Ultra-Shallow Junction Formation with Antimony Implantation

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SUMMARY Ultra shallow low-resistive junction formation has been investigated for sub-100-nm MOSFETs using antimony implantation. The pileup at the Si/SiO\textsubscript{2} interface and the resulting dopant loss during annealing is a common obstacle for antimony and arsenic to reduce junction sheet resistance. Though implanted arsenic gives rise to pileup even with a few seconds duration RTA (Rapid Thermal Annealing), antimony pileup was suppressed with the RTA at relatively low temperature, such as 800\degree C or 900\degree C. As a result, low sheet resistance of 260\,\Omega/sq. was obtained for a 24\,nm depth junction with antimony. These results indicate that antimony is superior to arsenic as a dopant for ultra shallow extension formation. However, increase in antimony concentration above $1 \times 10^{20}$\,cm\textsuperscript{-3} gives rise to precipitation and it limits the sheet resistance reduction of the antimony doped junctions. Redistribution behaviors of antimony relating to the pileup and the precipitation are discussed utilizing SIMS (Secondary Ion Mass Spectrometry) depth profiles.

key words: shallow junction, antimony, dopant loss, dopant pileup, sheet resistance

1. Introduction

MOSFET scaling has been mainly supported by reduction of gate oxide thickness and sophisticating doping technologies. Source and drain (S/D) junction formation is becoming more important as the scaling progresses. The S/D junction depth has been also scaled mainly for the suppression of short channel effects (SCE). Effectiveness of shallow junctions for the SCE suppression was demonstrated by several authors with 40–100\,nm gate length MOSFETs [1]–[3]. This role is still important, however, for sub-100-nm MOSFETs, ultra-shallow junction depth and low sheet resistance are at the same time demanded [4], because the S/D extension resistance is becoming comparatively large to channel resistance and is becoming the limiting factor of MOSFET drain current. Since the current pass cross section becomes smaller as the MOSFET and the junction depth are scaled, in order to reduce the sheet resistance, doping concentration must be increased. However, in general, heavy doping enhances diffusion and decreases dopant activation ratio. Therefore, to avoid these problems, annealing methods should be modified along with doping methods.

In this paper we focus to n\textsuperscript{+}/p junction formation for n-MOSFET S/D extensions. Suppression of boron transient enhanced diffusion (TED) and improvement in sheet resistance is the quite urgent issue for p-MOSFET scaling and CMOS performance improvement. Compared with p\textsuperscript{+}/n junction formation with boron, n\textsuperscript{+}/p junction formation with arsenic is not so difficult, because of its heavy mass and low diffusivity, as long as the junction is deeper than 40–50\,nm for MOSFETs larger than 100\,nm generations. However, as we will show in this paper, not only the boron doping but also the arsenic doping is facing the severe obstacle for low-resistive and ultra-shallow-junction formation. We have investigated the ultra-shallow n\textsuperscript{+}/p junction formation with antimony. Since antimony is heavier than arsenic, it is suitable for n\textsuperscript{+}/p shallow junction formation using ion implantation technique. In 1987 by Sai-Halasz et al. [5], the first-100-nm-gate-length MOSFET was fabricated with antimony-doped S/D extensions. However, the fundamental issues relating to annealing such as redistribution, activation, deactivation, and sheet resistance had not discussed well in the reports prior to our study [6]–[8]. In order to fill this gap, we have investigated n\textsuperscript{+}/p junction formation with antimony for this several years. The most fundamental obstacle for utilizing antimony for the S/D extension formation was relatively low thermal equilibrium solid solubility ($3 \times 10^{19}$\,cm\textsuperscript{-3} at 850\degree C and $4 \times 10^{19}$\,cm\textsuperscript{-3} at 1000\degree C [9]). As described after, the thermal equilibrium solid solubility is worthy index, but not satisfactory to estimate the potential as the dopant.

2. Pileup: The First Obstacle for Sheet Resistance Improvement

In this section, firstly, characterization and application [10],[11] of shallow junctions formed with furnace annealing is described. Figures 1(a) and (b) show SIMS (Secondary Ion Mass Spectrometry) depth profiles of arsenic and antimony. The implantation energy and dose were 10\,keV and $1 \times 10^{14}$\,cm\textsuperscript{-2}, respectively. Annealing was carried at 850\degree C and 30\,min in nitrogen ambient using a horizontal furnace. Arsenic and antimony were implanted into Si through a 5\,nm screen oxide. Though p\textsuperscript{+}/n junction formation with boron generally needs sub-keV implantation to obtain the sub-40 to -30\,nm junction depth, 10\,keV antimony implanta-

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Manuscript revised February 5, 2002.

Manuscript received November 26, 2001.
As Concentration \[ \text{cm}^{-3} \]\nDepth [nm]
After Anneal 2.2 kΩ/sq.
After HF Dip Retained As 4.6 x 10^{13} \text{cm}^{-2}

Sb Concentration \[ \text{cm}^{-3} \]\nDepth [nm]
After Anneal 1.7 kΩ/sq.
After HF Dip Retained Sb 3.4 x 10^{13} \text{cm}^{-2}

(a) As Implanted (Screen Oxide Removed)
(b) Sb Implanted (Screen Oxide Removed)

Fig. 1 SIMS depth profiles of (a) arsenic and (b) antimony implanted into through 5 nm thick screen oxide Si at 10 keV for 1 x 10^{14} \text{cm}^{-2}. Annealing temperature and time were 850°C and 30 min, respectively. Prior to the annealing, the screen oxide was stripped. During loading into a furnace, 2 nm thick oxide was formed.

tion, shown in Fig. 1(b), leads to the 16 nm junction depth defined at 1 x 10^{18} \text{cm}^{-3} for the as implanted profile. The junction depth for arsenic is 26 nm for the same implantation condition as shown in Fig. 1(a). Since sufficiently shallow profile is obtained with 10 keV antimony implantation, we have used this energy as the standard through our investigation. In addition to the shallowness of the as implanted profile, antimony shows very small diffusion during annealing. This is clear in Fig. 2 that shows the relationship between \( \Delta X_j \) (junction depth increase during the annealing) and implantation dose. The increase in junction depth for antimony is less than half of that for arsenic. The obtained sheet resistances for antimony and arsenic are 1.7 and 2.2 kΩ/sq., respectively as indicated in Fig. 1.

The dopant pileup is clearly observed in Fig. 1 for both antimony and arsenic. It is the major origin of retained dose reduction to less than half of the implanted dose. The pileup reduction is described in the latter half of this section. In spite that the retained antimony (3.4 x 10^{13} \text{cm}^{-2}) is below that for arsenic (4.6 x 10^{13} \text{cm}^{-2}), the sheet resistance for antimony is better than arsenic. This is probably attributed to the definition of the retained dose. The retained dose is obtained as an integration of the dopant concentration against depth for the annealed specimen. The evaluated specimens were dipped in HF acid to remove an oxide. In the case of antimony, the pileup is removed by the HF dipping. However, the small pileup remains for arsenic, as shown in Fig. 1(a). Assuming the retained small arsenic pileup after the HF dipping is the precipitation, the obtained retained dose includes electrically inactive arsenic. Therefore, higher sheet resistance with higher retained dose for arsenic is understood as a result of over estimation of the retained dose.

Fig. 2 Increase in junction depth during the annealing (\( \Delta X_j \)) is plotted against implantation dose. Antimony shows smaller \( \Delta X_j \) due to lower diffusivity.

The antimony and arsenic junctions were applied to MOSFET S/D extensions to confirm the effectiveness of shallow and low resistive junctions [10]. The implantation and annealing conditions were same as that for Fig. 1. As shown in Fig. 3, \( V_{th} \) roll-off characteristics, in other words SCE, are improved by using the shallower antimony extensions instead of the arsenic extensions. Transconductance is also improved by using the antimony extension by the reduction of extension sheet resistance, as shown in Fig. 4. In addition to the S/D extensions, antimony is recently used for SSR (Super Steep Retrograde) channel formation and Halo doping for p-MOSFETs [12]–[15] utilizing this low diffusive feature. Figure 5 shows the example of the steep profile obtained with antimony for SSR application [16]. In general, the Halo doping and the SSR channel is utilized to suppress the SCE and improve drain current.
In addition, we have reported $V_{th}$ (FET threshold voltage) fluctuation reduction by the antimony SSR [16].

The obtained sheet resistance value over 1 kΩ/sq. is not low enough for sub-100 nm generation MOSFETs. As described above, the pileup and resultant decrease in the retained dose give rise to increase in the sheet resistance. In the previous reports [6], [17], [18], the pileup is considered to locate at the SiO$_2$/Si interface. We support this based on the SIMS results shown in Fig. 6. The antimony depth profiles were obtained changing primary Cs$^+$ ion beam energy for SIMS measurement. Concerning the profile tail region around 20 nm in depth, the profile for 1 keV and 500 eV are identical. This indicates that the tail profiles obtained with 1 keV and lower is accurate. However, as the beam energy decreases the pileup profile becomes steeper. This means that the obtained pileup width is apparent and real pileup is steeper than SIMS profiles. We have observed the SiO$_2$/Si interface for these specimens by TEM (Transmission Electron Microscopy) to find the structure of the pileup, but the interface was quite identical to that for thermally oxidized Si and no precipitated atoms or unknown structure were observed. Based on these results, we believe that the antimony pileup has atomic-level steepness.

Figure 7 shows dependence of the sheet resistance on implantation energy. By decreasing the implantation energy to 5 keV abrupt increases in the sheet resistance is observed. This is attributed to the increase in dopant loss due to the screen oxide and pileup [11], [19]. It is noteworthy that both antimony and arsenic showed similar results. The loss due to the screen oxide can be reduced by thinning its thickness. However, the implantation energy reduction to obtain shallower junction increases the amount of pileup and results in severe increase in sheet resistance [19]. Though the pileup peaks becomes smaller as the Antimony implantation dose is decreased and almost negligible at the dose of $1.0 \times 10^{13}$ cm$^{-2}$, as shown in Fig. 8, this dose is moderate for SSR and Halo use but too low for the S/D extension. Therefore, the pileup should be prevented for the practical shallow junction formation.

The annealing condition was modified to reduce pileup and improve the sheet resistance using RTA (Rapid Thermal Annealing). Figures 9 and 10 show antimony and arsenic depth profiles after 10 s RTA in nitrogen ambient. Heat-up ramp rate for the RTA was 100°C/s. Though the antimony pileup is clearly

Fig. 4 Relationship between effective gate length $L_{eff}$ and transconductance $G_m$.

Fig. 5 SSR channel SIMS depth profiles formed with antimony and arsenic. Large mass and low diffusivity of Sb is the key to obtain a steep profile.

Fig. 6 Influence of primary Cs$^+$ beam energy on apparent Sb SIMS depth profiles. One keV is low enough to obtain an accurate tail profile but not sufficiently low for the pileup.

Fig. 7 Influence of antimony and arsenic implantation energy on the sheet resistance.
Variation of Sb depth profiles due to Sb implantation dose. As the dose is reduced, the pileup peak becomes smaller.

Sb depth profiles after RTA. The pileup is reduced by the RTA at 800°C and 900°C. On the contrary, clear pileup is observed for RTA at 1000°C like the furnace annealing at 850°C.

Arsenic SIMS depth profiles after RTA at 800°C and 1000°C. The pileup is clearly observed unlike the Sb cases in Fig. 9.

Observed for 1000°C, it is suppressed for 800°C and 900°C. The antimony depth profile for the 800°C RTA was almost identical to the as implanted profile. On the contrary, RTA is not effective for the suppression of arsenic pileup, as shown in Fig. 10. The relationships between the sheet resistance and the junction depth for various implantation and annealing conditions are summarized in Fig. 11. As a result of the antimony pileup reduction by the RTA, the sheet resistance was improved to 850 Ω/sq. for the 800°C RTA. Implantation dose and energy were $1 \times 10^{14}$ cm$^{-2}$ and 10 keV for this case. This value is much lower than 1.1 kΩ/sq. for arsenic under the same implantation and annealing conditions. In addition, it was reduced to about 300 Ω/sq. by increasing the antimony implantation dose to $3 \times 10^{14}$ cm$^{-2}$. Figure 12 shows the comparison between the SIMS depth profiles and carrier depth profiles [20]. Carrier depth profiles were obtained by differential Hall measurement technique. The junction was thinned utilizing repeated anodic oxidation of the Si surface and oxide stripping. The activation rate, defined as the ratio of carrier and antimony concentrations obtained by SIMS, exceeds 80%.

It is noteworthy that carrier activation up to $8 \times 10^{19}$ cm$^{-3}$ is higher than the thermal equilibrium solid solubility obtained. In general impurities whose concentration exceeds the solid solubility form precipitation. However, impurity atoms must redistribute to form the precipitation. In the case of low diffusive impurities such as antimony, practical solubility limit seems to be much higher than the thermal equilibrium limit.

Figure 13 shows an example of pileup modeling.
Though the detailed mechanism of pileup formation is not clear to date, in this case we assumed that antimony trapping occurs at a certain rate at the SiO$_2$/Si interface. As annealing proceeds, the pileup increases and mobile antimony in silicon that can diffuse decreases. Since the SIMS depth profile is different from a true profile because of mixing effects due to ion bombardment, it is simulated by taking front and back side tailing into account. The calculated profile well agrees with measured one. This implies that the antimony pileup can be explained at the interface trapping and the pileup suppression by the RTA is simply attributed to shortness of annealing time. The arsenic pileup that cannot be suppressed by the RTA is probably attributed to higher diffusivity of arsenic. The calculation model shown here has a few fitting parameters and further investigation is necessary for accurate quantitative discussion.

3. Precipitation: The Second Obstacle for Sheet Resistance Improvement

As described in the previous section, the RTA has been effective for the pileup suppression and the sheet resistance improvement for the implantation dose of 3 $\times$ 10$^{14}$ cm$^{-2}$ and down. By increasing the implantation dose to 6 $\times$ 10$^{14}$ cm$^{-2}$, the sheet resistance is reduced to 260$\Omega$/sq. for 800$^\circ$C 10 s RTA, as shown in Fig. 14 [21]. The junction depth defined for 1 $\times$ 10$^{18}$ cm$^{-3}$ for this condition was less than 20 nm as shown in Fig. 15. Although the sheet resistance reduces as the implantation dose is increased, reduction between 3 $\times$ 10$^{14}$ cm$^{-2}$ and 6 $\times$ 10$^{14}$ cm$^{-2}$ is very small, especially in the case of 900$^\circ$C RTA. The origin of this tendency is discussed using the antimony SIMS depth profiles in Fig. 15. The antimony profile for 900$^\circ$C has the shoulder whose height is about 2 $\times$ 10$^{20}$ cm$^{-3}$. A narrow peak above the shoulder is attributed to immobile antimony cluster, in other words precipitation, formation at high concentration condition. The shoulder is formed as a contrast of antimony mobility for the peak region and tail region. Solmi et al. [22] pointed out that antimony precipitation occurs very quickly when concentration exceeds the threshold of 3 $\times$ 4 $\times$ 10$^{20}$ cm$^{-3}$. The shoulder height that corresponds to the peak concentration of mobile antimony is about 2 $\times$ 10$^{20}$ cm$^{-3}$, which coincides with their results. The saturation in the sheet resistance reduction in Fig. 14 also supports the precipitation formation for the antimony implantation dose of 6 $\times$ 10$^{14}$ cm$^{-2}$. The peak antimony concentration for the implantation dose of 3 $\times$ 10$^{14}$ cm$^{-2}$ is about 3 $\times$ 10$^{20}$ cm$^{-3}$. Since this value is slightly lower than the precipitation threshold, the sheet resistance was effectively reduced by increasing the implantation dose from 1 $\times$ 10$^{14}$ cm$^{-2}$ to 3 $\times$ 10$^{14}$ cm$^{-2}$ because of the absence of antimony precipitation. Though precipitation is the limiting factor of the sheet resistance reduction, obtained sheet resistance of 260$\Omega$/sq. is sufficiently attractive for the practical application for the S/D extensions. In addition, we have already confirmed that the precipitation dose
not affect junction leakage current. We have fabricated n+/p diodes with antimony or arsenic and compared their reverse direction leakage current. They do not show meaningful difference in magnitude of the leakage current. In addition, the leakage current dose not show meaningful difference in the range of 1 × 10^14 cm^-2 to 6 × 10^14 cm^-2. Detailed data concerning the evaluation of the leakage current will be reported elsewhere.

As the challenge for the further reduction of the sheet resistance, we are investigating a laser-annealing method. Figure 16 shows our recent result of KrF excimer laser annealing [23]. The pulse duration defined by a full width at half maximum was 38 ns. Because of very short annealing, high dopant activation above the thermal equilibrium, in other words reduction of precipitation, is expected. The laser energy densities from 600 to 700 mJ/cm^2 and 800 mJ/cm^2 give rise to melt from surface to the bottom of amorphous layer and to crystalline Si, respectively. The amorphous layer is formed by the antimony implantation. In every case the antimony pileup is observed. The formation mechanism of this pileup is completely different from the pileup observed after the furnace annealing and the RTA. Since antimony tends to segregate to liquid phase from solid phase, as the re-solidification progresses, antimony atoms are transferred to surface. As a result, the pileup is formed and at the SiO2/Si interface. Different from antimony, boron and arsenic do not segregate to liquid phase and are suitable for the laser annealing accompanying the melting. The obtained sheet resistance and junction depth with antimony were comparable to the RTA results. In order to exceed the RTA, further investigating is necessary including non-melt annealing with lower energy density.

4. Conclusions

Shallow junction formation with Antimony was investigated aiming sub-100 nm MOSFET S/D extension application. The pileup reduction was the key issue for the sheet resistance reduction. Using the RTA technique and increasing antimony implantation dose to 6 × 10^14 cm^-2, the sheet resistance of the implanted layer was reduced to 260 Ω/sq. Compared with arsenic, shallower and lower resistive junctions were easily obtained. Redistribution process of antimony is discussed based on mainly SIMS depth profiles. The pileup is often formed at the SiO2/Si interface by a few different mechanisms. The reduction of the pileup is always the most important key to control the sheet resistance of antimony junctions.

Acknowledgments

The author thanks Mr. D. Onimatsu, Mr. K. Egusa, Mr. H. Furumoto, Mr. K. Kamesaki, and Mr. M. Mifuji. This paper is based on their graduate or undergraduate research. This work has been supported by many staff and students of Hiroshima University. The author greatly appreciates them.

Part of this work was supported by the Core Research for Evolutional Science and Technology (CREST) of Japan Science and Technology Corporation (JST) and a Grant-in-aid for Scientific Research (C) from the Ministry of Education, Science, Sports and Culture.

References


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