PERGAMON

Materials Science in Semiconductor Processing 4 (2001) 339–343

MATERIALS SCIENCE IN SEMICONDUCTOR PROCESSING

Varying implant dose rate for defect reduction in laser thermal processing

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Abstract

Laser thermal processing (LTP) of ion implanted silicon involves melting and recrystallizing an implantation induced amorphous layer containing dopants as a method of producing ultra shallow highly doped junctions in silicon. After LTP there can exist a high concentration of extended defects in the recrystallized region. These defects are commonly in the form of stacking faults and microtwins that propagate from throughout the region that had been amorphous prior to laser melting. In order to determine the origin of these extended defects, the effect of the dose rate of the silicon preamorphization implant was studied. A 10 keV $1 \times 10^{15}\,cm^{-2}$ Si^{+} implant was done into silicon at dose rates between 0.06 and 0.48 mA/cm^2. High-resolution cross-sectional transmission electron microscopy (HR-XTEM) results show the roughness of the amorphous crystalline interface increases with increasing dose rate up to 0.24 mA/cm^2 then decreases because of dynamic annealing. Quantitative plan-view TEM results of the defect density after LTP processing at 0.75 J/cm^2 laser power show a direct correlation between the amorphous crystalline interface roughness and the final defect density. Reduction in amorphous/crystalline interface roughness prior to laser thermal processing results in a dramatic reduction of LTP recrystallization defects.

1. Introduction

As feature sizes are continually scaled, alternate implantation and annealing techniques are needed for the formation of ultra-shallow highly doped junctions. Shallow junction formation is currently limited by inadequate dopant activation by conventional ion implantation and rapid thermal annealing. Laser thermal processing (LTP), which involves the melting and recrystallization of a preamorphized layer, has shown promising results in creating low resistance ultra shallow junctions [1]. However, as previously reported [2], there is a high density of stacking faults and microtwins after LTP processing. During LTP, the power is set such that only the amorphous layer melts and thus, the recrystallization process originates at the amorphous/crystalline (a/c) interface. Therefore, previous work has focused on the effect of the a/c interface morphology on the formation of extended defects [3]. Earlier studies investigated very low temperature anneals (VLTA) as a method of altering the implantation induced a/c interface [3]. Results showed that a 400°C 60 min VLTA reduced the a/c interface roughness. This reduced roughness resulted in a lower defect density after LTP. However VLTA reduces the thickness of the amorphous layer by 10–20%. The observed reduction in defect density might simply be due to the overmelting of the thinner amorphous layer by the fixed laser power. Thus a method of changing the a/c interface roughness without necessarily thinning the amorphous layer was desired. Another approach to alter the a/c interface morphology and thus possibly reduce the density of extended defects that form upon melt is to vary the implant dose rate.

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1369-8001/01/$ - see front matter
PII: S1369-8001(01)00004-X

Several authors have previously reported that variation in dose rate has a strong effect on amorphous layer depth [4]. The a/c depth was found to increase with increasing dose rate. This increase in the amorphization depth may be attributed to decreased recombination of point defects during the implant because there is less time for defect motion and annihilation between successive implantation events (cascade overlap) [5,6]. It is also known that increasing the dose rate can lead to sample heating, which can result in dynamic annealing or ion beam induced epitaxial recrystallization [7]. This can result in a reduction in the amorphous layer thickness.

Thus changing the dose rate can potentially change the a/c interface roughness by affecting point defect recombination in the cascade. This experiment shows that changing the dose rate does indeed change both the roughness and thickness of the amorphous layer and this is shown to directly correlate to a change in the defect density after LTP melting and recrystallization.

2. Experimental

In order to study the effect of dose rate on the a/c interface, silicon ions were implanted at an energy of 10 keV with a dose of $1 \times 10^{15}\,cm^{-2}$ into 8 in Czochralski (1 0 0) silicon wafers using a Varian VIIsion 80 LE (low energy) implanter. The beam current was altered to achieve dose rates of 0.06, 0.12, 0.24, and 0.48 mA/cm^2. The cooling performance of the implanter was measured using temperature stickers with implant temperature remaining around 25°C. The as-implanted amorphous layers were studied by cross-sectional transmission electron microscopy (XTEM) using phase contrast imaging on a JEOL 4000FX high resolution TEM. Both variable angle spectroscopic ellipsometry (VASE) and XTEM were used to measure the amorphous layer thickness for each dose rate condition. Amorphous layer thickness and peak to valley interface roughness were measured using a graduated eye lupe. Since the a/c interface is extremely rough after ion implantation, amorphous layer thickness was measured starting halfway between the peak and valley of the interfacial roughness and extending up to the surface. Roughness measurements were taken as the distance between the top of a peak and the bottom of a valley. All measurements were taken in 5 different locations on the TEM micrographs and averaged.

After the amorphous layers were analyzed, 25 mm^2 areas of the wafers were subjected to LTP using a 308 nm XeCl excimer laser operating at powers between 0.73 and 0.77 J/cm^2. This power range has previously been shown to melt the amorphous layer but not the crystalline Si below the amorphous layer and results in single crystal Si upon recrystallization. Laser exposure time was for a single 20 ns pulse. After LTP, plan-view transmission electron microscopy (PTEM) samples were prepared by standard procedures and were examined on a JEOL 200CX TEM using weak beam dark field $\mathbf{g}_{220}$ imaging conditions. The defect density was measured for several regions of each micrograph. In addition, selected area diffraction patterns were used to ensure the power was sufficient, to melt down to the a/c interface and thus avoid polycrystalline recrystallization.

3. Results and discussion

Fig. 1 shows amorphous layer thickness and a/c interface roughness as a function of beam current. The amorphous layer thickness increased with increasing dose rate up to 0.24 mA/cm^2 and then decreased for the 0.48 mA/cm^2. The decrease in thickness for the 0.48 mA/cm^2 dose is believed to be a result of dynamic annealing. As introduced by Morehead [8] in 1970, the lifetime of a collision cascade generated within silicon lasts about 10^{-13}–10^{-11} s. However, the minimum time between successive ion impacts is of the order of 10^{-3} s within any given 100 Å-diameter area. Since the minimum time between collisions is much longer than the lifetime of a collision cascade, overlapping of two cascades in progress is highly unlikely. Therefore, a mechanism other than cascade overlap must be responsible for the observed differences in amorphous layer thickness among different dose rates [9]. Morehead described dynamic annealing as a mechanism involving room temperature diffusion and interaction of the implant

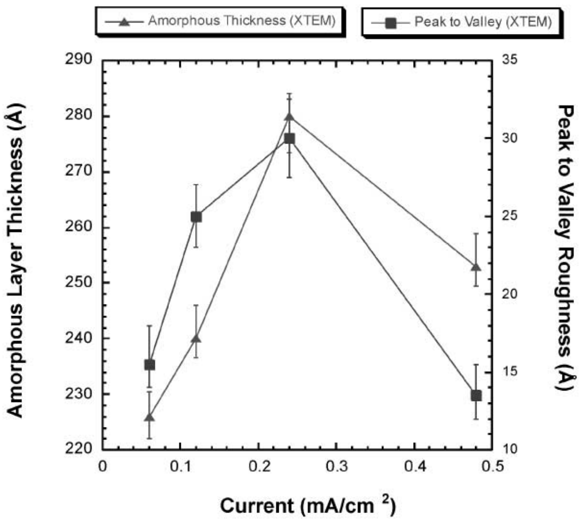

Fig. 1. Amorphous layer thickness and amorphous/crystalline interface roughness as a function of beam current for a 10 keV Si^+ $1 \times 10^{15}\,cm^{-2}$ implant.

induced mobile defects (vacancies and interstitials) during the implant. The dynamic annealing process is usually called self-annealing because the damage produced by ion implantation is subsequently annealed out by the ion beam itself [10]. It needs to be noted that the amount of dynamic annealing observed in this experiment is very small, of the order of 25 Å.

The roughness measurements from HR-XTEM show a trend similar to the amorphous layer thickness. Error bars represent the minimum and maximum peak to valley distance for each dose rate condition. It should be noted that $0.12\,mA/cm^2$ sample has a thinner amorphous layer than the $0.48\,mA/cm^2$, however the roughness is considerably greater for the $0.12\,mA/cm^2$ sample. The HR-XTEM micrographs in Fig. 2(a–d) visually show the difference in a/c interface roughness as well as the difference in amorphous layer thickness for 0.06, 0.12, 0.24, and $0.48\,mA/cm^2$ dose rates respectively. It can be seen that the highest dose rate of $0.48\,mA/cm^2$ created the most planar interface. Again this is believed to be a result of dynamic annealing.

Defect densities after LTP at powers of 0.73–0.77 J/cm^2 were investigated for all dose rates. Fig. 3(a–d) show the effect of dose rate on defect density. The defects were

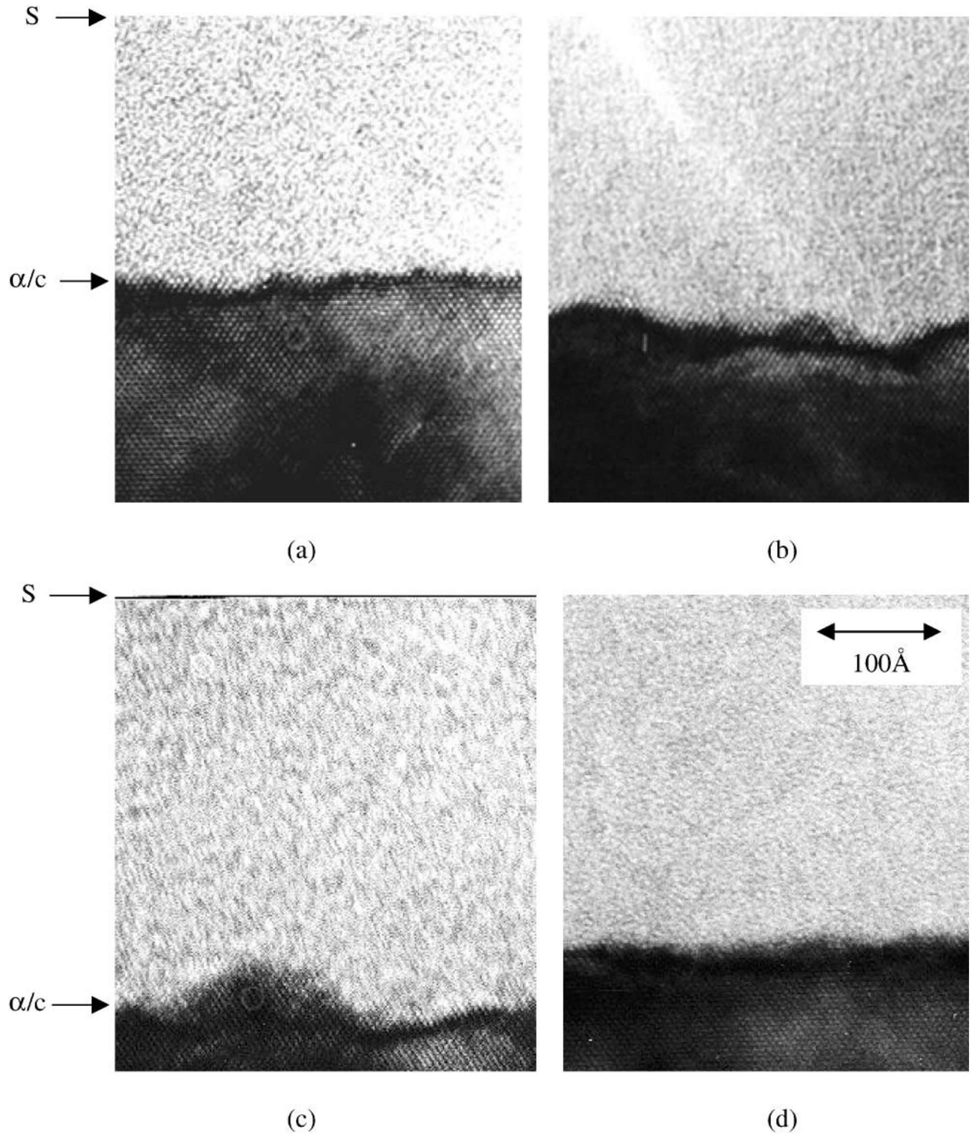

Fig. 2. HR-XTEM micrographs showing differences in amorphous layer thickness and a/c interfacial roughness for a 10 keV Si^+ $1\times10^{15}\,cm^{-2}$ implant at different beam currents. (a) 0.06 mA with a-depth of 226 Å, (b) 0.12 mA with a-depth of 240 Å, (c) 0.24 mA with a-depth of 280 Å, and (d) 0.48 mA with a-depth of 253 Å.

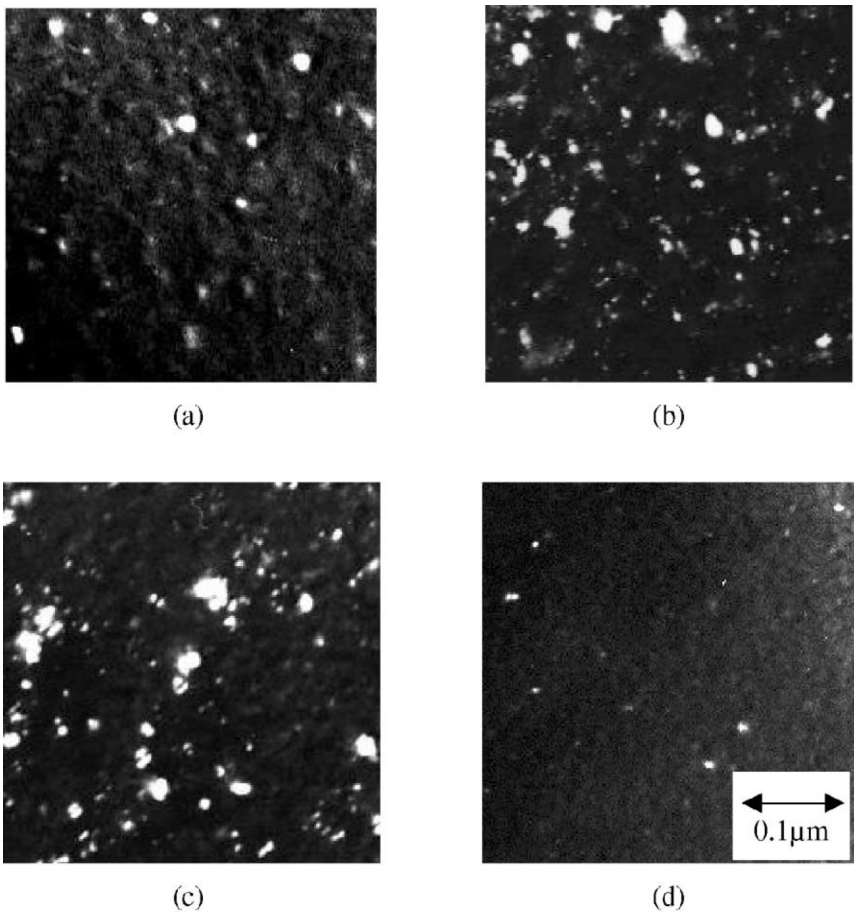

Fig. 3. Plan-view $\mathbf{g}_{220}$ TEM micrographs of different beam currents plus 0.75 J/cm^2 LTP. (a) 0.06 mA, (b) 0.12 mA, (c) 0.24 mA, (d) 0.48 mA. Decrease in number of defects in (a) and (d), corresponding to a reduction in a/c interfacial roughness.

identified by high resolution cross-sectional TEM to be a mixture of stacking faults and microtwins, extending from the surface to a depth equivalent to the depth of the a/c interface prior to melting. From Fig. 3 it is clear that increasing the dose rate increases the defect density up to 0.24 mA/cm^2. However, upon further increasing of the dose rate up to 0.48 mA/cm^2 the defect density decreases significantly. This trend is similar to the trend in the a/c interface roughness observed in Fig. 1. Fig. 4 graphically represents defect density determined by quantifying the results shown in Fig. 3 versus the a/c interface roughness shown in Fig. 1 for different dose rate conditions after a 0.75 J/cm^2 LTP (Fig. 5). There is a direct correlation between interface roughness and the defect density after LTP. As discussed in the introduction, there is a concern that small changes in the amorphous layer depth might play a role in the defect density after LTP. In Fig. 1 it should be noted that the 0.12 mA/cm^2 sample has a thinner amorphous layer than the 0.48 mA/cm^2, however the roughness is

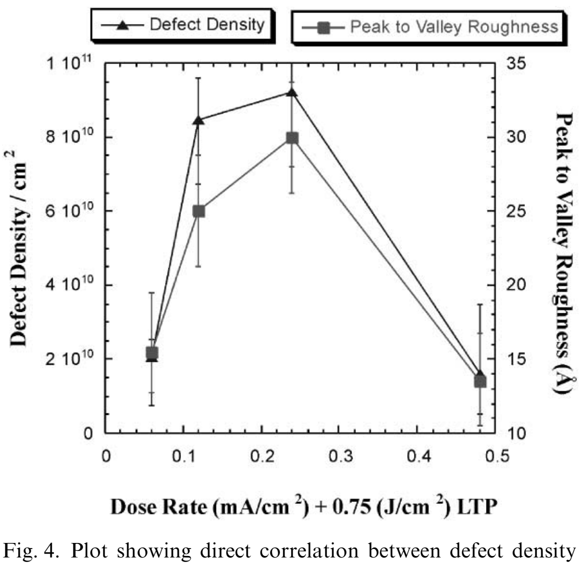

Fig. 4. Plot showing direct correlation between defect density and interfacial roughness.

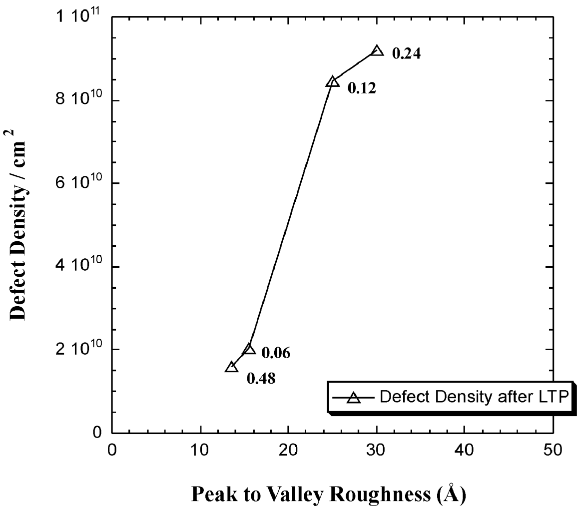

Fig. 5. A dose rate of 0.48 mA/cm^2 significantly reduces a/c interfacial roughness and therefore, defect density.

considerably greater for the 0.12 mA/cm^2 sample than the 0.48 mA/cm^2. If the thickness was the dominant factor in determining the defect density then the thinner 0.12 mA/cm^2 sample would be expected to have fewer defects than the thicker 0.48 mA/cm^2. However Figs. 3 and 4 show that the defect density is considerably higher for the 0.12 mA/cm^2 sample. Thus it is concluded that the dominant factor in determining the defect density after LTP is not minor changes in thickness but instead the a/c interface roughness.

Finally it should be mentioned that studies have been done recently that show that upon laser melting of the amorphous Si melts at a lower temperature than the crystalline Si [11]. Thus when the molten Si layer reaches the a/c interface it is supercooled with respect to crystalline Si. This causes the melt to crystallize rapidly even if the power is sufficient to melt the crystalline Si underneath. It is proposed that the rougher the a/c interface the greater the probability that the peaks of the interface will recrystallize prior to complete melting of the valleys and this can result in defect formation. Fig. 4 appears to support this hypothesis.

4. Conclusions

The effect of dose rate on the a/c interface has been correlated with the defect density after laser thermal processing. It was found that increasing the dose rate increased the roughness up to a maximum at 0.24 mA/cm^2 and then the roughness decreased from dynamic annealing. TEM analysis showed that the highest dose rate showed the lowest defect density. The decrease in defect density is not the result of a decrease in the amorphous layer thickness. Instead the defect density after LTP showed a direct correlation to the a/c interface roughness. This effect may be related to the supercooled nature of the amorphous Si melt in contact with the crystalline Si.

Acknowledgements

The authors would like to acknowledge the assistance of Gana Rimple at Verdant Technologies for assisting in the laser thermal processing. Also the authors would like to thank Heather Ohm for her assistance with the TEM sample preparation and ESB for additional assistance. This work was supported by SRC.

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