ION CLUSTER TECHNOLOGY

W. A. Krull
SemEquip, Inc., 34 Sullivan Road, N. Billerica, MA 01862 USA

A new implant technology has been developed as an alternative for low energy boron implant. The concept of this technology is to use a molecular ion which contains many boron atoms to avoid the fundamental issues with conventional ion implantation of low energy boron. A new chemical is used as the source of this molecule, octadecaborane, $B_{18}H_{22}$, and a new ion source has been developed to allow its utilization. It has been found that the implantation of $B_{18}H_{22}$ ions has additional advantages in terms of self-amorphization and elimination of crystal defects. Further, additional species with similar properties have been demonstrated, especially two molecules for delivering carbon.

INTRODUCTION

One of the challenges of scaling semiconductor technology is the need to constantly reduce junction depths as areal features are scaled. It is particularly challenging to scale the p-type junction depth because the ion implant equipment used throughout the industry is fundamentally unable to operate in the parameter regime necessary to produce the desired junctions. This problem has been avoided in recent technology nodes by evolving the annealing technology such that the reduction of implant energy has been delayed. With the advent of millisecond annealing technologies, there is no longer any opportunity to push annealing any further and the implant energy must be reduced. In this paper, a new implant technology is presented which directly solves the fundamental implant issues and provides a production worthy technology capable of satisfying scaling needs for the foreseeable future.

CLUSTER OR MOLECULAR IMPLANTATION

The basis concept of this new technology is the use of molecular ion species which contain more than one dopant atom. Conventional implant technology has always utilized ion species which contain only one dopant atom per ion. By using a species with “n” dopant atoms per electronic charge, the implant equipment operates at n times higher extraction voltage and thereby avoids the fundamental physics limitations of forming an ion beam at low extraction voltage. When this ion species enters the silicon wafer, the molecule dissociates and each atom behaves exactly as a conventionally implanted atom would, with atomic energy equal to the mass fraction of the total ion energy. It is noted that all atoms get exactly the same fraction of the ion’s energy, so there is no variation in the implant process results compared to implants performed by single atom ions. In this way, low energy boron implant processes can be performed on a conventional ion implanter with high productivity.

$B_{18}H_X^+$

A new chemical has been developed as a source of molecules which contain many boron atoms. The chemical is octadecaborane, $B_{18}H_{22}$. This chemical is used to produce an ion beam of species $B_{18}H_x^+$ which is found to be very useful for the range of low energy boron implants required for technology nodes at 65nm and smaller. For example, a 500eV equivalent boron implant is performed with an extraction voltage of 10keV using $B_{18}H_x^+$, a very comfortable range to operate any implantation system. This material is a solid at room temperature, which is beneficial for moderating the toxicity of this hydride material, but required the development of a new vaporizer technology for providing $B_{18}H_x^+$ vapor to the ion source. Fortunately, the material vaporizes in the range of 90-100^{o}C, allowing engineering solutions with high accuracy and reliability. At the other end, the material decomposes above 200^{o}C. Again, engineering solutions are easily able to operate in this temperature range with high robustness and moderate cost since the hardware can be fabricated from aluminum.

CLUSTERION SOURCE

In order to form an ion beam of $B_{18}H_x^+$, a new ion source was developed [1]. The basic concept of conventional ion sources is to break apart molecules to isolate the desired single atoms, and thus they operate with high temperature, high density plasmas as the basic ion excitation. In contrast, the ClusterIon source is designed to preserve the large molecule and so operates at low temperature with "soft ionization". The excitation for ionization is a low energy electron beam (~50mA of ~300eV electrons) which are generated remotely from the process vapor and transported to the region of ionization. In this way, a column of ionized vapor is created parallel and adjacent to the extraction slot, allowing for high efficiency extraction of the $B_{18}H_x^+$ ions. This soft ionization system has been demonstrated to be effective at ionizing the $B_{18}H_{22}$ vapor, and currents approaching 3mA of B_{18} ions have been demonstrated. The mass spectrum of the generated ion beam is shown in Fig 1, where it is seen that the dominant ion created is the $B_{18}H_x^+$ ion. The only other beam components are a small amount of doubly charged (B_{18}^{++}) and very small amounts of B^+ and H^+.

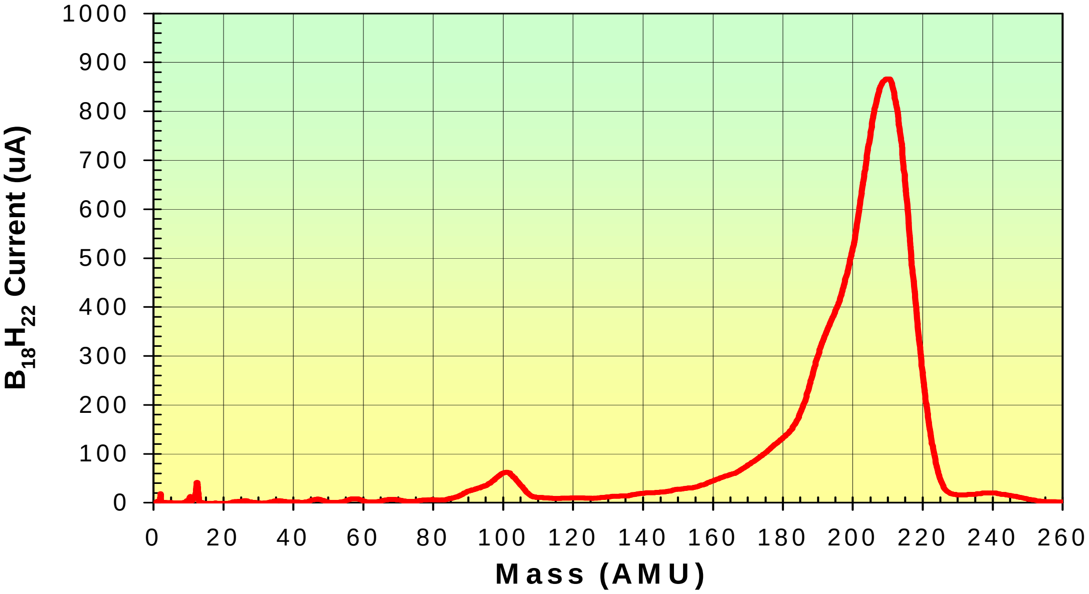


Fig. 1.. The mass spectrum of $B_{18}H_{22}$ using the ClusterIon source with an extraction of 20keV.

PROCESS FEATURES

While initially developed as a productivity solution, it has been found that $B_{18}H_x^+$ implants have several unique and potentially beneficial features. Of course, the low energy productivity has been realized, with beam current capability of 50mA at 3keV demonstrated [2]. This capability translates into high productivity for extremely low energy implants also, with mechanical limit capability down to 500eV and production worthy capability down to 100eV. This low energy capability is provided from a conventional ion implanter with only slight modifications to utilize the $B_{18}H_x^+$ species. The $B_{18}H_x^+$ implants are always performed in drift mode, and thereby avoid any energy contamination. Energy contamination is a result of the use of decel mode, which all conventional implantation systems employ to increase productivity for low energy implants. While the amount of energy contamination in a decel beam is generally low (<1%), it is variable with tuning and implanter condition and is less tolerable as technology scales. The combination of production worthy capability at extremely low energies and no energy contamination makes $B_{18}H_x^+$ very attractive for the SDE implant at the 45nm technology node and beyond.

SELF-AMORPHIZATION

With the implantation of such a large cluster of boron atoms, it was expected that the damage profile created would be different than a conventional monomer boron implant. There have now been many studies of the damage generated which lead to the concept of self-amorphization, starting with the work of Borland, et al [3]. The studies have shown that the $B_{18}H_x^+$ implant itself creates an amorphous layer at relatively low dose and that this amorphous layer allows the B_{18} implant to avoid most channeling without the use of an additional PAI implant. The studies have shown that the cluster impact on the silicon lattice imparts its momentum preferentially near the surface, relative to a monomer implant of equivalent parameters. This enhances the silicon damage at the surface while minimizing damage in-depth. Thus, a shallow amorphous layer is formed at the surface at a low dose, which is sufficient for eliminating channeling of the subsequent cluster implant. For $B_{18}H_x^+$, the threshold of amorphization is around 1E14/cm^2 dose, so a typical SDE implant would be 90% unchanneled. An example of the SIMS profile obtained by $B_{18}H_x^+$ implant is shown in Fig 2, where $B_{18}H_x^+$ is shown with and without PAI and monomer boron is shown with and without PAI. It is seen that most of the channeling has been avoided, although there remains some channeling effect. SemEquip has a detailed study of the self-amorphization process presented in another paper in this volume by Sekar et al [4].

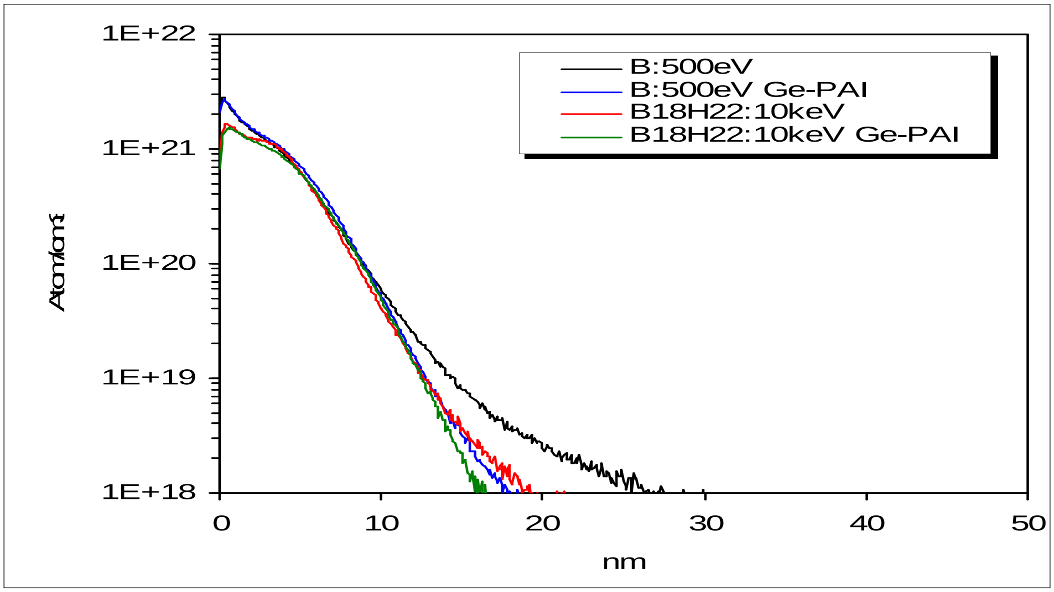
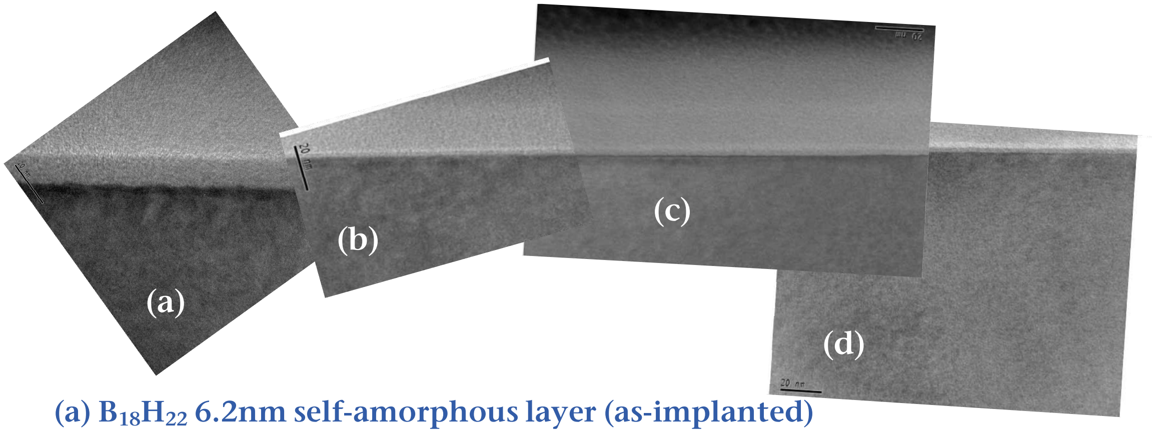


Fig.2. SIMS profiles of B18 and monomer B+ implants with and without a Ge PAI process. Slight channeling is observed for the B18 only implant.

Recently, we have been studying the self-amorphization process with other cluster ions, notably the carbon cluster molecules $C_{16}H_{10}$ and C_7H_7. These species provide a means of studying the damage creation mechanism with the same chemistry and are providing interesting results [4]. Notably, it is seen that much higher doses are needed to achieve amorphization with the smaller carbon cluster, so the damage deposition at the surface is strongly mass dependent.

ELIMINATION OF EOR DAMAGE

A further result of the different damage deposition process with $B_{18}H_x^+$ implant relates to the EOR damage and its annealing behavior. With any amorphizing implant, a major issue emerges with the requirement of completely annealing the total structure and eliminating all silicon crystal defects to achieve a low leakage junction. Since the amorphous region is by definition high damaged, it is expected that the silicon crystalline region immediately below the amorphous layer is also heavily damaged, and this is what is commonly refered to as EOR (end of range) damage. It is noted that the conventional process using a Ge^+ implant produces significant EOR damage which is challenging to anneal completely, especially with advanced annealing technologies. In contrast, the EOR damage created by the cluster implant is found to be less troublesome, with many studies now reporting that defect-free junctions are achieved, even with the most aggressive anneal technologies. Figure 3 shows some results from the work of Borland *et. al.,* where the $B_{18}H_x^+$ implant is shown to be defect-free with very advanced anneal conditions; flash, laser and SPE.



$B_{18}H_{22}$ X-TEM with various anneals

(JOB & NEC, IWJT2006 & SST2006)

(a) $B_{18}H_{22}$ 6.2nm self-amorphous layer (as-implanted)
(b) SPE with no EOR damage
(c) Laser with no EOR damage
(d) Flash with no EOR damage

Fig. 3. XTEM images of B18 implants as-implanted and with laser, flash and SPE anneals. No crystal defects are seen in any of the annealed structures.

This work also produced the results shown in Figures 4 and 5. Figure 4 shows photoluminescence results by the Accent method, showing the data for B, BF_2 and $B_{18}H_x^+$ implants with and without PAI and for a variety of annealing technologies. The PL signal indicates the presence of crystal damage, so low numbers are better. It is seen that the $B_{18}H_x^+$ only case produces consistently detection level results with any annealing technology. None of the other approaches to USJ formation produce as consistently low PL numbers.

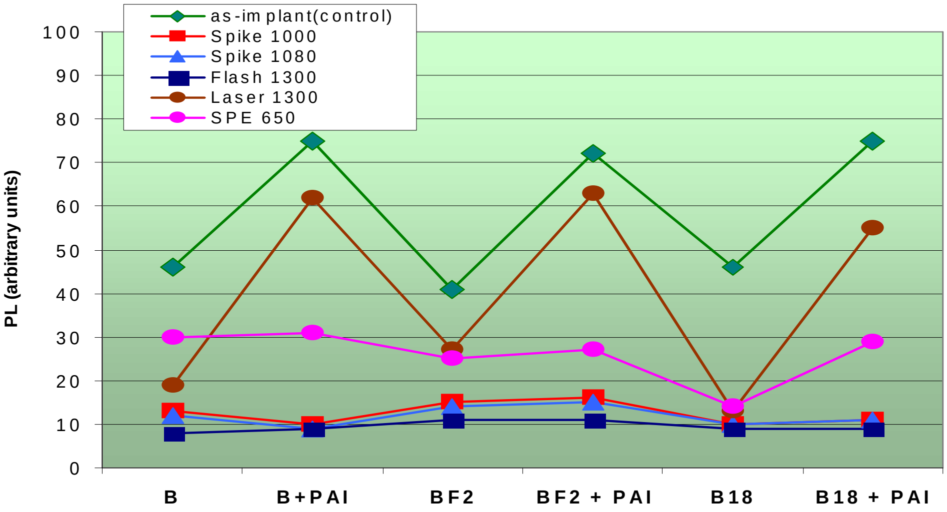


Fig.4. Photoluminesce data from Borland, etal. B_{18} only process is shown to produce very low PL numbers regardless of which annealing condition is chosen.

Figure 5 shows the corresponding data for junction leakage, as obtained by the Frontier method. It is remarkable that the structure of the figure is consistent with Figure 4, showing the correlation between crystal damage and junction leakage. Again, the B_{18} only case produced the most consistently low leakage, and achieved detection level leakage with any of the advanced anneal conditions. This mechanism of complete annealing of EOR damage has been further studied by SemEquip and detailed results are presented in another paper in this volume by Horsky et al [5]. An examples of this additional work plan view TEM analysis of the annealed $B_{18}H_x^+$ structure, still showing no observable crystal defects [5].

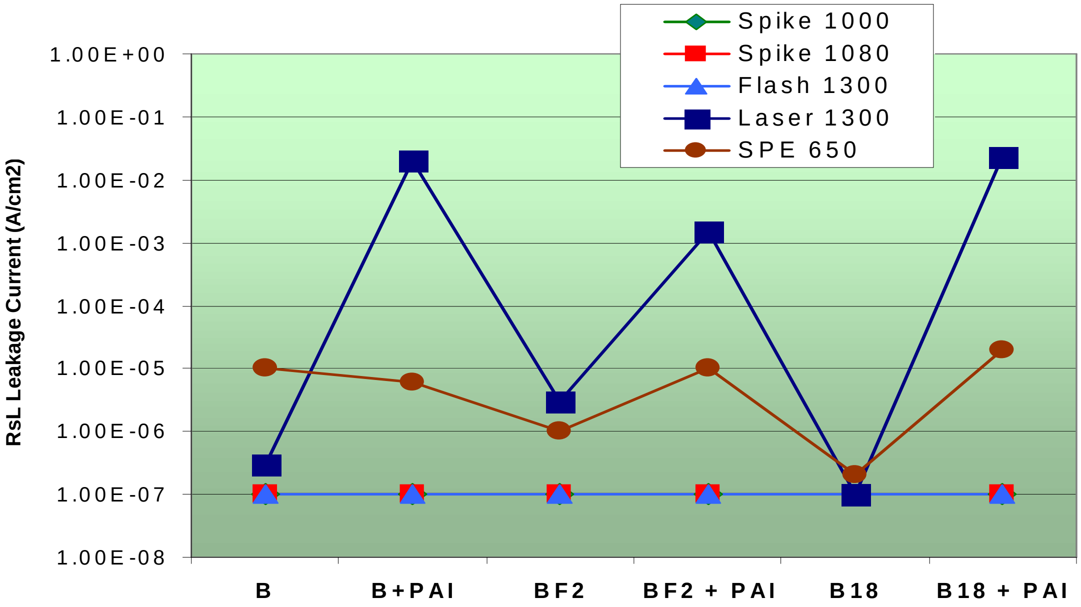


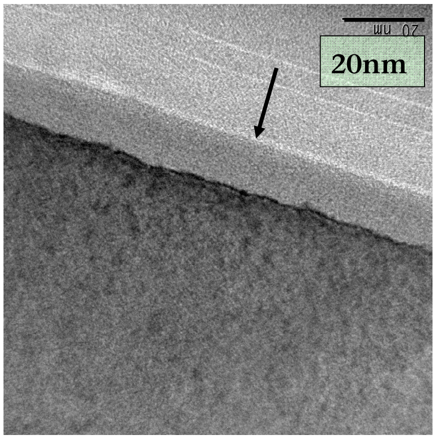
Fig. 5. Junction leakage as determined by the Frontier method, as a function of implant process and anneal conditions. $B_{18}H_x^+$ is shown to produce very low levels of junction leakage regardless of which anneal condition is chosen.

CARBON CLUSTERS

With the understanding that cluster implants have fundamental benefits for semiconductor applications, we have expanded the options by developing carbon cluster species. Hydrocarbon molecules were selected to have very similar physical properties to the $B_{18}H_{22}$ material, and are found to work very well with the same ClusterIon system. Two carbon species have been developed to address different process energy ranges, $C_{16}H_{10}$ and C_7H_7. The C_7 species allows implant processes with carbon energies up to 10keV per carbon atom, allowing carbon cluster solutions to the entire range of useful carbon implants.

DIFFUSION CONTROL

The most advanced process application of carbon in modern CMOS processing is for boron diffusion control. Many organizations are using carbon in this role at the 45nm technology node. The action of carbon is well known: reduction of boron diffusion, improvement of the abruptness of the boron profile, and increase of the boron solid solubility. These features are all achieved with carbon clusters also. The conventional process is typically Ge/C/B since it is required that the active volume where carbon acts is amorphous prior to anneal. We show that the simple process of $C_{16}H_x^+$/ $B_{18}H_x^+$ achieves the same results with two implants that will likely be performed at mechanical limit. In Figure 6 we show a TEM of the carbon cluster implant showing that it has the feature of self-amorphization which is critical to the diffusion control process. In Figure 7 we show results showing that the $C_{16}H_x^+$/ $B_{18}H_x^+$ sequence behaves like the conventional cocktail implant process. Further, we have found that the cluster sequence also has the benefit of elimination of EOR defects. In Figure 8 we show TEM images of the $C_{16}H_x^+$/ $B_{18}H_x^+$ process post anneal and find that no crystal defects remain.



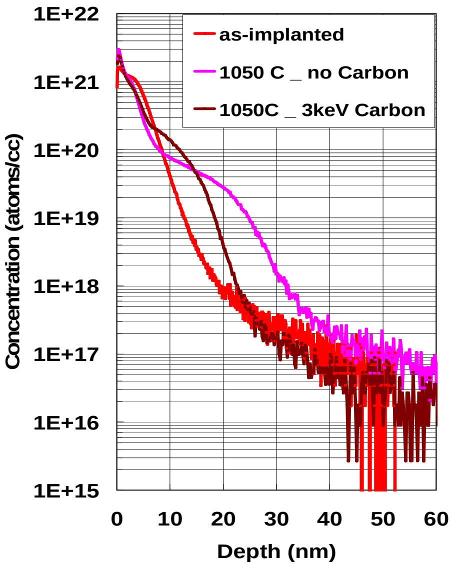


Fig. 6. XTEM image of $C_{16}H_x^+$ as-implanted structure showing self-amorphization layer of 14nm thickness. Implant conditions were 3keV per carbon atom and a dose of 1E15/cm^2 carbon. The arrow indicates the position of the surface.

Fig.7. SIMS profiles showing the benefit of $C_{16}H_x^+$ in controlling the diffusion of boron ($B_{18}H_x^+$) implant. As-implanted, without carbon and with carbon profiles are shown.

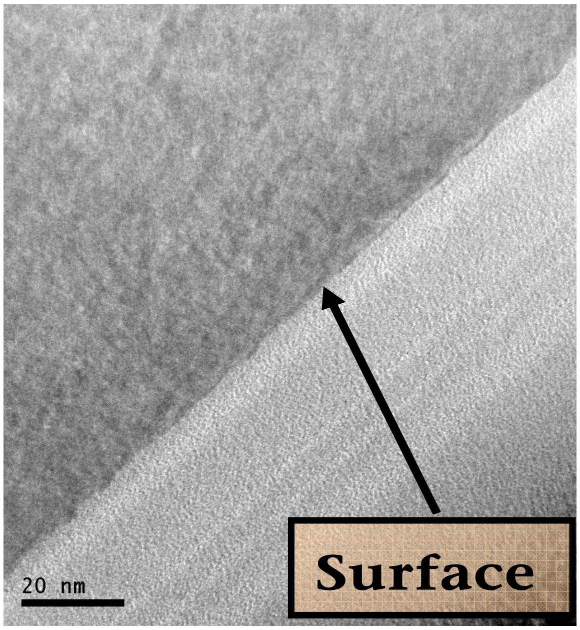


Fig. 8. XTEM image showing no EOR damage after an 5 sec anneal at 1025^{o}C for $B_{18}H_x^+$ 500eV per boron atom + $C_{16}H_x^+$ 3keV per carbon atom] both at 1e15 atoms/cm^2.

STRESS ENGINEERING

Recent developments of CMOS solutions for advanced technology nodes have focused largely on incorporating stress into the channel to improve mobility. This has been remarkably successful at improving the performance of the PMOS transistor by incorporating SiGe source and drain structures to place the PMOS channel under compressive stress. Stress engineering of the NMOS has been less successful, but much effort is currently in progress to use nitride structure to achieve tensile stress of the NMOS channel. Another potential method of achieving improvement of the NMOS is to use SiC alloys in the source and drain to create the proper tensile stress on the channel. The epitaxial methods under development are challenging. We propose a new alternative: the use of a carbon cluster implant to create the SiC alloy material with a simple and direct process. We have developed process recipes which have been shown to produce high degress of stress in blanket layers, as measured by Raman spectroscopy, as shown in Figure 9. It is found that the self-amorphization feature of the carbon cluster implant is very beneficial to the success of this process: the recrystallization of the amorphous layer directly promotes placing the carbon into substitutional sites, which is required to achieve the proper stress. In Figure 10, we show some stress results that we have achieved and see that stress values as high as 800MPa are reported.

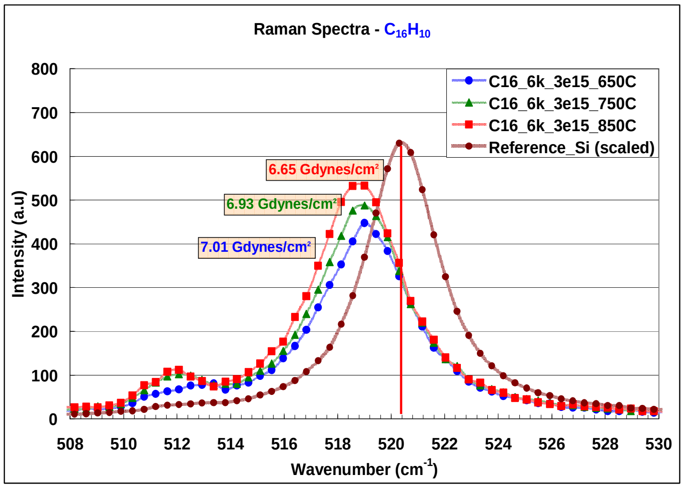


Fig.9. Raman spectroscopy results showing stress generated by carbon cluster implants.

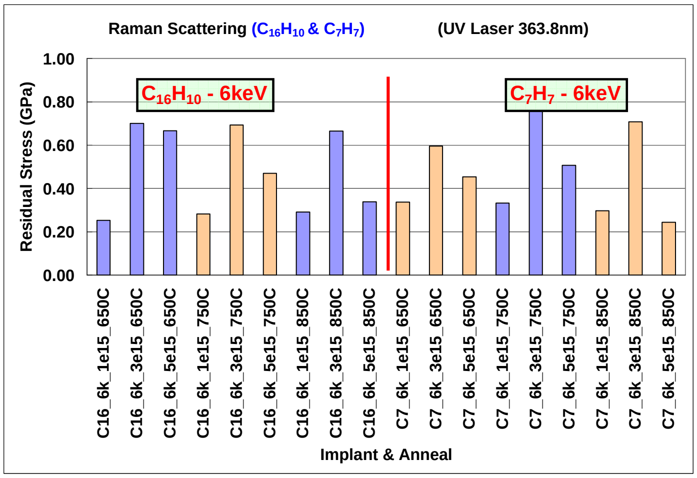


Fig. 10. Stress data for various carbon cluster implant conditions and anneal conditions. Both C_{16} and C_7 implants are shown to produce similar levels of stress. Data by UV Raman spectroscopy.

SUMMARY

A new implantation technology has been described: ClusterIon Technology. This technology suite has been developed to provide a production solution for the implantation of large molecules containing many atoms of the desired species, rather than the conventional method of implanting one atom at a time. It has been shown that this technology provides very high productivity for low energy implants while also producing process benefits. These process features include lack of energy contamination, self-amorphization and easy elimination of EOR damage, producing defect-free structures with low junction leakage. $B_{18}H_x^+$ and the carbon cluster species $C_{16}H_x^+$ and $C_7H_x^+$ have been described with direct application to the conventional uses of low energy boron and carbon implants. In addition, a new application for NMOS stress engineering has been described for the carbon cluster implant.

ACKNOWLEDGMENTS

I would like to thank Tom Horsky, Dale Jacobson, Bob Milgate, K. Sekar and other SemEquip team members for their help and suggestions to prepare and execute this article.

REFERENCES

(1) T. Horsky, Proc. 16th International Conference on Ion Implant Technology, p159 (2006)
(2) T. Horsky, G. F. R. Gilchrist, R. W. Milgate, Proc. 16th International Conference on Ion Implant Technology, p198 (2006)
(3) J.O. Borland, Proc. 16th International Conference on Ion Implant Technology, p6 (2004)
(4) K. Sekar, W. A. Krull, T. Horsky, D. C. Jacobson, K. Jones, D. Henke, Proc. of International Conference on INSIGHT in Semiconductor Device Fabrication, Metrology and Modeling, May 6 – 9, Napa, USA (2007)
(5) T. Horsky, W. A. Krull, D. C. Jacobson, K. Sekar, J. O. Borland, Proc. of International Conference on INSIGHT in Semiconductor Device Fabrication, Metrology and Modeling, May 6 – 9, Napa, USA (2007)