Simplifying the 45nm SDE Process with ClusterBoron® and ClusterCarbon™ Implantation

Wade Krull[1], Brian Haslam[1], Tom Horsky[1],
Kurt Verheyden[2] and Klaus Funk[2]

[1]SemEquip, Inc., 34 Sullivan Road, North Billerica, Massachusetts 01862, USA
[2]ASM, Leuven Belgium and Munich Germany

Abstract. The processes used to form an advanced PMOS SDE become increasing complex with each technology generation. Aggressive requirements for junction depth, sheet resistance and abruptness are difficult to satisfy with conventional technologies. The fundamental issues are the low productivity of implant systems at the required low boron implant energies and the diffusion rate of boron in silicon at the temperatures needed for activation. We propose an alternate process sequence with the goal of simplifying the process module by eliminating the Ge PAI implant and using a conventional spike anneal.

Our approach is to utilize a ClusterCarbon implant to control boron diffusion, a ClusterBoron® implant for high productivity at low process energy and a conventional spike anneal at moderate temperature. The ClusterCarbon™ implant uses the same ClusterIon® source and related system as the ClusterBoron implant. This process combination provides a solution to the technology requirements using conventional production tools, high productivity and a simple, direct path to optimizing the SDE conditions.

Keywords: cluster implantation; molecular implantation; boron diffusion control
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INTRODUCTION

The requirements for the PMOS SDE are becoming increasingly difficult to achieve. The ITRS Roadmap for the 45nm node indicates that a junction depth of 7-10nm is required, consistent with the conventional scaling requirement that the SDE be around 1/3 of the physical gate length. In addition, there are requirements for low sheet resistance, extremely abrupt junctions and the necessity of managing leakage currents. Such requirements can only be met with a boron implant in the range of 200eV with pre-amorphization and a diffusionless anneal. However, the requirements listed in the ITRS have become increasingly abstract and divergent from typical processes used in the fabrication of advanced ICs. Many organizations are using processes less extremely scaled than the ITRS numbers. For these applications, SDE junction depths in the range of 12-20nm are acceptable, and this is the realistic target of the work described herein.

Most of the development activity directed at achieving the PMOS SDE is following a single path. First, a Ge PAI implant is used to create an amorphous surface layer and thereby avoid channeling issues, and achieve the shallowest possible as-implanted profile. A carbon implant is used to inhibit boron diffusion. Next, a BF2 boron implant is used to enhance the productivity of the low energy boron implant process. The fluorine inherent in the BF2 implant has both positive and negative aspects; it reduces the diffusion of boron, but also inhibits boron activation and complicates the elimination of EOR damage during the anneal. Finally, in order to achieve a diffusionless anneal with the maximum activation, a laser thermal or flash anneal is being developed but these processes require equipment which is new, expensive and not yet proven to be production worthy.

Our concept is to adopt an alternative approach with the goal of simplifying the process sequence while achieving very high productivity and using production proven equipment. The approach utilizes the demonstrated self-amorphization feature of cluster implants to eliminate the Ge PAI implant step [1,2]. Next, we make use of the very high productivity capability of ClusterBoron implant at very low process energies. This will allow for some diffusion to occur and still meet the junction depth requirements. To reduce the amount of diffusion, we will use a ClusterCarbon implant (describe herein for the first time) which

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has the same high productivity and self-amorphization advantages of the ClusterBoron implant technology. Finally, we will use a conventional, production proven spike anneal (at moderate temperatures) and the demonstrated high activation of ClusterBoron [3] to achieve the junction depth and sheet resistance requirements. A further goal of this work is to keep the amorphization depth low and below the active junction, so that the beneficial effect of the surface will enable complete elimination of the EOR damage. Since the amorphization depth is set by the ClusterCarbon energy in this process, we will restrict the carbon energy to 3keV per carbon atom and below. In all cases, the carbon is implanted first, then boron.

The goals of this work are to optimize the implant conditions of ClusterCarbon and ClusterBoron to achieve a low resistance, shallow and abrupt junction while using conventional spike annealing technology. Figure 1 below shows the benefit of using the carbon implant. The figure shows a 500eV boron equivalent implant, as-implanted and with 1050 spike anneal with and without carbon. It is seen that the carbon implant reduces the amount of diffusion, increases the active boron concentration, and improves the junction abruptness. The experiment was designed to explore the parametric implant space to achieve the best combination of Rs, Xj and junction abruptness.

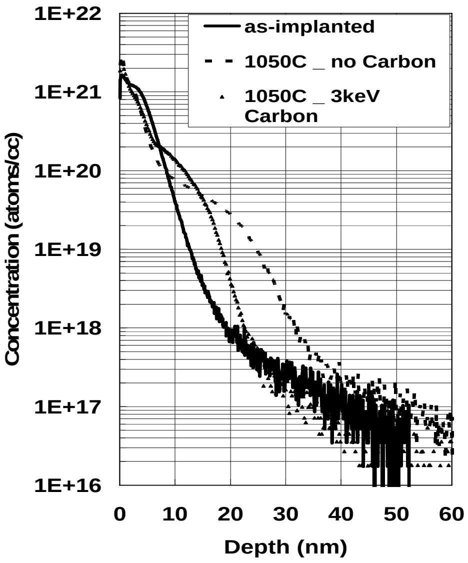

FIGURE 1: ClusterBoron implant of 500eV equivalent at 1E15 dose; as-implanted, and with 1050C spike anneal with and without carbon.

CLUSTERION TECHNOLOGY

The use of ClusterBoron implant has been established as an alternative approach to low energy boron implant. This technology utilizes a new source material (B18H22) and the ClusterIon ion source to provide a beam of B18 ions. The ClusterIon source uses soft ionization and temperature control to preserve the large borane molecule, in contrast to a conventional ion source which uses an intense plasma to disassociate molecules such as BF3. The advantages of using ClusterBoron implant are very high productivity down to very low process energies, freedom from energy contamination and self-amorphization. It has been shown that very high quality shallow junctions are formed with B18 for any annealing technology [3]. The ClusterBoron chemical is a solid at room temperature so the ClusterIon technology includes a low temperature vaporizer and vapor flow control to provide a stable flow of ClusterBoron vapor to the ion source [4]

We introduce a new cluster species for low energy carbon implant: ClusterCarbon. By appropriate choice of hydrocarbon molecule, we have a molecule whose physical properties are very similar to ClusterBoron. The ClusterCarbon chemical is also a solid at room temperature and vaporizes in the same temperature range as ClusterBoron. The soft ionization system developed for ClusterBoron also works very well for the ClusterCarbon vapor, which produces slightly higher electrical beam currents due to the narrower AMU spectrum of ClusterCarbon. In addition, the ClusterCarbon ion is in the same AMU range as ClusterBoron (~200AMU) so the remainder of the implant system works the same as with ClusterBoron. The implants in this experiment were performed on the SemEquip demo system; an Eaton GSD implanter upgraded with the ClusterIon system.

EXPERIMENT

The anneals in this work were all performed on the ASM Levitor demo system installed at Imec in Leuven, Belgium. The Levitor is a conventional, production proven rapid thermal annealing system capable of anneals over a wide temperature range with controllable ramp rates up to 1000C/s. For this work, we utilized spike anneals to a peak temperature in the range of 950-1075C. The anneals were done in a He environment with ramp rates in the range of 800C/s.

Since the application for this work is an advanced PMOS SDE, implant process conditions were chosen to be appropriate for such application. It is well established that a boron implant with energy of 500eV and dose of 1E15 is appropriate for the junction range of interest. This requires a ClusterBoron implant of 10kV. The carbon implant energy was limited to 3keV per atom and below and carbon doses were investigated between 1E14 and 2E15. For all implant combinations, a spike anneal sweep between 950C and 1075C was performed to evaluate annealing response of the implanted structure. The primary responses evaluated were sheet resistance (conventional 4pp), junction depth (SIMS at 5E18 concentration) and junction abruptness (1E18-1E19 concentration gradient). We also introduce a new response parameter, the product of Rs and Xj, to provide a single parameter corresponding to the net electrical concentration in the shallow junction.

One of the experimental designs for this study is related to leakage control. It is reported that carbon in silicon enhances the risk of leakage, so carbon energies were intentionally limited to values below the typical boron energy for the Source/Drain implant, or 3keV. This will keep the carbon out of the source/drain junction where the large area would produce high leakage current. This is consistent with recent work [5] where it was demonstrated that low energy carbon reduces leakage current. It remains to be evaluated with real structures what the leakage impact of such carbon implants would be.

RESULTS

The process conditions chosen produced shallow junctions in the range of 12-20nm for most of the experimental space investigated. Junction abruptness values in the range of 2-5nm/dec were achieved, with the shallower junctions showing improved abruptness. However, significant tradeoff with Rs is seen for all of the process conditions, as expected. The sheet resistances measured were in the range of 800-3000 ohms/square with the lowest values corresponding to the deepest junctions and the highest annealing temperatures.

The plots of Fig. 2 show the response values as a function of annealing temperature for the best case with carbon and without carbon. It is seen that the addition of the ClusterCarbon implant significantly reduces the junction depth and improves the junction abruptness. While the Rs values are higher than ideal, they are better than can be achieved by spike anneal without carbon for the same Xj.

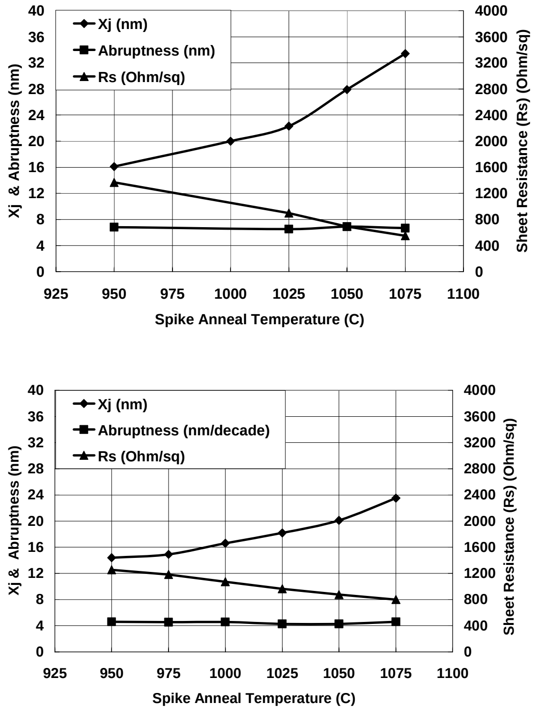

FIGURE 2. Results of Rs, Xj and abruptness for B18 implants of 500eV, 1E15 equivalent, without (above) and with 3keV 1E15 ClusterCarbon implant, as a function of anneal temp.

The response data is plotted in Rs/Xj space in Fig. 3. This figure includes data from several carbon implant recipes. It is clearly seen that the best carbon recipe is 3keV, 1E15 and that this process produces junctions with better Rs/Xj characteristics than can be obtained without the carbon implant. The datapoints on each curve are for different anneal temperatures. It is seen that the carbon implants with higher dose than 1E15 produce inferior results: shallow Xj but higher Rs than could be obtained without the carbon implant. Likewise, comparing 2keV carbon with 3keV carbon shows that the 2keV produces a shallower, but higher Rs junction. Since the shallower carbon also results in higher concentration of carbon in the active layer, it is likely that carbon acts as a scattering center, reducing mobility and thereby increasing Rs.

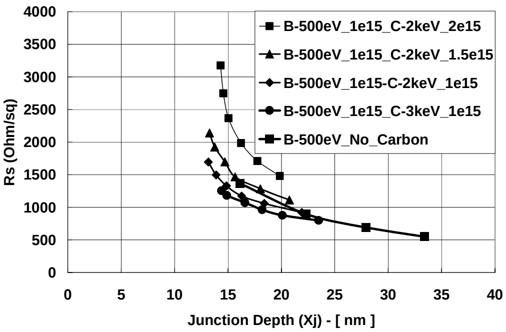

FIGURE 3. Data for B18 with various carbon implant process conditions plotted in Rs/Xj space.

The boron profiles in depth were evaluated by SIMS analysis. Figure 4 below shows the anneal sequence for the 3keV, 1E15 carbon case. As expected, lower anneal temps produced more shallow junctions and were the most abrupt. Solubility values in the range of 1-2E20cm-3 were observed for all but the highest anneal temperature

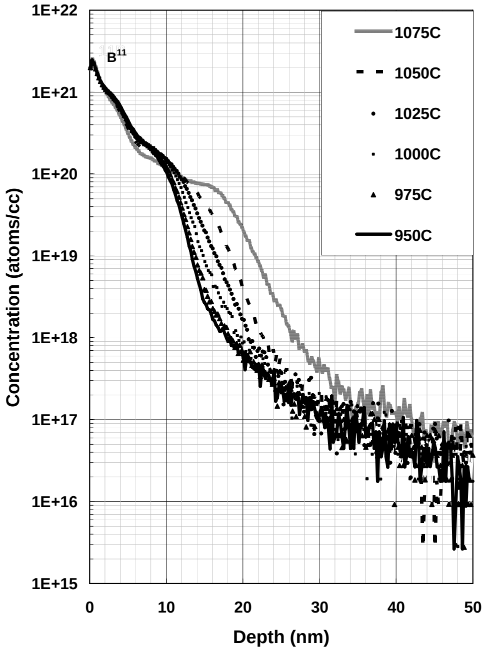

FIGURE 4 SIMS profiles for B18 500eV 1E15 with carbon 3keV 1E15 as a function of anneal.

This process is difficult to optimize due to the necessity of tradeoff between Rs and Xj, which naturally move in opposite directions as the conditions are modified. In an attempt to understand this tradeoff more explicitly, we examiine the product of Rs and Xj. It is noted that an ideal box profile would have Rs and Xj varying inversely and thus would produce a constant value of the product as the junction depth is reduced. The product Rs*Xj has units of inverse concentration, so a lower number indicates better activation. We show in Figure 5 the results for the Rs*Xj product for our experiment. The response without carbon anneal is a line which increases with reduced annealing temperature. The response with 1E15 carbon (either 2 or 3keV) shows a curve nearly flat, indicating near theoretical tradeoff between Rs and Xj. Higher doses of carbon produce higher values, indicating lower active concentration.

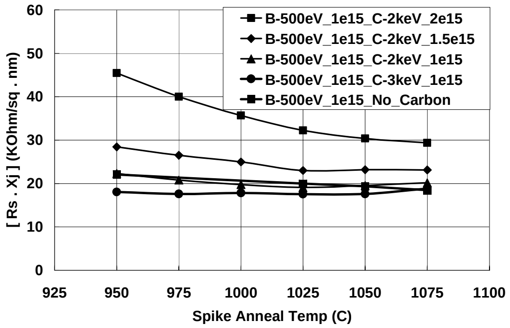

FIGURE 5: Product of Rs and Xj vs. anneal temp

SUMMARY

We introduce a new cluster species for low energy carbon implantation: ClusterCarbon. It is shown that ClusterCarbon inhibits boron diffusion during the anneal process, consistent with other developments using monomer carbon. Further, the combination of ClusterCarbon, ClusterBoron and conventional spike annealing technologies are shown to produce ultra-shallow junctions appropriate for the 45nm SDE. These junctions are shallower and more abrupt than can be achieved without the carbon implant. It is also shown that the optimized process has near ideal scaling of junction parameters as the anneal is varied. This process combination simplifies the process sequence for advanced PMOS SDE while using production proven tools with high productivity.

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