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An Extensive Study on the Boron Junctions Formed by Optimized Pre-Spike / Multiple-Pulse Flash Lamp Annealing Schemes: Junction Formation, Stability and Leakage

S. H. Yeong^{1,2}, D. X. M. Tan³, B. Colombeau¹, C. H. Poon¹, K. R. C. Mok¹, A. See¹, F. Benistant¹, K. L. Pey³, C. M. Ng¹, L. Chan¹, and M. P. Srinivasan²

¹ Chartered Semiconductor Manufacturing Ltd, 60 Woodlands Industrial Park D, Street 2, Singapore 738406.

² Department of Chemical and Biomolecular Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576.

³ Microelectronics Center, School of Electrical and Electronic Engineering, Nanyang Technological University, Nanyang Avenue, Singapore 63979.

Abstract. In this work, the electrical activation of Boron in Germanium pre-amorphized silicon substrate upon flash lamp annealing (FLA) is investigated. We demonstrate that FLA helps in the reduction of the EOR defects, resulting in minimal transient enhanced diffusion and dopant deactivation effect. It has also been observed that the junction stability improves with the increasing number of flash pulses, which is clearly reflected by the dopant deactivation level upon post-thermal treatment. In another FLA scheme, the spike rapid thermal annealing (RTA) performed prior to the flash further enhances the junction stability. However, this pre-spike RTA step induces extensive dopant diffusion and an overall degradation in sheet resistance. The above observations are concluded to be due to the different extent of silicon interstitial supersaturation that can be explained by the interactions between the extended defects and dopants. Lastly, leakage current for the junctions formed under different FLA schemes are compared. Typical single pulse FLA junction shows high leakage current and it can be reduced through the additional pulses of FLA or effectively suppressed by the pre-spike RTA flash scheme. In addition, it is also found that the junction leakage can be correlated to the FLA residual defects.

Keywords: Flash Lamp Annealing, Boron, Activation, Deactivation, Residual defects

PACS: 61.72.jd, 61.72.jj, 61.72.Cc, 61.72.uf, 85.40.Ry, 85.30.Kk

INTRODUCTION

Recent advancement in ultra-shallow junction formation has provided various possibilities in the annealing approaches. As the CMOS devices scale down to the sub-nm technology, conventional implantation process coupled with rapid thermal annealing (RTA) does not cater to the stringent requirements in the advanced ultra-shallow junction formation. Pre-amorphizing implant (PAI) was later developed to be integrated into the formation of ultra-shallow junction to inhibit the ion channelling effect but however, it creates a rich end-of-range (EOR) defect band beyond the amorphous/crystalline (a/c) interface [1]. These EOR defects which mainly comprise of free interstitials migrate towards the substrate surface during the thermal annealing cycle and cause dopant deactivation and transient enhanced diffusion (TED) [2-7].

Flash Lamp Annealing (FLA) has proven to be one of the most potential techniques for the

integration in state-of-the-art CMOS process due to its reduced thermal budget. FLA offers the ability to form highly activated shallow junctions with a much shorter soak annealing duration at higher temperature [8]. Although ultra-shallow junctions with minimum TED can be optimized using FLA [9], the dopant activation level and density of residual defects after FLA are the main concerns. In the device level, these residual defects contribute to high junction leakage [10-13]. The junction stability and leakage current are intimately related to the presence of these residual defects, which eventually affect the overall performance of the devices. In this paper, we demonstrate the stability of the B junctions in terms of dopant activation and diffusion formed by FLA in Ge-PAI silicon substrates. The effects of multiple-pulse FLA and pre-spike RTA are also shown. In addition, the junction leakage study associated with the various FLA schemes is studied with the diodes.

EXPERIMENTAL DETAILS

silicon wafers at 15 keV with a dose of $5 \times 10^{14} \text{ cm}^{-2}$ followed by 1 keV B implant with a dose of $2 \times 10^{15} \text{ cm}^{-2}$. The front side of the wafer surface was mounted facing the xenon flash lamps with the backside in contact with the hot plate. The implanted wafers were raised to an intermediate temperature of 500°C by the hot plate before the xenon flash lamps were triggered for irradiation. There is no re-crystallization of the Ge-PAI induced amorphous layer at the intermediate temperature of 500°C. (verified by TEM). FLA was carried out in N₂ ambient for one, three, and six pulses with the intensity of 26 J/cm² and a pulse duration of 0.8 ms. The peak wafer temperature was estimated to be around 1120°C to 1150°C. In addition, some of the wafers were subjected to a 950°C spike RTA to anneal out the residual defects before the FLA. Post-RTA isochronal annealing of temperature ranging from 600°C to 1050°C for 60s, was conducted on some samples to study the junction stability through the dopant de/re-activation behavior. The RTP annealing temperature was monitored and measured using thermocouple. The dopant diffusion profiles were characterized by secondary ion mass spectrometry (SIMS) using the Cameca IMS 6f instrument. A primary beam of O₂⁺ ions with net energy of 1 keV at 56° incidence was scanned over an area of 250 × 250 μm². High resolution transmission electron microscopy (TEM) was performed to analyze the degree of amorphization, as well as to investigate the remaining residual defects. The electrical characterizations were performed using the 4-point probe and Hall measurements were used for the investigation of junction activation and stability. P+/n diodes with Ni silicide contacts were also fabricated for junction leakage measurement.

RESULTS AND DISCUSSION

Optimized FLA conditions can be developed to achieve the desired ultra-shallow junction characteristics. Junction formation with the implementation of FLA on the Ge-PAI and non-PAI B doped silicon substrates (solid symbols and lines) was carried out. In figure 1(a), Rs values of those samples underwent Ge-PAI and non-PAI with different number of flash pulses are compared. It is noticed that generally with the integration of Ge-PAI, the junction appears to be more activated than the non-PAI case. The Ge-PAI has resulted in an amorphous region of 26 nm being formed in the top surface layer, as seen from the XTEM (not shown). During the fast ramp FLA thermal cycle, the amorphous layer undergoes a solid phase epitaxial regrowth (SPER), achieving higher

The p+/n B junctions were formed by performing Ge-PAI on the Czochralski grown (100) n-type dopant solid solubility and better activation than the non-PAI crystalline counterparts.

When the multiple-pulse FLA scheme is performed, the Rs trend for the non-PAI and Ge-PAI cases exhibits the opposite phenomenon. In the case of non-PAI, a continuous Rs reduction with the increase of flash pulses has been observed and attributed to the enhanced thermal budget. However, it is interesting to see that the Rs characteristic of Ge-PAI samples is indeed increases with the pulses of FLA being applied. This observation indirectly implies that the different number of flash pulses can affect the interactions between the EOR defects and the dopants, lowering the B activation (higher Rs).

FIGURE 1. Sheet resistance as a function of the number of flash pulses for (a) non-Ge-PAI and Ge-PAI boron-doped samples, which annealed with (b) FLA and (c) pre-spike RTA 950°C followed by FLA.

In addition, figure 1 also shows the Rs trend of the PAI samples when an addition of 950°C pre-spike RTA treatment was included before the FLA. The main purpose of this scheme is to remove or reduce the EOR defects by pre-spike RTA. It resembles that of the non-PAI case since the amorphous layer created by Ge-PAI has been recrystallized by the prior RTA step before the subsequent flash annealing was carried out. This explains the continuous Rs reduction characteristic with respect to the flash pulses on this pre-spike FLA scheme. It is also noticed that the overall Rs level is higher than that of the direct FLA on the PAI samples without pre-spike RTA. The reason is due to the fact that the amorphous layer induced by the Ge-PAI has been recrystallized during the pre-spike RTA, but not during the FLA. Therefore, larger Rs is achieved due to the lower dopant activation level comparing to the direct FLA. The observation is consistent with some of the published findings, claiming that reduced BI clustering and higher dopant activation are achieved with the faster SPER process (higher temperature ramping rate) [16-17]. Nevertheless, the application of FLA on Ge-PAI B doped samples, either on the

multiple or pre-spike flash annealing schemes, is not simply dependent on the thermal budget being used but on the dopant-defect interactions during FLA. It is essential to further understand the underlying involved physical mechanisms.

Figure 2 shows the R_s values of the samples performed with the various flash pulses of one, three and six as well as the pre-spike flash scheme. These samples were subsequently treated with post-RTA annealing from 600°C to 1050°C for 60 s. Clearly from figure 2 for the case of one pulse FLA, R_s at the post-RTA annealing temperature of 800°C has the largest value. This suggests that at this temperature, the dopants are noted to have the maximum degree of de-activation. This de-activation phenomenon can be explained by the formation of the boron-interstitials cluster (BICs) created by the upward migration of the free silicon interstitials from the EOR defects during the post-annealing cycle. With a more detail analysis on the R_s trend, it is noticed that the R_s values typically register an initial de-activation up to the peak temperature of 800°C then followed by a latter re-activation behavior with the R_s decreases. The enhancement in dopant activation at higher temperatures is attributed to the dissolution of the immobile BICs and B diffusion at the tail.

FIGURE 2. Sheet resistance value (R_s) as a function of 60s isochronal annealing temperature.

With the increment of the flash pulses, similar R_s characteristic is also been acquired. However, it is interesting to note that when the samples are subjected to more number of flash pulses, the peak R_s value at 800°C drops accordingly. With comparison made to the de-activation variation curve of the pre-spike RTA flash scheme, it is clearly seen that larger R_s is obtained during the initial low temperature post-RTA (600°C). However, the relative de-activation trend (normalized to the sample without post-annealing) is observed to be among the least compared to other FLA schemes. The reason pertaining to this behavior is due to the removal of the EOR defects by the preceding 950°C spike annealing. Hence with the annihilation of most of the EOR defects, the supersaturation of silicon

interstitials towards the surface from the EOR defect region has been greatly reduced. This in turn, lessens the dopant deactivation due to the BI clustering effect. Therefore, it can be deduced that with the integration of pre-spike RTA on top of the flash annealing regime could allow for the effective dissolution of the EOR defects.

Figure 3 illustrates the junction depth obtained for the various samples in correspondence to the post-RTA treatment temperatures. Apparently with the low post-RTA temperature of 700°C, the junction depths of the samples previously irradiated with the various flash pulses demonstrate no significant dopant diffusion. It has however been observed that the sample performed with the pre-spike RTA has attained the highest junction depth value. This is due to the reason that the high temperature 950°C pre-spike RTA has resulted in the substantial diffusion of dopants deep into the substrate. Interestingly, junctions with the various FLA schemes and treated with post-RTA 800°C exhibit similar junction depths. Nevertheless, the eventual dopant diffusion trend can be realized by making close observations to the higher post-RTA temperature at 900°C. The sample subjected to the pre-spike RTA is shown to have the shallowest junction depth. This is because the pre-spike annealing has caused the removal of the existing EOR defects. Therefore, in the subsequent annealing cycle, the supersaturation of free interstitials towards the surface has been greatly reduced. In addition, junction depths with the multiple-pulse FLA scheme decrease with the increasing number of flash pulses, which could be also possibly attributed to the lowering level of interstitial supersaturation due to the smaller density of extended defects at the EOR region.

FIGURE 3. Junction depths of the Ge-PIA B doped samples subjected to the different FLA schemes plotted against the range of post-RTA temperatures.

On this note, with the results obtained from both figures 2 and 3, it can be evidenced that the dopant activation and diffusion behavior is closely related to the interactions between dopants and EOR defects. Optimized multiple-pulse FLA is able to achieve

higher junction activation and shallower junction depth profiles by reducing the existing EOR defects. Although the pre-spike RTA treatment is able to acquire the shallowest junction depth as compared with the other annealing schemes, the Rs value of the junction is however noted to be the highest. Therefore, it has no absolute advantage over the direct FLA in terms of dopant activation even though the incorporation of pre-spike RTA is beneficial for dissolving the residual defects.

With the understanding of the effects of FLA on the dopant de/re-activation being established, the junction leakage characteristics of the p+/n diodes fabricated by the identical FLA schemes are being investigated. Figure 4 illustrates the I-V characteristics of the p+/n diodes. The sample subjected to the pre-spike RTA has proven to display the best junction current leakage properties, referring to the reversed biased at -2V. This observation can be explained by the fact that the pre-spike RTA annealing treatment has removed majority of the EOR defects induced by the PAI. With the low concentration of residual defects present within the silicon substrate, there are literally lesser alternative pathways of leakage for the current to flow. In addition, the degradation of the junction leakage current becomes more severe as the number of flash pulses reduces. It is therefore understandable that every addition of flash pulses irradiated onto the samples aids in the removal of the EOR defects and leads better lattice repairing.

FIGURE 4. I-V characteristic of p+/n diodes (B junctions in n-type silicon) subjected to the FLA with (a) different number for flash pulses and (b) prior spike RTA schemes.

CONCLUSION

In conclusion, this study provides a detailed insight on the various FLA schemes for the dopant diffusion and activation. The physical mechanisms involved during FLA has been discussed and demonstrated through the junction stability and leakage measurements.

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