# INTERACTION OF PHOSPHORUS AND CLUSTERCARBON$^{TM}$ IN THE NMOS Si:C STRESS APPLICATION

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The NMOS strain application requires the introduction of carbon into the source/drain regions, where n-type doping is also present. The most direct means of introducing carbon is implantation, such as ClusterCarbon implant. For this carbon to produce the tensile strain in Si which enhances the mobility, it is important to place carbon in a Si substitutional site, while dopant activation (n-type, P) also requires P to occupy a substitutional site. This competition for the substitutional sites produces a trade-off between carbon and P occupancy, and therefore a trade-off between dopant activation and tensile strain formation. In this study we have investigated the dose ranges for both P and Clustercarbon implants along with some anneal parameters to produce low Rs, high tensile strain and a defect-free Si:C layer formation. We used Rs, SIMS, XTEM and HRXRD techniques to characterize the Si:C layer obtained using ClusterCarbon and P implants

## INTRODUCTION

Aggressive scaling of CMOS technology imposes critical importance to dopant profile engineering on the source and drain regions. The requirements are low sheet resistance and ultra-shallow junctions for short-channel effect control and high device performance. With the recent advent of Cluster ion implantation, or molecular implantation, as a production alternative for USJ formation, it is important to characterize dopant profile engineering with respect to dopant activation, junction depth and defect-free USJ structures after anneal. In this paper we discuss the use of ClusterCarbon ($C_7H_x^+$) in conjunction with Phosphorus (P) implants for NMOS source drain and also strain engineering applications by Si:C formation with ClusterCarbon implants.

It has been shown that Germanium(Ge) & Carbon(C) co-implants are necessary to reduce Phosphorus TED and obtain better P activation [1,2]. For activation, it is required that P atoms occupy substitutional sites. Carbon acts as a sink for excess Si interstitials produced by the Ge-PAI implants. But carbon also needs to occupy substitutional sites to act as a sink. There is a competition between C and P atoms to occupy the substitutional site. Carbon implant alone does not stop TED because the monomer carbon does not produce an amorphous layer and recrystallization of the amorphous layer is the mechanism for driving the carbon to substitutional sites. Thus, an additional Ge-PAI implant is used to provide an amorphous layer, which also eliminates channeling of P dopants thus providing an abrupt junction upon annealing. It is well understood that ClusterCarbon implants are self-amorphizing [3], producing Si amorphous layers ranging up to few tens of nm. This self-amorphizing feature of these implants can eliminate the Ge-PAI implants. It is important to study if a ClusterCarbon implant with P implants is sufficient to reduce P TED and provide better activation with an abrupt junction. Another opportunity with ClusterCarbon is to form a Si:C stress layer, where the appropriate anneal sequence is critical (our study includes spike and millisecond anneals).

It has been shown that with the ClusterCarbon implant approach it is possible to obtain > 2% substitutional carbon ($[C]_{subs}$), which is sufficient to produce significant mobility enhancement [4,5].
For all these processes (P activation, junction abruptness (TED reduction) and Strain with Si:C) P dopant atoms and C atoms are required to occupy substitutional sites. Thus it is important to characterize the interaction of P dopant atoms with carbon atoms produced with ClusterCarbon implants.

The problem is that the presence of carbon reduces P activation. We will show the results of an implant series of samples with various P doses for a given ClusterCarbon dose with spike and flash anneals. We will show the relationship between P activation and carbon substitution and determine the trade-off for various P and C doses. We will also show the effect of carbon dose on obtaining defect-free structures after the anneals. The results include data obtained using the SIMS, 4PP, XTEM and HRXRD techniques.

## EXPERIMENTAL

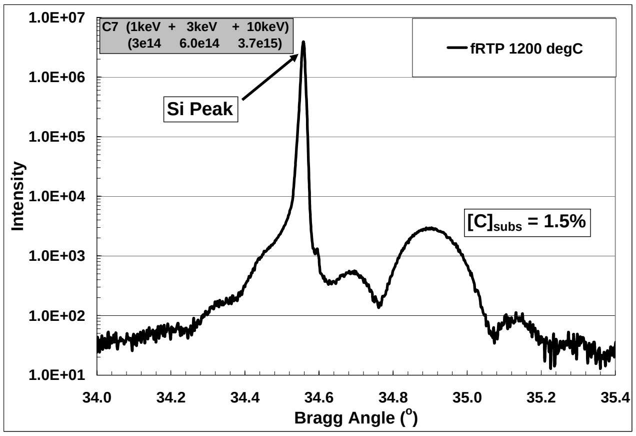
All of the wafers used in this study were 200mm, p-type, (100) silicon substrates. The wafers were implanted with Clustercarbon at different energies and doses using $C_7H_7$ species from a ClusterIon® source. $P_2$ 3keV (monomer equivalent) 2e15 atoms/cm$^2$ were implanted in a high current ion implanter. The sequence of implant is: carbon implants first and then $P_2$ implant. To produce the carbon profile desired for stress creation, a sequence of $C_7H_7$ implants were performed: such as $C_7$, 1keV_3.0e14, 3keV_6.0e14, 10keV_3.7e15 atoms/cm$^2$). Variations to the doses were used to produce layers with different carbon concentrations.

The anneals in this work were all performed on the Mattson Technology Canada flash anneal system using impulse RTP (iRTP) anneal and Flash Assist RTP or fRTP[6]. Sheet resistance measurements were carried out using a four-point probe. Secondary Ion Mass Spectrometry (SIMS), XTEM and High Resolution X-ray Diffraction (HRXRD) measurements were carried out using commercially available facilities.

## RESULTS AND ANALYSIS

### CLUSTERCARBON FOR STRAIN APPLICATIONS

Fig. 1 shows HRXRD spectrum of a multiple $C_7H_7$ implant sequence : (1 keV+3keV+10keV) at doses (3e14+6e14+3.7e15) atoms/cm$^2$ respectively. The sample was flash annealed at 1200°C. The profile shows a bulk Si peak (lower angle) and a strained layer peak to the right of Si peak. The separation between the bulk Si peak and the strained Si peak (higher angles) provides information about the substitutional carbon and its substitutional percentage is determined using Kelires model [7,8].
Appearance of fringe peaks generally is an indication of good quality strained Si:C layer.
This clearly demonstrates that ClusterCarbon implants can make strained Si:C layer.
Details about the dependence of anneal conditions on [C]subs using ClusterCarbon can be found elsewhere [4,5]



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The critical issue is the interaction between C and P. P diffusion in Si also depends on the carbon concentration. For low or intermediate concentration, the isolated substitutional P are immobile and the mobile species are only pairs of P and point defects, mainly the phosphorus-interstitial (PI) pair. For higher concentration of P, this pair diffusion mechanism give rise to the well known “kink and tail” profile shape of P diffusion. This diffusion can take place even in the absence of any implantation defects, due to a strong interstitial supersaturation generated by the dissociation of the pairs and the interstitial out diffusion towards the surface which remains at thermal equilibrium. Coming to carbon, substitutional carbon is known to strongly interact with dopants and defects induced by implantation [9,10]. The defects induced by implantation could favor precipitation of substitutional carbon. Carbon is known to reduce P diffusion [1].

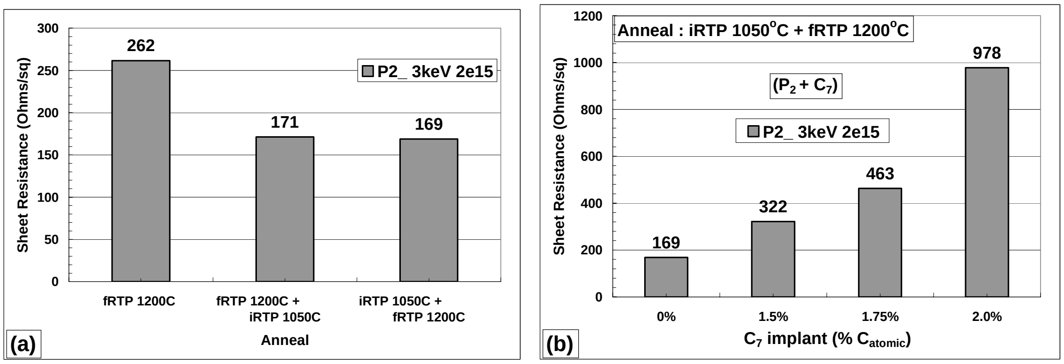
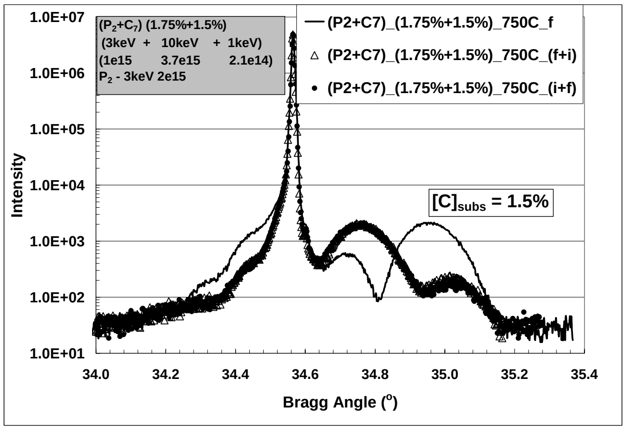


Fig. 2(a) , shows Rs measurement 3keV, 2e15 $P_2$ implant. Fig. 2(b) shows Rs measurement with ($P_2$+$C_7$) implants. The sample was first annealed with an impulse spike anneal (iRTP) at 1050$^o$C and then with a flash anneal (fRTP) at 1200$^o$C.

Fig. 2(a) shows sheet resistance (Rs) measurements for P only implants (no carbon implant) at various anneal sequences. For flash anneal only case (fRTP 1200$^o$C), the sheet resistance is 262 $\Omega$/sq. If the flash anneal is followed by a spike anneal (iRTP 1050$^o$C) then Rs goes lower to 171 $\Omega$/sq due to diffusion of P. If the order of the anneal is reversed, there is no change in Rs value. SIMS profile of these two samples (not shown here) is almost identical indicating the spike anneal dominating P diffusion over flash anneal. Fig. 2(b) shows Rs measurements for ($P_2$+$C_7$) implants at various carbon atomic concentrations ranging from 0% to 2.0% for a given anneal sequence. In this case the anneal sequence is iRTP 1050$^o$C and then fRTP 1200$^o$C.

The sheet resistance increases with increase in carbon concentration. The Rs value increased dramatically beyond 1.75%. At a carbon atomic percent of 2.0%, the Rs value is 978 Ω/sq. This gives a clear clue that for devices that require low Rs numbers need to keep carbon concentration moderate.

Fig. 3 shows HRXRD profile for ($P_2$+$C_7$) case with 1.75% atomic carbon at three different anneal sequences. At fRTP 1200°C anneal, the percentage of $[C]_{subs}$ is around 1.5%. The fitting for this profile needs to take into account at least two layers. In the case of flash anneal followed by an impulse spike anneal at 1050°C, a strained peak appears to the left of the original strained peak indicating a reduction in $[C]_{subs}$ . Lower $[C]_{subs}$ after spike anneal due to the release of substitutional carbon to interstitial sites. Reversing the anneal sequence did not alter the profile showing no change in percentage of $[C]_{subs}$. This is also supported by Rs measurements in Fig. 2(a) where there is no drastic change in sheet resistance.



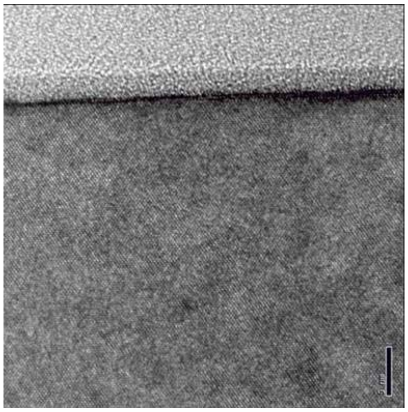


Fig. 3 shows HRXRD profiles for ($P_2$+$C_7$) implants at three different anneal sequences. Notation "f" refers to fRTP 1200°C and "i" refers to iRTP 1050°C. After a spike anneal, the substitutional carbon percentage is lowered.

Fig.4 shows XTEM image for $C_7$ 1.5% annealed first with fRTP 1200°C followed by iRTP 1050°C.

Fig. 4 shows a XTEM image of multiple $C_7$ implants (carbon atomic percentage of 1.5%) annealed first with fRTP 1200°C followed by iRTP 1050°C. The image shows no EOR defects or crystal regrowth defects. This shows that with 1.5% carbon, there is no issue with crystal recovery growth upon annealing. The challenge will be demonstrate good crystal anneal recovery growth for higher carbon atomic concentrations.

Fig.5 shows dopant SIMS profiles for as-implanted $P_2^+$, 3keV, 2e15 atoms/cm$^2$ and as-implanted ($P_2$+$C_7$)_1.75% sample. SIMS profiles of the above two samples and also profiles after a two step anneal are shown. The anneal sequence is fRTP at 1200°C and followed by iRTP 1050°C. The Xj (@5e18 atoms/cm$^3$) for as-implanted cases are 24nm & 18nm. Lower Xj for as-implanted case for ($P_2$+$C_7$)_1.75% sample is due to the amorphous layer created by the cluster carbon implant sequence. The amorphous layer thickness for the as-implanted sample is around 36nm. In the case of P only implant, the profile shows a long tail indicating the presence of channeling. After the anneal sequence P diffused deeper giving rise to a deeper junction (Xj ~ 47nm). Practically for the anneal sequence the junction moved from 24nm to 47nm. In the case of ($P_2$+$C_7$)_1.75% sample, presence of carbon reduced P diffusion by trapping Si interstitials that are available for P diffusion.

The junction depth for this case is around 24nm. The junction moved just 6nm after the flash and spike anneal. The P profile also looks like a perfect box-like one showing an abrupt junction. The junction abruptness calculated between 1e19 – 1e18 atoms/cm$^3$, showed a junction abruptness of 2.5nm/decade. Without carbon the junction abruptness is in the range of 20nm/decade.

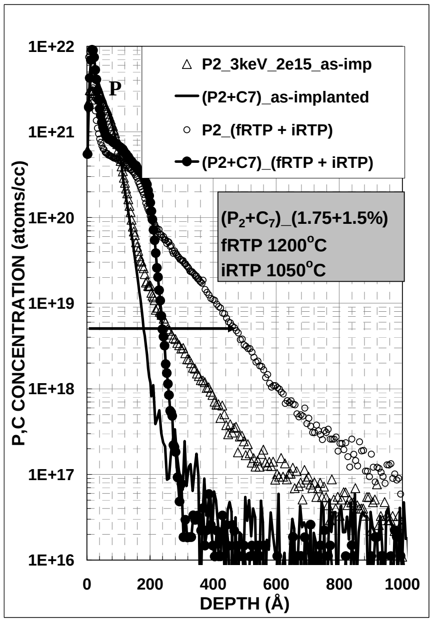


Fig.5 shows dopant SIMS profiles for as-implanted and annealed samples of $P_2^+$, 3keV, 2e15 atoms/cm$^2$ and $(P_2+C_7)$_1.75% sample. The anneal sequence is fRTP at 1200°C and followed by iRTP 1050°C.

## CONCLUSIONS

ClusterCarbon implants can be used to fabricate tensile strained Si:C layer for NMOS device applications.

It has been shown that P and C compete for the Si substitutional site and so there exists a trade-off between P activation and C substitution. The percentage of substitutional carbon decreases with increase in P concentration. Increase in C concentration leads to lower dopant activation. The percentage of $[C]_{subs}$ is very sensitive to anneal conditions. Under moderate carbon concentration we have shown that low sheet resistance, higher $[C]_{subs}$, and good crystal recovery growth could be achieved. By suitably choosing P and C dopant concentrations along with an optimal anneal conditions, one can realize good device performance by forming a tensile strained Si:C layer which enhances the mobility of the charge carriers.

ClusterCarbon approach is a viable alternative option for fabrication of present and future NMOS devices.

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