon oxide. They include a linear structure Si-O-B-Si (I) and structures in which B is bonded to two O and one Si atoms (II) or to three O atoms (III). The main assumption is that B diffusion through silicon oxide proceeds as a succesion of B hops from one stable structure to another. Energy gains for stable structures formations and barriers for B hops have been evaluated. Both neutral B and the boron ion, B^+, are considered although the main thrust of the calculations involves neutral B. Energy gain for B insertion with the structure I formation is 2.7 - 3.4 ev depending on the model. Structures II and III are found to be lower in energy than the structure I by 0.6 ev or more. The barrier for B hop between Si-O-B-Si and Si-B-O-Si structures (hop 1) which is a necessary step of B diffusion is 0.5 ev. The rate determining step is B hop (2) from II to I with a barrier 2.1 -2.2 ev. For B^+ the energy gain in the case of a linear insertion is larger (6.3 - 6.8 ev) than for neutral B and the rate determining step is the hop (1) with a barrier of 2.7 ev. Calculated rate determining barriers do not make it possible to draw an unambigious conclusion whether boron diffusion in silicon oxide proceeds via neutral or ionic B. However, one factor indicates that B diffusion proceeds more probably via neutral B: the calculated energy necessary for boron transfer from a silicon oxide cluster to a pure silicon cluster is lower in the case of neutral boron.

SESSION B6: POSTER SESSION:
GENERAL POSTER SESSION
Chairs: Paul A. Packan and Lourdes Pelaz
Tuesday Evening, April 25, 2000
8:00 PM
Salon 1-7 (Marriott)

B6.1
Ar AND B LOW-ENERGY IMPLANTS INTO SILICON. A MOLECULAR DYNAMICS STUDY OF DAMAGE OF A VICINAL SURFACE. A.M. Mazzone, C.N.R.-Istituto Lamel, Bologna, ITALY.

Computer simulations of the type molecular dynamics are used to study implants of Ar and B with a kinetic energy in the range from 5 to 30eV into silicon. These implant conditions are assumed to be representative of secondary damage events occurring during ion etching and electronic device fabrication. The purpose of the simulations is to study damage production mechanisms and their relationship with the surface structure. Therefore the bombarded surface has a realistic vicinal structure and contains one step, either SA or SB. Two main modes of damage formation have been identified. One is the formation of Ar and B interstitials at a selected depth below the surface. The second one is a corrugation of the atomic rows. The dependence of these events on the surface morphology and on the incident atom is analyzed.

B6.2
Abstract Withdrawn.

B6.3
AN ANALYTICAL MODEL FOR FIELD-ENHANCED DIFFUSION OF IONIZED IMPURITIES IN HIGHLY DOPED Si. Bogdan S. Sokolovskii, Ivan Franko National Univ., Inst. of Applied Physics, Lviv, UKRAINE; Liubomyr S. Monastyrskii, Ivan Franko National Univ., Dept. of Physics, Lviv, UKRAINE; Roman M. Kovtun, Ivan Franko National Univ., Dept. of Industrial Safety, Lviv, UKRAINE.

In the paper, it is derived a new expression for concentration dependence of field-enhanced diffusion coefficient of ionized impurity in highly doped semiconductors including Si of p- and n- type of conductivity. The model developed is valid for the whole range of carrier degeneracy under condition that impurity concentration greatly exceeds intrinsic carrier density. The derived expression indicates that the carrier degeneracy gives rise to increase of the diffusion coefficient, with its magnitude substantially exceeding that corresponding to the nondegenerate situation. Such a behaviour of the diffusion coefficient is due to reduction of the impurity field screening by mobile carriers at the degenerate conditions. The obtained expression gives, as particular cases, widely used formulae describing concentration dependence of the field-enhanced diffusion coefficient in the regions of strong and weak degeneracy. It is also generalized the concentration dependence of diffusion coefficient for the case when the band gap narrowing effect takes place. The narrowing of band gap is turned out to lead to decreasing the diffusion coefficient as compared to its magnitude corresponding to the case of unperturbed band structure. This is a result of reducing the built-in field due to the fact that a lowering of carrier energy in the highly doped regions counteracts moving free carriers from those regions. Our calculations, performed on the basis of known experimental dependencies for both p-Si and n-Si, show that initial part of the concentration dependencies of diffusion coefficient may be of a decreasing type. Minimum of the diffusion coefficient is located in the region of weak degeneration where contribution of the carrier degeneration to the concentration nonlinearity of the diffusion coefficient is small, with the value of minimum reducing under the increase of temperature.

B6.4
DOPANT - EXTENDED DEFECTS INTERACTION: THE CASE OF ALUMINUM. Christophe Ortiz, Laboratoire de Micro-Electronique de Puissance, Tours, FRANCE; Daniel Mathiot, Laboratoire PHASE, Strasbourg, FRANCE; Christiane Dubois, Laboratoire de Physique de la Matiere, Villeurbanne, FRANCE; Daniel Alquier, Roberto Jerisian, Laboratoire de Micro-Electronique de Puissance, Tours, FRANCE.

Thanks to the absence of channeling, silicon pre-amorphization is a possible way to obtain shallow P+/N junctions by B implantation. However the redistribution of the dopant is influenced by the End Of Range (EOR) defects left behind the amorphous / crystal interface after total solid phase epitaxy regrowth. Moreover substrate amorphization happens also during high dose implantation of heavy dopants, such as arsenic or aluminum. Thus a good understanding of the various interactions between the dopants and the extended defects is required to optimize the junction engineering. In the specific case of aluminum, we have recently shown that high dose implantation leads to the formation of extended defects, even in sub-amorphization conditions, and that strong interactions between these defects and the

dopant significantly affects the final profile. However the detailed mechanisms governing these interactions are still unclear. Thus in order to clarify these interactions, we performed specific experiments using Al redistribution in the vicinity of a well defined EOR band formed by Ge pre-amorphization (150 keV, 2× 10^{15} cm^{-2}). N-type < 100 > FZ Si wafer were implanted with Al at high energy (3 MeV) to a low dose (5× 10^{13} cm^{-2}) before the pre-amorphization step. The Al implant energy was chosen high enough to put the as-implanted Al peak in the bulk of the substrate, away from the EOR band. SIMS and spreading resistance was then used to follow the evolution of the Al profile and to characterize its interaction with the EOR band during subsequent rapid thermal anneals, in the 900 - 1000°C temperature range, for times between 10 and 200 sec. The results of this study, which will be reported in this contribution, evidence a clear accumulation of the dopant on the extended defects, indicating a direct trapping mechanism of the dopant by the EOR.

B6.5
LOW ENERGY IMPLANTATION OF BORON WITH DECABORANE IONS. Maria A. Albano, Vijay Babaram, John M. Poate and Marek Sosnowski, New Jersey Institute of Technology, Newark, NJ; Dale C. Jacobson, Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Formation of p-type shallow junctions in the future generations of Si devices will require ion implantation of B at very low energies, i.e. below 1 keV, where the beam formation and transport at reasonably high currents are hindered by Coulomb repulsion of ions at high volume density. An alternative to implantation of monomer ions at very low energy is implantation of large molecular ions at a higher energy. In an ion beam of decaborane ($B_{10}H_{14}$) each of the B atoms carries only 9% of the ion kinetic energy. We have examined ionization properties of decaborane and built an experimental ion source and an implantation apparatus with magnetic mass analysis. The electron impact ionization source allows tuning the electron energy for optimum generation of $B_{10}H_x^+$ ions. Analyzed decaborane ion beams with energies from 2 to 10 keV and beam currents of several microamperes were obtained. Si samples were implanted with decaborane ions and the implanted dose measured by current integration was compared with B content obtained by nuclear reaction analysis using the $^{11}B(p,\alpha)^8Be$ reaction at a proton energy of 650 keV. Experiments with electrostatic beam deflection show that the large ions survive the transport in the implanter environment and that neutralization is negligible. The results confirm the feasibility of shallow implantation of B into Si by using decaborane ion beams.

B6.6
PHOSPHORUS / SILICON INTERSTITIAL ANNEALING AFTER ION IMPLANTATION. P.H. Keys, M.E. Law and K.S. Jones, Swamp Center, Dept. of Materials Science and Engineering, University of Florida, Gainesville, FL.

The release of interstitials from extended defects after ion implantation acts as a driving force behind transient enhanced diffusion (TED). Implantation of $^{28}Si^+$ ions into regions of phosphorus-doped silicon provide experimental insight into the interaction of silicon interstitials and dopant atoms during primary damage annealing. The presence of phosphorus influences the morphology of secondary defects during initial nucleation. Transmission electron microscopy (TEM) is used to differentiate between defect types and quantify the interstitials trapped in extended defects. This analysis reveals that phosphorus results in a reduction of interstitials trapped in observable extended defects. The interstitial flux released from the implanted region is also affected by the phosphorus doping. This phenomena is closely studied using secondary ion mass spectrometry (SIMS) to monitor diffusion enhancements of dopant layers. Shifts in diffused dopant profiles are correlated with the different morphologies of the extended defects and the decay of the silicon interstitial supersaturation. This correlation is used to understand the clustering of excess silicon interstitials with phosphorus atoms. Results of this experiment provide important data useful for modeling the effects of phosphorus on TED.

B6.7
TEM AND HRTEM ANALYSIS OF {311} DEFECTS WIDTH IN B^+ IMPLANTED Si. Jinghong Li, Craig Jasper[1], Mark E. Law[2] and Kevin S. Jones, Swamp Center, Dept. of Materials Science and Engineering, Gainesville, FL. [1]Dept. of Computer and Electrical Engineering, University of Florida, Gainesville, FL, [2]ACT, Motorola Inc., Mesa, AZ.

The {311} defect is known to both contribute to transient enhanced diffusion of implanted dopants in Si as well as act as a source for dislocation loops. One of the key modeling issues is how does the width of the {311} defect vary with length. Plan and cross-section transmission electron microscopy (P-TEM and X-TEM) and high-resolution transmission electron microscopy (HRTEM) have been used to study {311} defects in 50 keV, 100 keV and 1MeV B+ implanted Si at a dose of 1.0E14/cm^2. After implantation the samples were annealed at 750°C for 30 min. Increasing the implant energy resulted in a significant increase in the length of the {311} defects that formed upon annealing. However no significant increase in the average width of the {311} defects was observed by HR-XTEM. The widths of {311} defects in B+ implanted Si with different energies have been determined to be in a range from 20 A to 50 A from cross-section HRTEM. There were a few defects that were wider and this will be discussed further. The widths observed are correlated to theoretical calculations of the width.

B6.8
DEPTH PROFILES BY HIGH ENERGY RECOIL IMPLANTATION OF BORON INTO SILICON. L. Shao[1,2], X.M. Lu[1,2], J.Y. Jin[1,2], Q.M. Li[1], J.R. Liu[1], P.A.W. van der Heide[3], W.K. Chu[1,2], [1]Department of Physics, University of Houston, Houston, TX; [2]Texas Center for Superconductivity, University of Houston, Houston, TX; [3]Materials Research Science and Engineering Center, University of Houston, Houston, TX.

We have studied boron profiles by the using ion beam recoil implantation. A boron layer was first deposited onto Si, followed by irradiation with Si ions at various energies to knock the boron previously deposited on the surface into the bulk of the Si sample. Surprisingly enough, higher energy collisions produce shallower boron profiles. In this talk, we will present experimental results and theoretical calculations on the title subject. We will also discuss the potential of such a method for shallow junction formation.

B6.9
ON THE FORMATION AND DISSOLUTION OF IMPURITY PRECIPITATES AT DEFECT CLUSTERS IN MULTI-CRYSTALLINE Si. Bhushan Sopori, National Renewable Energy Laboratory, Golden, CO.

Multicrystalline Si wafers are used extensively for commercial solar cell fabrication yielding 14%-15% efficiency with the current processing techniques. The dominant mechanism that limits the device performance is related to defect clusters in the substrates. In a finished device, the defect clusters manifest a behavior of distributed shunts that primarily degrade the voltage-related parameters. The device efficiency can exceed 18% if the effects of these defect clusters are eliminated. To overcome the effects of defect clusters, it is necessary to know the kinetics of their formation, the composition of impurity precipitates, and methods to ameliorate their effects. This paper describes the results of our investigations to identify the formation of defect clusters, their properties, and how one can diminish their effects. Defect clusters are an agglomeration of extended defects that involve dislocation networks, stacking faults and grain boundaries. In addition, because these materials are rich either in O or C, and transition metals, the defect clusters are sites for impurity precipitation. We have used variety of defect mapping techniques to identify defect clusters in the substrates and performed detailed analyses using TEM, SIMS, SPV, and X-ray methods to identify the nature of impurities at the localized sites. The analyses have shown that the precipitates that are predominantly metallic may have significant amounts of oxygen associated with them. This may indicate that metallic precipitation can occur at the oxygen precipitates. It is also possible that oxygen or C precipitation is the primary phenomenon that is accompanied by secondary effects related to local stress relaxation. This suggests that point defect injection can lower the temperature and time required to dissolve such precipitates. The objective of our work is to develop suitable processing methods that can dissolve and getter the impurities at the defect clusters.

B6.10
ION IMPLANTATION EFFECT ON DISLOCATION PROPAGATION IN PSEUDOMORPHICALLY STRAINED P/P^+ SILICON. Petra Feichtinger, Hiroaki Fukuto, Randy Sandhu, Ben Poust, Mark S. Goorsky, Dept. of Materials Science and Engineering, University of California, Los Angeles, CA.

We studied damage evolution and influence on defect interactions as a function of Si self implantation in p/p+ silicon wafers. Si-28 (doses 1 x 10^{12} and 1 x 10^{14} cm^{-2} at 100 keV) was implanted into nominally un-doped p-type epitaxial layers. We employed highly boron doped 150 mm diameter silicon substrate wafers with a 2 μm thick pseudomorphic epitaxial layer (p/p+). Due to the misfit strain, misfit dislocations formed during the epitaxial growth process around the wafer edges. This non-uniform dislocation distribution was utilized to study the role of the implant on both the nucleation and growth of the misfit segments. The silicon self implantation was performed at room temperature. A simulation program was used to study the point defect distribution during the implantation process. Triple axis x-ray diffraction was used to determine that the layer was not amorphous at any point. Double axis x-ray topography combined with rapid thermal

annealing was used to measure the evolution and nucleation of misfit segments after annealing. SRP measurements were done in both implanted and un-implanted regions before and after ion implantation in order to characterize the carrier concentration profile. SIMS measurements confirmed that transient enhanced diffusion of boron was not appreciably different in the two regions. The implanted regions exhibited neither growth nor nucleation of misfit dislocation segments, in marked contrast to the growth and nucleation of misfits observed in the non-implanted regions. This comparison indicated that the excess point defects and crystallographic damage act to impede both dislocation motion and dislocation nucleation.

B6.11
NON-DESTRUCTIVE, IN-LINE CHARACTERIZATION OF SHALLOW JUNCTION PROCESSES. G. Jonathan Kluth, Advanced Micro Devices, Sunnyvale, CA; Laurie Bechtler, Peter Borden, Jian Mi, Boxer Cross, Inc., Menlo Park, CA.

Formation of the shallow junctions necessary for 0.18 um devices and beyond pose stringent requirements not only for process equipment, but also for metrology equipment. New processes for shallow junction formation, such as amorphization and ultra-low energy implants, place new demands on current metrology. The need exists for a tool that can be used as an in-line monitor of the amorphization implants and low energy implants that will be an integral part of future device flows. As described previously [1], a newly developed optical metrology tool is capable of measuring the active doping depth of shallow implants. Because the measurement is non-destructive and can be performed on patterned wafers with high throughput, the tool is well suited for in-line monitoring of shallow junction processes. This paper describes the application of this method to in-line monitoring of shallow junction processes in a production setting. Recent results demonstrate the sensitivity of junction depth to implant dose and energy, as well as to annealing temperature. Data will also be presented on monitoring of amorphizing implants. Measurements are compared with results obtained by destructive techniques such as SIMS and SRP. These results demonstrate that the optical method has the capability to provide in-line control of shallow junction processes. [1] Peter Borden, Regina Nijmeijer, and Karen Lingel, 'Non destructive profile measurements of annealed shallow implants'. Mat. Res. Soc. Proc. 1999, in press.

B6.12
NONDESTRUCTIVE CHARACTERIZATION OF ACTIVATED SHALLOW BORON AND ARSENIC IMPLANTS IN FULL NMOS AND PMOS PROCESS FLOWS. L. Larson, B. Murto, B. Covington*, C. Ferguson and B. Nguyen, Sematech, Front End Processes Division, Austin, TX; *present address Southwest Texas State University, Dept. of Physics, San Marcos, TX; P. Borden, L. Bechtler Boxer Cross Inc., Menlo Park, CA.

A new method for non-destructive, small area characterization of ultra-shallow junctions has recently been developed[1]. Called Carrier Illumination^{TM} (CI), it uses a laser to create a quasi-static carrier distribution. A second laser probes this distribution to determine the junction depth.
This work attempts to validate the CI measurement in full CMOS and NMOS process flows, with the ultimate aim of providing in-line characterization of junction depth and uniformity on product wafers. Measurements have been carried out on wafers at various steps in the SEMATECH standard process flow. The CI method was used to characterize annealed 800 eV B11 PLDD implants into n-wells and annealed As75 NLDD source/drain (S/D) implants into p wells.
The PLDD studies correlate the CI signal to active dose over the range of 4.5e14/cm^2 to 6.5e14/cm^2, showing a dose resolution of about 1%. SIMS and SRP are used to validate the junction depth measurements and 49 site CI junction depth maps showing across-wafer LDD layer depth uniformity. The depth resolution is found to be 2 $\AA$. The n-well, doped to 3x10^{17}/cm^3, is shown to have negligible effect on the measurement.
The NLDD study used an As S/D energy split ranging from12 to 47 keV at a dose of 3e15/cm^2. The measured junction depths increase with implant energy and show a linear correlation to SIMS. The n-well is shown to negligibly affect the measurement. Additionally, the CI measurement was able to identify four mis-implanted wafers, and isolate the problem to an incorrect implant recipe.
Finally, modeling results will be shown to predict the extensibility of these results to measurements in patterned structures. It is found that the CI measurement should provide accurate results when the structure is larger than the diffusion length in the annealed implant. For typical high-dose shallow implants, this is on the order of 10mm.
[1] Proceedings of the Fifth International Workshop on Measurement, Characterization and Modeling of Ultra-Shallow Doping Profiles in Semiconductors, usj-99, Research Triangle Park, NC, March 1999, pp. 314-18.

B6.13
THE IMPACT OF POINT DEFECTS ON STRESS-INDUCED DISLOCATION GENERATION IN SILICON. Konstantin V. Loiko, Giri Nallapati, Keith M. Jarreau, Roy A. Hensley, Dale Simpson, Thomas E. Harrington, Dallas Semiconductor, Dallas, TX; Igor V. Peidous, University of the West Indies, Dept. of Physics, Kingston, JAMAICA.

Dislocation nucleation in silicon is often considered as a result of point defect interaction under high stresses. In the present work, the correlation between crystal defects, associated with point defects, and dislocations has been studied in LOCOS structures. A denuded zone of varying width was created in starting wafers. In some wafers, bulk oxygen precipitation was enhanced by polysilicon deposition on the backside. Nitride and pad oxide films of several thicknesses and different oxidation conditions were used to vary stress levels in LOCOS structures. By changing the parameters of plasma etching of a nitride mask, the influence of plasma-induced damage on dislocation generation was also evaluated. Densities of oxide precipitates, stacking faults, and dislocations were found to correlate both on the surface and in the bulk of the structures. Polysilicon on the wafer backside often caused the formation of stacking fault rings where a high density of stress-induced dislocations was observed as well. In the area of surface defect rings, the density of bulk oxygen precipitates and stacking faults was higher and the denuded zone was significantly reduced. Similar defect ring patterns were found on the wafers subjected to excessive plasma etching. In the structures with aggressive nitride/oxide stacks, dislocation pileups could be seen at the edges of wide nitride lines. High field oxidation ramp rates aggravated this effect. SUPREM-4 simulations of stresses and distributions of self-interstitials injected during LOCOS processing were performed. The results of the modeling and experiments are interpreted in terms of factors responsible for the onset of dislocation generation in the fields of localized high stresses. The agglomeration of silicon interstitial atoms does not seem to play a notable role in dislocation nucleation. It is rather associated with the presence of such dislocation sources as oxide precipitates and surface mechanical damage. Critical stresses obtained for dislocation generation in the presence of oxide precipitates are almost three times as low as those for the precipitate-free silicon.

SESSION B7: CARBON DIFFUSION AND INTERACTION WITH POINT DEFECTS
Chairs: Peter A. Stolk and Jim Williams
Wednesday Morning, April 26, 2000
Salon 3/4 (Marriott)

8:30 AM *B7.1
DIFFUSION ENGINEERING BY CARBON IN SILICON: AN OVERVIEW. Ulrich Gosele, René Scholz, Peter Werner, Pierre Laveant, Max Planck Institute of Microstructure Physics, Halle, GERMANY.

Carbon is incorporated in crystalline silicon mainly on substitutional sites in an electrically inactive form. Recently, it was reported that incorporation of a high concentration of carbon can drastically reduce or even prevent implantation-induced transient-enhanced diffusion (TED) of boron. The present contribution will give an overview on what is known about the properties and behavior of carbon in silicon and how the observed prevention of TED of boron may be understood and simulated in terms of the kick-out and the Frank-Turnbull mechanism of carbon diffusion in silicon. The role of undesirable carbon precipitation at long processing times and/or high processing temperatures will be discussed as well as the potential influence of oxygen on carbon diffusion. Application of localized carbon doping to dopant diffusion engineering in heterobipolar SiGe transistors will also be dealt with.

9:00 AM B7.2
KINETIC MONTE CARLO SIMULATIONS OF CARBON DIFFUSION IN SILICON. Ruth Pinacho[1], Martin Jaraiz[1], Hans-Joachim L. Gossmann, George H. Gilmer, Janet L. Benton, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; Peter Werner, MPI of Microstructure Physics, Halle, GERMANY. [1]permanent address, Dto Electricidad y Electronica, Univ Valladolid, SPAIN.

In this work, we investigated different models for carbon diffusion in silicon in order to fit experimental data, using the Monte Carlo atomistic simulator DADOS. These profiles are superlattice carbon structures grown by MBE and annealed at different temperatures from 680°C to 950°C. Carbon concentrations ranged from 2×10^{19}cm^{-3} to 2×10^{20}cm^{-3}, exceeding by far the solid solubility. The thermal equilibrium of intrinsic point defects at the surface is simulated by the injection of point defects, together with their surface recombination. The experimental profiles can not be fitted assuming

the simple kick-out mechanism and including well established values of the product of diffusivity and equilibrium concentration of the intrinsic point defects. In particular, samples annealed at 950°C exhibit an immobile fraction of C that can only be explained by the introduction of carbon complexes. The low solubility of carbon in silicon at the annealing temperatures explains why these complexes are formed, even under conditions where the self-interstial concentration is below the equilibrium value.

9:15 AM B7.3
PROBING POINT DEFECTS IN SILICON BY DIFFUSION OF SUPERSATURATED CARBON. H. Rücker, B. Heinemann, R. Kurps, D. Krüger and H.J. Osten, IHP, Frankfurt (Oder), GERMANY.

Diffusion of supersaturated C out of C-rich Si is a new way to create non-equilibrium point defects [1]. We have shown that B and P exhibit suppressed, and As and Sb enhanced diffusion in C-rich Si [2]. This is attributed to undersaturation of Si self-interstitials and supersaturation of vacancies caused by outdiffusion of C from regions of high C concentration. We have measured the diffusion of B, P, As, and Sb from highly doped substrates into Si and Si:C layers by secondary ion mass spectroscopy. Furnace anneals were performed at temperatures between 800°C and 900°C. Coupled diffusion equations of C and Si point defects were solved to calculate point defect densities and to fit diffusion profiles of dopants and C. The analysis provides evidence for the formation of vacancies in regions of low interstitial and high C concentrations. Reaction rates for the formation of vacancies were determined from measured diffusion profiles. Also, this analysis confirms that diffusion of B and P is predominantly by an interstitial mechanism (> 98%) and diffusion of As and Sb is dominated by a vacancy mechanism. The reported suppression of the interstitial mechanism (B, P) and enhancement of the vacancy mechanism (As, Sb) allow the use of C doping to modify dopant diffusion during device processing in a controllable way.
[1] H. Rücker et. al. Appl. Phys. Lett. 73, 1682 (1998), R.F. Scholzet. al. Appl. Phys. Lett. 74, 392 (1999).
[2] H. Rücker et. al., IEDM Tech. Dig. (1999), in press.

9:30 AM B7.4
BORON DIFFUSION IN SILICON IN THE PRESENCE OF HIGH CARBON CONCENTRATION. M.E. Law, Michelle Griglione and Misty Northridge, Dept. of Electrical Engineering, University of Florida, Gainesville, FL.

High carbon concentrations have been observed to complexly affect point defect concentrations in silicon. Specifically, reduced transient enhanced diffusion of boron during ion implantation has been observed in the regions of high C concentration. This behavior has been attributed to interactions between C and Si interstitials that deplete the interstitials available to assist B diffusion. Most molecular beam epitaxy, Float Zone and Czochralski processes result in C concentrations in Si which exceed the solid solubility limit. It is, therefore, important to predict the impact of these high C concentrations on point defect and dopant behavior in Si. It is generally believed that the kickout (KO) mechanism, in which a substitutional C interacts with a Si interstitial to form a C interstitial, governs C diffusion in Si. But there is also a possibility that the Frank-Turnbull (F-T) reaction, in which a C interstitial interacts with a lattice vacancy to form a C substitutional, operates simultaneously. Therefore, in the overall model of C interaction with Si, concentrations of vacancies as well as Si interstitials must be considered. In this contribution, we have performed simulations with the FLorida Object Oriented Process Simulator (FLOOPS) accounting for both the KO and F-T mechanisms to predict C and B diffusion in Si with high C background concentration. We have satisfactorily fitted previously reported C in Si diffusion data for processing temperatures from 730 to 900°C and C concentrations from 10^{18} to 10^{20} cm^{-3} using consistent reaction rates for each mechanism. Using the same model, we have also satisfactorily fitted B diffusion data under three different surface conditions: oxidation, nitridation, and vacuum. We will describe our most recent attempts to use this model as well to fit the diffusion of B in regions of varying C background concentration.

9:45 AM B7.5
DAMAGE ENHANCED DIFFUSION OF BORON IN SiGe FILMS. D. Chidambarrao, B. Jagannathan, K.T. Schonenberg[1], A. Turansky[2], P.A. Ronsheim[2], O.H. Dokumaci, IBM Semiconductor R&D Center, Hopewell Junction, NY; [1]IBM T.J. Watson Research Center, Yorktown Heights, NY; [2]IBM Analytical Services, Hopewell Junction, NY.

In this paper we study the diffusion enhancements of boron in silicon germanium (SiGe) from Si (5e13#/cm^2, 40keV) and C (1e14#/cm^2, 120keV) implants. Boron (with peak concentration of 1e19 #/cm^3) is grown-in as a sharp profile within an 80nm epitaxial film which is either Si or $Si_{0.9}Ge_{0.1}$. Both types of wafers were then capped with a 0.3μm Si layer. For 10% Ge films, the 80nm thickness is below the critical value for misfit dislocation formation. The effect of various anneal temperatures and times on the diffusion enhancements of boron from the implants are examined in Si and $Si_{0.9}Ge_{0.1}$ films. Diffusion enhancements decrease as Ge content is increased. We evaluate these enhancements in the context of previously observed {311 dissolution rates from the Si implant. The competition between enhancement caused by damage from the C implant versus the retardation from trapping of interstitials by C is also discussed. Interesting asymmetries in the B profile from the C implant are discussed. Possible mechanisms are suggested to explain the observations and we consider both chemical and stress effects.

SESSION B8: GROUP V DOPANT DIFFUSION AND ACTIVATION
Chairs: Jim Williams and Peter A. Stolk
Wednesday Morning, April 26, 2000
Salon 3/4 (Marriott)

10:30 AM B8.1
DEACTIVATION KINETICS AND CLUSTERING EQUILIBRIA IN As DOPED Si. Dario Nobili, Sandro Solmi, CNR-Lamel Institute, Bologna, ITALY; Jenta Shao, Shanghai Institute of Optics and Fine Mechanics, Shanghai, CHINA; Marco Merli, INFM, University of Ferrara, Ferrara, ITALY.

The kinetics of electrical deactivation of As in silicon after annealing at temperatures in the range 550 - 800 C, was studied in conditions which approach clustering equilibria. The present work complements the previous one which was performed in conditions where the reverse rate was negligible ([1] D. Nobili, S. Solmi, J. Shao and M. Merli, J. Electrochem. Soc., 146, Nov (1999)). Moreover, we determined the equilibrium values n_{eq} of the carrier density vs dopant concentrations C_{AS} at the temperatures of 700, 800 and 900 C .
Experiments where performed on SOI samples obtained by wafer bonding techniques, uniformly doped at concentrations C_{AS} up to $8x10^{20}$ cm^{-3} and patterned with the Wan der Pauw geometry. After isothermal annealing carrier concentration and mobility were determined by resistivity and Hall measurements.
It was verified that the deactivation kinetics obtained by annealing the different compositions at 800 C, can be accurately simulated by the rate equation reported in [1], by addition of a term which accounts for the declustering, i.e.:

$$-\frac{dn}{dt} = A \exp(-1.9/kT)[\exp(\alpha\ n/kT) - \frac{n_o - n}{n_o - n_{eq}} \exp(\alpha\ n_{eq}/kT)]$$

where n_o is the initial carrier density. A and α are constants which depend only on total As concentration and are independent of temperature. At lower temperatures an additional phenomenon, which is under investigation, modifies the deactivation kinetics near to the equilibrium conditions.
Concerning the equilibrium values of the carrier density n_{eq}, it was found that with increasing C_{AS} they show a marked saturation behavior which is more pronounced with decreasing temperature. A normalized empirical expression which describes the dependence of the equilibrium carrier density on both temperature and As concentration has been determined.

10:45 AM B8.2
TRANSIENT ENHANCED DIFFUSION OF ARSENIC BY SELF-IMPLANTATION. Ryangsu Kim, Takenori Aoki, Yoshikazu Furuta, Hiroyuki Kobayashi, Jianxin Xia, Tomoya Saito, Yoshinari Kamakura and Kenji Taniguchi, Department of Electronics and Information Systems, Osaka University, Osaka, JAPAN.

The effects of low dose Si-implantation damage on transient enhanced diffusion (TED) of arsenic in Si has been investigated. Arsenic was implanted into p-type Cz-Si wafers at 30keV for doses of 5×10^{13} and $5\times10^{14}cm^{-2}$, which were split into two lots. One was followed by annealed in the temperature at 720-820°C. The other was preannealed to recrystallize the amorphous layer formed by implanted As itself, then implanted with 50keV Si at three different doses (1×10^{13}, 5×10^{13} and $1\times10^{14}cm^{-2}$), followed by annealed in the temperature at 720-820°C. The As diffusion in Si-implanted substrates was enhanced compared to that of Si-unimplanted substrates at the end of transient stage, and the enhancement increased with increasing Si-implantation dose. This result shows that TED of As which diffuses both interstitial- and vacancy-mechanism is driven by interstitials induced by implantation. However, TED in some of the high dose As implanted substrates was slightly suppressed by Si-implantation compared to that of Si-unimplanted substrates during initial transient stage. This implies that As atoms and self-interstitials might form clusters on Si implantation or during initial stage of annealing because such a suppression by Si-implantation was not found in the case of low dose As implantation.

11:00 AM B8.3
IDENTIFICATION, DIFFUSION AND ELECTRICAL PROPERTIES OF VACANCY-IMPURITY COMPLEXES IN N-TYPE Si. K. Saarinen, J. Nissila, M. Hakala, M.J. Puska, and P. Hautojarvi, Laboratory of Physics, Helsinki University of Technology, FINLAND.

In the As and Sb doping of Si the concentration of free electrons saturates at the level of $\leq 5 \times 10^{20} cm^{-3}$ when the impurity concentration is increased. This behavior is indicative of the formation compensating defects that trap free electrons. There is presently no consensus on the detailed nature of these defects. Theoretical results propose that the vacancy-impurity complexes are formed very abundantly and they may also play distinct roles in the diffusion and clustering of impurities [1]. In this work we continue our earlier study [2] and show that the detailed atomic structure of vacancy-impurity complexes in Si can be experimentally determined by combining positron lifetime and electron momentum distribution measurements. The vacancies complexed with a single impurity, V-P and V-As, are identified in electron irradiated Si. The formation of native vacancy defects is observed in highly As-doped Si at the doping level of $10^{20} cm^{-3}$. The defects are identified as monovacancies surrounded by three As atoms. The formation of $V - As_3$ complex is consistent with the theoretical descriptions of As diffusion and electrical deactivation in highly As doped Si [1]. In particular, we discuss the creation of $V - As_3$ complex as a result of the migrations of V-As and $V - As_2$ at the growth temperature. New results concerning the the thermal stability of $V - As_n$ (n = 1 - 3) complexes will also be shown.
[1] M. Ramamoorthy and S.T. Pantelides, Phys. Rev. Lett. 76, 4753 (1996).
[2] K. Saarinen et al., Phys. Rev. Lett. 82, 1883 (1999).

11:15 AM B8.4
INTERACTIONS BETWEEN ARSENIC, GERMANIUM, AND SILICON INTERSITIALS. Richard Brindos, Patrick Keys, Mark Law and Kevin Jones, Swamp Center, University of Florida, Gainesville, FL.

Understanding the solid solubility and diffusion of arsenic in silicon is becoming very important in the development of new devices. The ability to accomplish this will depend on our understanding of how arsenic and silicon interstitials interact. This work investigates the fundamental issue of how arsenic and silicon interstitials interact in reference to the release of silicon interstitials. A 5keV 5×10^{14} cm^{-2} arsenic or germanium implant was done into silicon with CVD grown boron marker layers. The samples then received an RTA anneal of 1050°C for 15 sec to repair implant damage from the arsenic or germanium implant. Following the RTA anneals all samples received an 25keV 1×10^{14} cm^{-2} silicon implant. The samples were then furnace annealed at various temperatures and times in an nitrogen ambient. SIMS analysis was done throughout this experiment on the boron marker layers, as well as on the arsenic and germanium profiles. The Boron marker layers were used to monitor TED from the surface and help determine the interactions between arsenic, germanium, and silicon interstitials. SIMS results were inserted into FLOOPS and time averaged enhancement values were extracted. These enhancement values plus a simple model for arsenic-interstitial interaction will be presented and discussed.

11:30 AM B8.5
ANTIMONY CLUSTERING DUE TO HIGH DOSE IMPLANTATION. Kentaro Shibahara, Dai Onimatsu, Hiroshima Univ., Research Center for Nanodevices and Systems, Higashi-Hiroshima, Hiroshima, JAPAN.

We have reported that the sheet resistance of an Sb implanted layer was reduced by changing activation process from furnace annealing (FA) to rapid thermal one (RTA) because of reduction in Sb pileup at the SiO_2/Si interface[1]. The obtained sheet resistance was 450 Ω/sq. for 24-nm-deep junctions fabricated with 10 keV and 3x10^{14} cm^{-2} Sb^+ implantation. In this paper further increase of Sb dose beyond an Sb precipitation limit of 4x10^{14} cm^{-2} in bulk silicon under FA has been investigated[2]. Antimony was implanted into Si through a 5-nm-thick screen oxide at 10 keV and up to 6x10^{14} cm^{-2}. By RTA at 800°C for 10 s the Sb pileup was not observed in the SIMS profile at a dose of 6x10^{14} cm^{-2}, while the sheet resistance was 600 Ω/sq. which is higher than the case of 3x10^{14} cmc dose. The SIMS analysis has indicated the existence of Sb_2^- molecular ions which arise from Sb clusters in Si. Clustered Sb atoms are electrically inactive. The Sb_2^- ions were detected not only in annealed specimens but also in as implanted ones. The Sb_2^- depth profile for 800°C RTA specimens was almost the same as that for as implanted. The peak position of Sb_2^- distribution moved to the surface side with the increase of annealing temperature. This implies that Sb clusters were formed during the implantation and redistributed during annealing. [1] K. Shibahara et al., Extend. Abst. 1999 Int. Conf. Solid State Devices and Materials pp. 314-315. [2] M. Hashimoto et al., Jpn. J. Appl. Phys. Vol. 33 (1994) pp. L1799-L1802.

11:45 AM B8.6
NITROGEN IN SILICON: FAST DIFFUSION THROUGH A PURELY INTERSTITIALCY MECHANISM. Peter A. Schultz and Jeffrey S. Nelson, Sandia National Laboratories, Albuquerque, NM.

Nitrogen implantation can be used to regulate gate oxide thicknesses, and enable the the growth of ultra-thin gate oxides. The critical element appears to be the rapid diffusion of the N to the Si/SiO_2 interface, but the process by which this diffusion is enabled is poorly understaood. We use first-principles local density functional calculations to study substitutional N in Si and its interaction with Si self-interstitials. In addition to describing the mechanism by which N diffuses rapidly through Si, the results also rationalize the low solubility of substitutional N in Si. Nitrogen captures a Si interstitial with 3.5 eV binding energy to form an N interstitialcy with three bonds. The low-energy diffusion path is through a two-bonded N interstitialcy, rather than via a kick-out mechanism into a non-bonded state, with a barrier <1 eV. Rapid diffusion of N through Si is achieved in a path where N never has fewer than two bonds. Since the Si self-interstitial has a formation energy of 3.6 eV, the N interstitialcy has a near-zero (∼0.1 eV) formation energy, explaining the low solubility of N[sub].

SESSION B9: VACANCY-TYPE DEFECTS–INTERACTION AND CHARACTERIZATION
Chairs: Scott T. Dunham and John M. Poate
Wednesday Afternoon, April 26, 2000
Salon 3/4 (Marriott)

1:30 PM *B9.1
VACANCIES IN MeV IMPLANTED SILICON. V.C. Venezia, Lucent Technologies, Bell Labs, Murray Hill, NJ.

High energy ion implantation into silicon creates a net defect distribution that is characterized by a concurrent supersaturation of interstitials, near the project-ion range (Rp), and vacancies, at approximately half the projected ion range (Rp/2). In this talk I will discuss the evolution of the vacancy supersaturation in MeV implanted silicon, from free vacancies to vacancy clusters, reviewing experimental and theoretical results. The excess vacancy region was originally observed as open volume defects in high-energy, high dose O and Si implanted silicon by positron annihilation spectroscopy. Impurities, such as oxygen and transition metals, have been observed to getter at Rp/2, similar to impurity gettering at He and H induced voids. The getter at Rp/2 has since been associated with the presence of vacancy clusters created by high-energy implantation and annealing. Based on the observations of Rp/2 metal impurity gettering, we have developed a technique known as Au labeling to profile vacancy clusters in silicon. Free vacancy supersaturations are measured by quantifying the enhanced diffusion of a dopant that diffuses by a vacancy mechanism, such as Sb. Correlating the results of Sb diffusion experiments with Au labeling results, which measures vacancy clusters, the evolution of the excess vacancy region in MeV implanted silicon has been tracked. During the very early stages of annealing a large burst of free vacancies dominates the region between the surface and Rp. Within this burst, stable vacancy clusters form that release free vacancies at a rate similar to the formation of thermal vacancies, indicating that the binding energy of these clusters is similar to the vacancy formation energy in silicon. These observations imply that after the initial burst of vacancies, the vacancy clusters provide a sink for interstitials but not a significant source of free vacancies.

2:00 PM B9.2
CALIBRATION OF THE "Au-LABELING" METHOD TO MEASURE EXCESS VACANCY PROFILES IN MeV-IMPLANTED Si. R. Kalyanaraman, V.C. Venezia*, T.E. Haynes, H-J. Gossmann*, D.C. Jacobson*, D.J. Eaglesham* and C.S. Rafferty*, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN. *Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

It has been shown recently[1] that "Au labeling" can be used to qualitatively profile the excess vacancy defects in the ΩR_p region of MeV self-implants in Si. The technique is based upon the presumption that the concentration of trapped Au is proportional to the excess vacancy concentration. Using controlled injection of known doses of interstitials into prepared vacancy profiles, we provide direct evidence that the trapped Au concentration is indeed proportional to the vacancy concentration. Furthermore, the change in the trapped Au concentration as a function of the injected interstitials enables us to

obtain the "calibration factor", representing the ratio of vacancies to trapped Au. The results of this work clearly show that the "Au profiling" technique provides a convenient way to quantify the excess vacancy profiles. Based on the calibration experiments, the reliability and sensitivity of this technique will be discussed. [1]V.C.Venezia et al, Appl. Phys. Lett.73, 2980 (1998).

2:15 PM B9.3
THE FORMATION AND STABILITY OF VACANCY CLUSTERS AND VOIDS IN SILICON FOLLOWING ENERGETIC ION BOMBARDMENT. J.S. Williams, M.J. Conway, X.F. Zhu, B.C. Williams, J. Wong-Leung, Department of Electronic Materials Engineering, The Australian National University, Canberra, AUSTRALIA; M.C. Ridgway, F. Fortuna, M-O. Ruault, H. Bernas, CSNSM, Centre National Recherche Scientifique-IN2P3, Orsay, FRANCE.

The formation of open volume defects (vacancy clusters and voids) during ion bombardment and their stability during subsequent annealing is currently a topic of considerable interest. For example, the appearance of so-called $R_p/2$ defects has been attributed to vacancy excesses in the near-surface region during implantation but such defects have not yet been characterised in any detail. In this study, we have addressed the formation and stability of such open volume defects in Si in a comprehensive series of experiments. In particular, 245 keV Si^+ ions, at various doses and target temperatures up to 300°C, have been implanted into Si(100) wafers with and without a pre-existing band of nanocavities. The samples were subsequently annealed up to 850°C. Ion channeling and XTEM were used to determine disorder distributions and defect structure. The preferential decoration of open volume defects with Au was also used as a sensitive detector of residual voids after annealing. Results indicate that nanocavities close to the ions end of range shrink during bombardment, whereas the density of open volume defects closer to the surface increases with dose. Moreover, the depth distribution of ion-induced open volume defects is both temperature-dependent and dose-dependent. In some cases this distribution can extend from > $R_p/2$ up to the surface. There is also evidence that open volume defects can survive amorphisation in some cases. For example, if buried amorphous layers are formed at higher doses and overlap regions originally containing open volume defects at lower doses, such open volume defects re-emerge when the buried layers are crystallised during annealing. The above results are discussed in terms of defect interactions during both implantation and annealing.

2:30 PM B9.4
CONCENTRATION PROFILES OF VACANCY DEFECTS FROM MeV IMPLANTS IN Si: DEPENDENCE ON ION SPECIES AND DOSE. T.E. Haynes, R. Kalyanaraman, H-J. Gossmann*, D.C. Jacobson* and C.S. Rafferty*, Solid State Division, Oak Ridge National Laboratory, Oak Ridge, TN. *Bell Laboratories, Lucent Technologies, Murray Hill, NJ.

Monte Carlo simulation codes such as TRIM or MARLOWE show a net displacement of interstitials with respect to vacancies from the Frenkel pairs produced in implant cascades. This effect is most evident for high-energy and/or large mass implants. As a result of this displacement, calculated damage profiles show an excess of vacancies in the shallow region of these implants, with excess interstitials near R_p. In this work, the "Au profiling" technique has been used to quantitatively analyze and compare the depth profiles of excess vacancies produced by implants of B, Si, and Ge into Si for a range of doses. Specific conditions, like matching of the projected range of the implanted ions, matching of the nuclear energy deposited at ΩR_p, similar doses, etc. have been compared. This detailed study provides the first systematic, quantitative measurements of the excess vacancy concentrations over such a range of species and doses. Interestingly, some general characteristics of the excess vacancy profiles differ from simulations. For example, while the calculations predict essentially flat profiles up to the surface, the experimental observations differ in that there is a depletion of the vacancy concentration near the surface. We will discuss the origins of this and other aspects of the measured vacancy profiles.

2:45 PM B9.5
EXCESS-DEFECT MODEL APPLIED TO DEFECT INTERACTIONS FROM ION IMPLANTATION OF Si. E.G. Roth and J.L. Duggan, University of North Texas, Department of Physics, Denton, TX.

Application of a new, excess-defect model provided descriptions of resultant defect distributions following ion implantation and post-implant thermal annealing of Si. The validity of this excess defect model is ascertained through a variety of experiments that apply the model for the successful prediction of excess defects that survive both the implant and the anneal. Co-implantation of high- and medium-energy Si^+-ions was used to reduce the concentration of complementary defects by inducing recombination of the spatially correlated defects. Exploring the synergism of dual implants of high- and medium-energy (both below and above the amorphization threshold) implants increases the understanding of resulting defect interactions and dynamics following ion irradiation of Si. The dependence of these interactions between complementary excess defects will be discussed as functions of implant parameters, specifically fluence and temperature, as well as annealing parameters, both time and temperature. Several analyses in conjunction with relevant calculations will attempt to not only qualify, but also, quantify resulting defect configurations to further the understanding of dynamic defect interactions.

SESSION B10: REGROWN AMORPHOUS LAYERS
Chairs: John M. Poate and Scott T. Dunham
Wednesday Afternoon, April 26, 2000
Salon 3/4 (Marriott)

3:30 PM B10.1
THE ROLE OF VACANCIES AND DOPANTS IN Si SOLID PHASE EPITAXIAL CRYSTALLIZATION. Claudine M. Chen[1], M.P. Petkov[2], S. Rassiga[2] , M.H. Weber[2], K.G. Lynn[2] and H.A. Atwater[1]. [1]T.J. Watson Laboratory of Applied Physics, California Institute of Technology, Pasadena, CA, [2]Washington State University, Pullman, WA.

We investigate the role and interaction of vacancies and dopants in crystallization of amorphous Si (a-Si) by solid phase epitaxy (SPE). To this end, we correlate: (i) the solid phase epitaxy rate measured by time-resolved reflectivity (TRR), (ii) the total and electronically-active doping concentrations measured by secondary mass spectrometry (SIMS) and spreading resistance analysis, and (iii) the vacancy concentration measured by positron annihilation spectroscopy (PAS) in crystallization of a-Si. Float-zone silicon samples were implanted with B, P and both P and B ions to create nonuniform doping profiles at degenerate doping levels, after an amorphization step by $^{29}Si^+$ ions. Samples were vacuum annealed with the amorphous-crystal interface stopped at various depths relative to the doping profile, providing frozen frames of the SPE process. PAS is used to obtain vacancy depth profiles, as well as to identify the impurity-defect complexes. Momentum-resolved PAS measurements enable the detection of bound vacancy-P and vacancy-O complexes. Other features observed in PAS depth profiles will be discussed. This work is supported by the United State Department of Energy, Basic Energy Sciences.

3:45 PM B10.2
BORON ACTIVATION DURING SOLID PHASE EPITAXIAL REGROWTH. Chad D Lindfors, Kevin S. Jones, Univ. of Florida, Dept. of Materials Science and Engineering, Gainesville, FL; Dan Downey, Varian Semiconductor Equipment Association, Gloucester, MA.

To continue scaling down dimensions of transistors higher dopant concentration levels are needed for ultra-shallow contacts. Therefore studies of dopant activation have been performed in preamorphized silicon wafers with various boron implants conditions to determine the maximum achievable dopant concentrations after solid phase epitaxial regrowth alone. Si wafers are implanted with silicon or germanium at an energy and dose of 40 keV, 1×10^{15} cm^{-2} for silicon and 80 keV, 1×10^{16} cm^{-2} for germanium. Following this preamorphization step, the wafers were implanted with boron at an energy of 2 keV in the dose range of 5×10^{14} cm^{-2} to 2×10^{16} cm^{-2}. Solid phase epitaxial regrowth (SPER), in the temperature range of 500°C to 650°C was performed to examine activation as a function of annealing time. Variable angle spectroscopic ellipsometry (VASE) was utilized to determine amorphous layer thickness so exact times to complete regrowth are known. Secondary ion mass spectrometry (SIMS) is used to determine the dose retained and the integrated dose in the regrown Si during SPER. Measurements on the Hall effect system yield the activated dose of dopant, which is used with the SIMS results to find the percent activation. It is observed that the dopant is activated during incorporation in the crystalline Si and the maximum dopant incorporation during SPER is comparable to that observed during RTA at high temperatures.

4:00 PM B10.3
EFFECT OF VERY LOW TEMPERATURE ANNEALING ON THE AMORPHOUS/CRYSTALLINE INTERFACE IN ION IMPLANTED SILICON PRIOR TO LASER THERMAL PROCESSING. H.B. Banisaukas, K.S. Jones, Swamp Center, Dept. of Materials Science and Engineering, University of Florida, Gainesville FL; S. Talwar, Verdant Technologies, San Jose, CA; D.F. Downey, Varian Semiconductor Equipment Associates, Gloucester, MA.

The further scaling of device dimensions prompts an investigation into alternate implantation and annealing techniques for the formation of

defect free ultra-shallow highly doped junctions. Laser thermal processing (LTP), which involves melting and recrystallization of an implantation induced amorphous layer, has shown promising results in creating ultra shallow junctions. However, a better understanding of the effect of the laser annealing process on the formation of extended defects is needed. In order to possibly reduce the density of extended defects that form upon melt recrystallization, a low temperature pre-annealing process was studied. The effect of very low temperature annealing (VLTA) on the amorphous/crystalline interface created by a 10 keV 1E15 Si implant was studied by high-resolution cross-sectional transmission electron microscopy (HR-XTEM). The annealing temperatures studied were 400C to 450C in order to avoid recrystallization of the amorphous layer by solid phase regrowth. The amorphous/crystalline interface peak to valley roughness was reduced from 45$\AA$ to 15$\AA$ after 400C 60 min. Upon laser thermal processing, the defect density was reduced significantly. Results comparing defect density after LTP with and without VLTA over a variety of annealing and laser processing conditions will be presented. Further correlations of the effect of the amorphous/crystalline interface roughness on defect formation will be presented.

4:15 PM B10.4
A PHYSICALLY BASED MODELING OF BORON TED IN AMORPHISED Si. E. Lampin, V. Senez, IEMN/Dept. ISEN, Villeneuve d'Ascq, FRANCE; A. Claverie, CEMES/CNRS, Toulouse, FRANCE.

We have developed a physically based modeling of TED of implanted boron in amorphised Si. The simulation starts with a supersaturation of Si free interstitials (Si(int)s) located below the c/a interface which, upon annealing, tend to diffuse out or to precipitate in the form of extended defects (clusters, {113}s, loops). The modeling of the nucleation and growth of these defects is divided into 3 distinct stages: the nucleation, driven by a decrease of the free energy, the pure growth where the defects mostly act as sinks for the remaining free Si(int)s, and the Ostwald ripening where the defects act as sources and sinks and evolve in dynamical equilibrium with the free Si(int)s. This system can interact with a surface (characterized by a given recombination velocity for Si interstitials) only after the SPE regrowth is completed. Implementation of this model into a process simulator allows to describe the isothermal and isochronal evolutions of the sizes and of the densities of dislocation loops in agreement with TEM observations. Assuming that boron TED is caused by the concomitant time and space variations of the free Si(int)s supersaturation in the wafer, boron TED can be accurately predicted for a variety of experimental conditions. It is shown that, while not affecting too much the defect evolution itself, the value of the recombination velocity is a crucial parameter to estimate the amount of TED after given annealing conditions.
This model simulates all the intriguing characteristics of TED and sheds light on the role and influence of experimental parameters such as, the initial supersaturation (ion dose), the distance between defects and surface (ion energy) and the recombination velocity (annealing ambient).

4:30 PM B10.5
EFFECTS OF NONMELT EXCIMER LASER ANNEALING ON 5KEV BORON IMPLANTED SILICON. Susan Earles, Mark E. Law, Kevin S. Jones, Swamp Center, University of Florida, Dept of Electrical and Computer Engineering, Gainesville, FL.

The effects of excimer laser annealing (LTP) on boron implanted silicon has been studied. Silicon was implanted with 5keV, 1e15/cm^2 boron and then laser annealed for 15ns at energies low enough to have high activation without melting the silicon. Furnace anneals and RTA followed by Hall Effect, SIMS, and Plan-view TEM were then done to study the activation, diffusion, and microstucture of the boron implanted silicon. Results show nearly 100% boron activation following the LTP and RTA along with an increase in hall mobility as the laser energy was increased. Samples receiving the LTP showed no diffusion when compared to the as-implanted profile. However, samples receiving LTP and RTA diffused more than samples just receiving the RTA. TEM of samples which also had the RTA had similar loop densities. However, as the laser energy was decreased more of the loops shown terminated at the surface.

SESSION B11: STRUCTURE AND PROPERTIES OF POINT AND EXTENDED DEFECTS
Chairs: David J. Eaglesham and Martin D. Giles
Thursday Morning, April 27, 2000
Salon 3/4 (Marriott)

8:30 AM *B11.1
ATOMISTIC PROCESS MODELING: AN ACCURATE AND STRAIGHTFORWARD APPROACH FOR COMPLEX PROCESSING SCENARIOS. M. Jaraiz, L. Pelaz, J. Barbolla, Univ. Valladolid, Dept. Electronica, Valladolid, SPAIN; G.H. Gilmer, C.S. Rafferty, Lucent Technologies Bell Labs, Murray Hill, NJ.

The level of sophistication reached by todays Si device fabrication technologies has called for new modeling and simulation schemes, capable of handling the wide variety of interaction mechanisms that govern the complex phenomena that can occur at the atomic level. The kinetic Monte Carlo technique seems particularly apt for this task. It takes as input basic materials parameters, derived from ab inito calculations or from experiments, and is capable of carrying out a detailed simulation up to the dimensions and time scales of current ULSI Si device fabrication. In addition, it can accommodate and efficiently simulate complex interactions between multiple dopant and defect types. We describe the approach and present examples of application in both materials processing and device fabrication.

9:00 AM B11.2
Abstract Withdrawn.

9:15 AM B11.3
SELF-INTERSTITIAL CLUSTERS IN SILICON. M.M. De Souza, M. Shishkin and E.M. Sankara Narayanan, Emerging Technologies Research Centre, De Montfort University, Leicester, UNITED KINGDOM.

It is well established that the Transient Enhanced Diffusion (TED) of ion-implanted boron in silicon limits the progress of VLSI scaling. A hierarchy of interstitial defects ranging from smaller sized clusters, to large sized {311} defects have been found to influence TED. In this paper, we present the results of a detailed study of the formation of clusters from the single point defect in silicon. The study fills an important gap in our understanding of the relative stability and evolution of defect species during TED in silicon. Furthermore, for the first time, the results presented herein show the link between the structural properties at the atomic and the {311} cluster level. Recently, we proposed the possible existence of planar point defect self-interstitials in the {113}/{332} planes in silicon [1]. These interstitials, which are formed by a variation from the perfectly symmetrical hex-site in silicon, leave no dangling bonds and are therefore electrically neurtral. *We have developed a model for the formation of a chain by these interstitials in the* $< 110 >$ *direction.* Our investigations based upon state-of-the-art ab initio pseudo-potential calculations using CASTEP [2], indicate that the basic unit required for the formation of these chains is stable and has a strong correlation with the relevant crystallographic planes. This confirms that the habit plane of the aggregated {113} rod-like defect arises from the defect at the atomic level.
It is well known that the conventional dangling bond model to build chains in the $< 110 >$ direction results in an exponential reduction in the formation energy with size. In order to evaluate the stuctural dependence of formation energy for cluster sizes <12, simulations were carried out with a 4x4x4 cell using the empirical Ackland potential. Our analysis reveals a non-monotonic dependence of the formation energy for cluster sizes <12 because of the elimination of dangling bonds, which is consistent with the trend shown by experiments [4].
References:
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9:30 AM B11.4
OPTICAL, ELECTRICAL AND STRUCTURAL MODIFICATIONS IN THE TRANSITION FROM POINT-LIKE TO EXTENDED-DEFECTS IN ION IMPLANTED c-Si. Sebania Libertino, Salvatore Coffa, Domenico Arcifa, Antonino La Magna and C. Spinella, CNR-IMETEM, Catania, ITALY.

The use of ion implantation in Si processing requires a deeper understanding of the transition from point-like defects to extended defects and dopant-defect interaction in Si. In this work photoluminescence (PL), Deep Level Transient Spectroscopy (DLTS) and Transmission Electron Microscopy (TEM) measurements were used to characterize both p-type and n-type Si samples implanted with Si or B ions at energies of 0.04-1.2 MeV and doses of 1x10^9-1x10^{14} cm^{-2}. Samples were annealed at 300-800°C for times from 5s to 30h. After annealing at low temperatures (300-500°C), signatures of point-like defects dominate the electrical and optical spectra. The PL spectra are dominated by the W-line (at 1224nm, due to small I-pairs). PL measurements of samples implanted at doses $\geq$ 1x10^{12} Si/cm^2 and annealed at T $\geq$ 600°C show two broad features centered at ~1300 and 1400nm. On the same samples, also DLTS reveals broad features. These strong modifications in the electrical and optical properties are associated to the formation of I-clusters

producing a high strain in the lattice, as confirmed by TEM cross-sections. The presence of B produces significant modifications in the kinetics of I-clusters formation. Finally, DLTS and PL allowed us to monitor the transition from I-cluster to {311} defects. A characteristic PL line at 1376nm dominates the PL spectra when {311} are detected in TEM. We found that a dose and a temperature threshold exists for this transition. {311} form for doses $\geq$ 1x10^{13} Si/cm^2 and only after annealing $\geq$ 650°C. In fact, for a dose of 5x10^{13} Si/cm^2 implant, we did not observe {311} after annealing at 600°C for times up to 30h. These results suggest that an abrupt structural transition, probably involving I rearrangement, occurs in the evolution from I-cluster to {311} defects. Kinetic lattice Monte Carlo simulations, used to model I-cluster agglomeration and evolution upon annealing, confirm this scenario.

9:45 AM B11.5
MONTE CARLO ANALYSIS OF THE EVOLUTION FROM POINT TO EXTENDED INTERSTITIAL TYPE DEFECTS IN c-Si. Antonino La Magna, Salvatore Coffa, Sebania Libertino, CNR-IMETEM, Catania, ITALY.

We present a detailed study of the micro-structural evolution leading to {311} defects formation upon annealing of a damaged Si-crystal. System kinetics is simulated by means of a Monte-Carlo approach, based on a super-lattice matrix which includes both regular sites and tetrahedral interstitial sites. Self-interstitials (I) agglomeration is modeled by using effective two bodies local interactions and considering the energetic cost of under/over coordinated Si atoms belonging to an I complex. The static properties of the I aggregates as derived by molecular dynamics calculations, in the two extreme regimes of very small and very large clusters, has been mapped in the model. A key feature of the model is to allow the transition of a Si-atom in a regular site to a empty first-neighbor tetrahedral site and viceversa. Such transition drives the kinetic evolution of small size aggregates including dumbbell diffusion, cluster reconfiguration and capture/dissolution processes. We have found that the early evolution stage of a interstitial super-saturation is characterized by the formation of cluster consisting of few interstitials in a over-coordination state. When I super-saturation exceeds a critical value, larger agglomerates, containing a few of these small I clusters all preserving their original structure, are formed. These non-structured agglomerates are the precursors of the correlated $< 110 >$ I-chains which are the structural units of {311} defects. Indeed, if the thermal budget is high enough, a transition takes place leading to I rearrangement along the chains. Such transition is driven by the recover of four-fold I-coordination and by back displacements of defective atoms to regular sites. The transition to {311} occurs only when I-saturation and annealing temperature exceed threshold values; otherwise the system remains frozen in a early evolution stages. These simulations suggest an unique explanation for several experiments on the optical, structural and electrical properties of ion implanted Si.

10:30 AM B11.6
EXPERIMENTS AND MODELLING OF EXTRINSIC DEFECT ENERGETICS AND ITS ROLE IN NONEQUILIBRIUM DOPANT DIFFUSION. Alain Claverie, CEMES/CNRS, FRANCE; Nicholas Cowern, Philips Research Laboratories, Eindhoven, THE NETHERLANDS; Rapid Consortium.

Annealing of ion-implanted Si leads to the formation of a range of extrinsic defects which drive nonequilibrium dopant diffusion. For accurate process TCAD it is important to understand the mechanisms by which small clusters evolve into {113} defects and then, at sufficiently high dose levels, transform into dislocation loops of different types. This ripening process is mediated by the interchange of free Si interstitials between different extended defects, leading to a decrease in total energy. Owing to the hierarchy of defect formation energies, both as a function of defect type and defect size, the defect evolution proceeds qualitatively as follows. First, small interstitial clusters evolve into {113} defects, then there is a {113} growth phase, an instability transition from large {113} defects into loops, and, finally, competitive growth between perfect and faulted dislocation loops. The consequence is a time-dependent decrease in super-saturation as seen in TED studies. The extent to which the defects evolve before finally evaporating to the surface, depends on the implant dose and the distance between the defect layer and the surface. At low doses/shallow implants, only small clusters are formed, while for high dose/deep implants the damage evolves through to loops which take a long time to dissolve. To handle this complex system we have developed a deceptively simple ripening model which is capable of modeling the entire range of defects from clusters to loops. The model simulates microstructural evolution under a wide range of ion implant and annealing conditions, and predicts a hierarchy of levels of nonequilibrium diffusion, ranging from supersaturations $S \sim 10^7$ in the presence of small clusters, through $S \sim 10^4$ in the presence of {113} defects, to S in the range 100 down to 1 as the loops evolve and finally evaporate. In summary, a detailed analysis of defect energetics has been carried out and it is shown that Ostwald ripening is the key concept for understanding and modelling TED of dopants in silicon.

10:45 AM B11.7
ENERGY DEPENDENCE OF TRANSIENT ENHANCED DIFFUSION AND DEFECT KINETICS. Hugo Saleh, Mark E. Law, Univ of Florida, Dept. of Electrical and Computer Engineering; Kevin S. Jones, Univ. of Florida, Dept. of Material Science and Engineering; Temel Buyuklimanli, Charles Evans East.

Boron, a P-type dopant, experiences Transient Enhanced Diffusion (TED) via interstitials resulting in the broadening of desired doping profiles. This paper explores Boron TED and {311} dissolution simultaneously and determines if there is an energy dependence. Silicon implants of 1E14 cm^{-2} at energies of 20, 40, 80, and 160 keV were used to create different damage profiles above a CVD grown buried boron marker on CZ wafers. Samples were annealed at 750, 800, and 900 C for a range of 15 to 135 minutes to observe the TED of the marker layer and to determine its dependence on the {311} type defects. Initial SIMS data for the 750 C anneals agree with the previous results; higher energy implants cause greater diffusion. Decay time constants of {311}s are extracted using PTEM analysis and are correlated with SIMS data.

11:00 AM B11.8
DEPTH DEPENDENCE OF {311} DEFECT DISSOLUTION. V.C. Venezia, R. Kalyanaraman, H.-J.Gossmann, C.S. Rafferty, D.J. Eaglesham, Bell Laboratories, Lucent Technologies, Murray Hill, NJ; L. Pelaz, Dto Electricidad y Electronica, Univ. Valladolid, SPAIN.

We have investigated the depth dependence of {311}-defect dissolution in silicon. {311} defects are agglomerates of excess interstitials that form in silicon during post-implant annealing. There is much experimental evidence that links the flux of interstitials from {311} dissolution to the phenomena of transient enhanced diffusion (TED). For instance, the time for cluster dissolution was found to be similar to the duration of TED, and the measured dose of interstitials in {311}'s is consistent with the doses required to match TED simulations. It has been previously shown that the duration of TED varies with implant depth. We report here on the depth variation of {311} dissolution, and show that it is consistent with the TED behavior. In this study we have created a deep band of {311} defects with a 350 keV Si implant followed by a cluster forming anneal. The depth of this band was varied by chemically etching off silicon surface layers. By varying the depth in this fashion we are assured that only the depth and no other feature of the distribution is changed, as would be the case if the implant energy were changed. We have found that the dissolution time for {311} defects formed by deep implantation is approximately 5 times greater than is predicted by the simplest model using only one cluster binding energy. Our data is fit extremely well by the model of Hobler, et al., which takes into account the variation of binding energy with cluster size. In addition we have also found that the dissolution time varied almost linearly with depth, confirming that dissolution of {311} defects is controlled by surface recombination, consistent with analogous observation of the depth dependence of TED.

11:15 AM B11.9
EFFECT OF SURFACE PROXIMITY ON THE END-OF-RANGE DEFECT MORPHOLOGY. Sushil Bharatan, Mark E. Law, Kevin S. Jones, University of Florida, Dept. of Materials Science and Engineering, Gainesville, FL.

At low implant energies, the implant and damage profiles are very close to the surface. Thus the effect of the surface on the interstitial supersaturation and evolution of extended defects following the implant and subsequent anneals becomes very important. Silicon samples are implanted at room temperature with Si^+ ions at an energy of 10 keV and to a dose of 1e15 cm^{-2} with different dose rates. The thickness of the amorphous layer formed is reduced by chemo-mechanical polishing. Thus the amount of damage beyond the amorphous/crystalline interface remains constant but its proximity ot the silicon surface is varied. The samples are then annealed in a furnace at 750°C in a flowing N_2 ambient for various times. After annealing, the defect morphology in the samples is studied using plan view transmission electron microscopy. For a higher dose rate implant (5 μA/cm^2) when the thickness of the amorphous layer is reduced from 250 $\AA$ to 50 $\AA$, the EOR defect morphology changes from a combination of type II dislocation loops and a few {311} defects to mainly {311} defects with a few dislocation loops. For low dose rate implants (25 nA/cm^2) there is a decrease in the amorphous layer thickness thus leading to an increase in the net excess interstitial concentration in the EOR region. Upon annealing only type II dislocation loops are formed and the trapped interstitial content is high enough to cause metworking. The same morphology is seen even when the amorphous layer thickness is reduced prior to annealing.

Additional data on the defect evolution along with an empirical model will be presented.

11:30 AM B11.10
RELATIVE STABILITY OF SILICON SELF-INTERSTITIAL DEFECTS: A COMPARATIVE STUDY OF FORMATION ENERGIES OF {311} DEFECTS AND DISLOCATION LOOPS.
G. Subramanian, K.S. Jones, University of Florida, Department of Materials Science and Engineering, Swamp Center, Gainesville, FL; M.E. Law, University of Florida, Department of Electrical and Computer Engineering, Swamp Center, Gainesville, FL; M.J. Caturla, S. Theiss and T. Diaz de la Rubia, Lawrence Livermore National Laboratory, Livermore, CA.

Small self-interstitial clusters, {311} defects and dislocation loops can be formed after implantation and annealing of a silicon wafer. Recent Transmission Electron Microscopy studies by J. Li and K.S. Jones have shown that sub-threshold dislocation loops nucleate from {311} defects. It is, therefore, interesting to understand the relative stability of different configurations and sizes of Si self-interstitial clusters. In this study we used the Stillinger Weber interatomic potential to calculate the formation energies of Si self-interstitials arranged in different configurations: chains of interstitials, {311} defects and dislocation loops. The conjugate gradient method is used to relax these structures. For small interstitial clusters molecular dynamics simulations were used to calculate the minimum energy configuration. The results obtained are discussed. We also study the stability of {311} defects depending on the length and the width of the interstitial chains. From these simulations consequences are extracted regarding the stability of {311} defects vs. dislocation loops as a function of size.

11:45 AM B11.11
FORMATION ENERGIES AND RELATIVE STABILITY OF DISLOCATION LOOPS IN SILICON.
Fuccio Cristiano, Benjamin Colombeau, Bernadette de Mauduit, Mourad Omri, Alain Claverie, CEMES/CNRS, Toulouse, FRANCE; Felipe Giles, Max Plank Institute for Microstructure Physics, Halle, GERMANY.

Diffusion of dopant impurities in silicon is strongly influenced by the thermal behaviour of the various types of extrinsic defects which form when annealing ion implantated silicon. These include small interstitial clusters, {113} defects, faulted dislocation loops (FDLs) and perfect dislocation loops (PDLs). The competitive growth of all these defects is governed by an Ostwald ripening process so that the final defect population is dominated by the most energetically stable defects. After a high thermal budget anneal, the dominant defect types are faulted and perfect dislocation loops. However, a discrepancy emerges from several plublished studies in which, depending on the experimental conditions, FDLs and PDLs are alternatively identified as the most stable defect. In this work, we have calculated the formation energies of both types of dislocation loops and explain this apparent discrepancy. For loop radii up to about 40 nm, the formation energy of FDLs is lower than PDLs. These calculations have been used to interpret experimental data obtained from two sets of silicon samples in which the initial supersaturation of Si interstitial atoms left after implantation differed by a factor 3. It is found that in the samples with a lower Si interstitial supersaturation, the formation energy of FDLs is lower than PDLs for all the anneal times studied. This is in accordance with the TEM observations which show that FDLs are the dominant defect type in these samples. Similar agreement is obtained in highly supersaturated samples, where PDLs appear as the most stable defects.