Post BF_2^+ Implant Annealing using Single Wafer Rapid Thermal Furnace

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ABSTRACT

$^{49}BF_2^+$ implanted wafers were annealed in the temperature range of 900°C and 1100°C using a single wafer rapid thermal furnace for 30 sec to 1800 sec under N_2 ambient at atmospheric pressure. Sheet resistance and its uniformity were measured. Boron and fluorine depth profiles at different annealing temperatures and times were analyzed using secondary ion mass spectroscopy (SIMS). The minimum sheet resistance of 67.46Ω/sq. with a uniformity of 0.57% (1σ) was achieved at 1000°C for 90s annealing time. Good uniformity with good productivity was attained with the sheet resistance decreasing as annealing temperature and time increased. Boron moved toward the silicon surface during annealing as was observed through SIMS analysis and fluorine desorption was enhanced with increasing annealing temperature and time. The electrically activated dopant concentration was calculated by evaluation of the sheet resistance and the junction depth estimated from SIMS depth profile. The concentration was on the order of 10^{20} atoms/cm^3 regardless of annealing temperature and was closer to the solid solubility of boron in silicon as reported in the past [1]. It is recommended that the appropriate dosage and implant energy should be selected in order to prevent inactive dopant existence and unnecessary diffusion due to an unnecessarily high gradient of dopant concentration.

INTRODUCTION

As device dimensions shrink, source/drain engineering is one of the most critical technologies for fabricating advanced ultra large scale integrated circuit devices (ULSI). It requires making the source/drain contact layer shallower with appropriate contact resistance for making the smaller devices. A rapid thermal annealing (RTA) has been used for high concentration implanted source/drain contact formation with minimal dopant diffusion.
Recently, the dopant concentration at the source/drain contact is approaching a percent of the number of silicon atoms. It is, however, unknown how the high levels of implanted impurities behave in the silicon crystal during the post implant annealing process.

In this paper, $^{49}BF_2^+$ implanted wafers (30keV, 3E15 atoms/cm^2) were annealed by a single wafer rapid thermal furnace (SRTF) in the temperature range of 900°C to 1100°C from 30 sec to 1800 sec. To estimate the effect of temperature and time, the extreme conditions were also chosen. Electrical characteristics such as sheet resistance and its uniformity with respect to the annealing conditions is reported. The boron atoms depth profile, as well as that of fluorine, was analyzed by secondary ion mass spectroscopy (SIMS).

EXPERIMENTAL

Single Wafer Rapid Thermal Furnace

A schematic cross-section of the process chamber assembly in the SRTF system is shown in Figure 1. A process chamber is made of clear quartz with three quartz stand-offs. An R-type (Pt-13% Rh/Pt) thermo-couple is embedded in one of the quartz stand-offs to monitor the idle process environment temperature and wafer temperature during the process. The wafer is placed on the quartz stand-offs

(8–9 mm tall) in the center of the quartz process tube. The distance between wafer and quartz walls is kept equidistant at ~10 mm for top and bottom. Wafer pick and place was done by a three-axis wafer-handling robot with a quartz end effecter. No moving parts are used inside the process chamber to provide high reliability and minimize particle generation. The quartz process chamber is located within a SiC cavity that acts as a heat distributor to create a nearly isothermal process environment. The process chamber is heated to a process temperature set point by a three-zone heater assembly. The SRTF maintains the SiC cavity temperature at a steady state temperature and wafers move in and out of the heated cavity instead of controlling the wafer temperature through complex wafer monitoring and feedback systems.

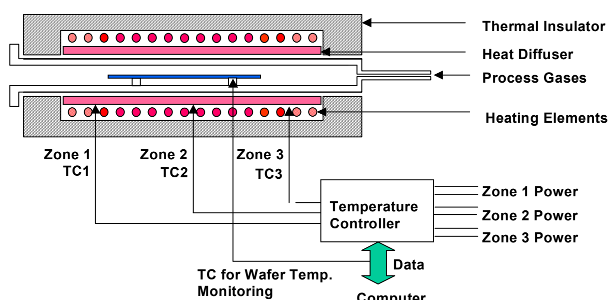

Figure 1 Schematic illustration of process chamber assembly.

Wafer Preparation

$^{49}BF_2^+$ ions were implanted at 30 keV at a dosage of 3E15 atoms/cm^2 into 200 mm n-type Si (100) wafers. The implanted wafers were annealed with the SRTF in the temperature range of 900 to 1100°C, for 30-1800 sec under a atmospheric pressure nitrogen ambient. Annealing time is defined as the residence time of a wafer in the process chamber which includes temperature ramping up.. Longer annealing times were intentionally chosen in this study to evaluate thermal history effects. After the annealing process, sheet resistance and its uniformity were measured at 49 points using a four-point-probe system. Distribution profiles of boron and fluorine versus depth for as-implanted and annealed wafers were analyzed using secondary ion mass spectroscopy.

RESULTS AND DISCUSSION

Sheet Resistance

The average post annealing sheet resistance of $^{49}BF_2^+$ implanted wafers is shown in Figure 2. The sheet resistances of the wafers annealed below 1000°C decreased with increasing annealing time. In the range of the annealing time at each temperature, that is, <1800 sec at 900°C, <1200 sec at 950°C and <360 sec at 1000°C, dopant activation and junction depth broadening can be seen. due to thermal diffusion. The sheet resistance of the wafers annealed at 1050°C and 1100°C had a minimum at 240 sec and 60 sec, respectively, while wafers annealed with the longer annealing time showed an increase in sheet resistance. This can be explained as the electrically activated dopant concentration in the formed junction layer was decreased by thermal diffusion with longer annealing times than 240 sec at 1050°C and 60 sec at 1100°C.

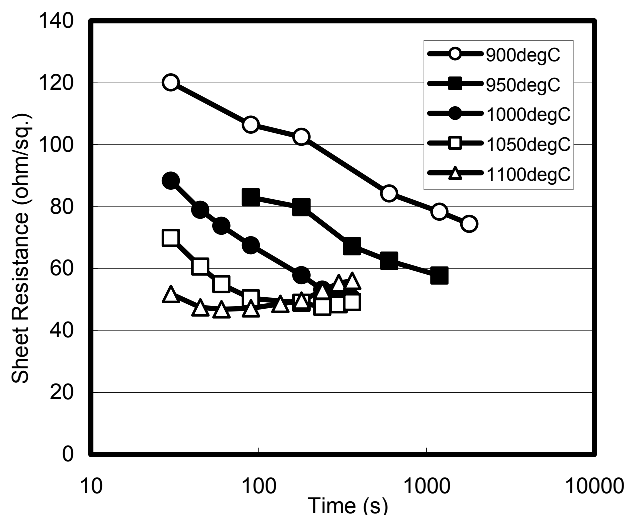

Figure 2. Post annealing sheet resistance of $^{49}BF_2^+$ (30keV, 3E15 atoms/cm^2) implanted wafers

At 900°C, a uniformity of less than 1% (1σ) was obtained with times shorter than 180 sec. At 1000°C, the minimum sheet resistance 67.46 Ω/sq. with a uniformity of 0.57% (1σ) was achieved at 90 sec annealing time.

Boron and Fluorine Redistribution during Annealing

Dopant distribution and its activation is one of the most important topics in source/drain junction formation technology. In order to investigate the behavior of boron and fluorine atoms during annealing, the wafers annealed with different temperature and time were analyzed using SIMS.

Figure 3 shows the boron depth profile and sheet resistance values obtained while annealing at 900°C. The sheet resistance was monotonically decreasing with increasing annealing time due to the progression of the dopant activation and/or extension of the junction depth by thermal diffusion.

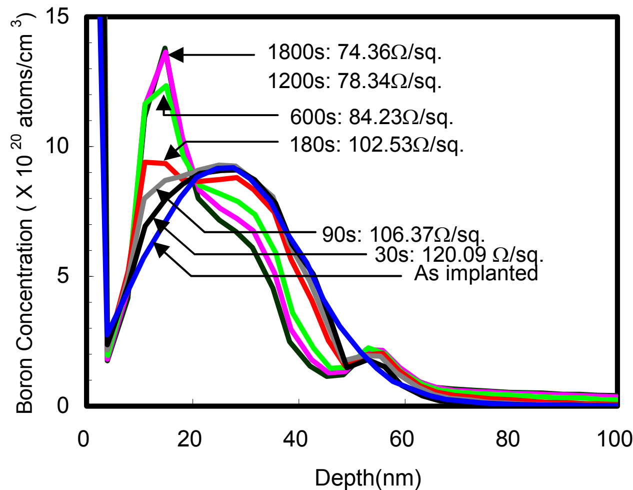

Figure 3. Dependence of B depth profile and sheet resistance on annealing time ($^{49}BF_2^+$, 30keV, 3E15 atoms/cm^2, implanted wafers annealed at 900°C)

As annealing time increased, boron atoms moved toward the silicon surface and formed an obvious peak at a 15 nm depth from the silicon surface. The boron peak concentration was increasing with annealing time at 900°C. After annealing at 900°C for 1800 sec, the peak concentration was 1.5 times higher than that of a pre-annealed wafer. The peak formation cannot be explained considering only the thermal diffusion of boron atoms, since the peak concentration after annealed was higher than that of the pre-annealed wafer. It is suspected that some defects were created during the dopant implantation under such high dose concentrations and were not fully repaired even with annealing at 900°C, thus contributing to boron atoms migration. The diffusing boron atoms might be 'captured' at such defects or strained field regions.

The fluorine concentration depth profiles for anneals at 900°C with different annealing time are shown in Figure 4. The fluorine atom concentration decreases with longer annealing time with fluorine atoms adsorption during anneal. Three fluorine concentration peaks were observed at 15 nm, 30 nm and 53 nm. The fluorine atom peak at 15 nm behaved totally differently from that of boron atoms. The number of boron atoms was increased, but fluorine atom concentration was reduced for longer anneal times. That means boron was moving as a boron atom or its cluster, not as BFx. It is possible that fluorine atoms may further desorb in subsequent processing and corrode metals so the amount of incorporated fluorine should be minimized for maintaining electric performance.

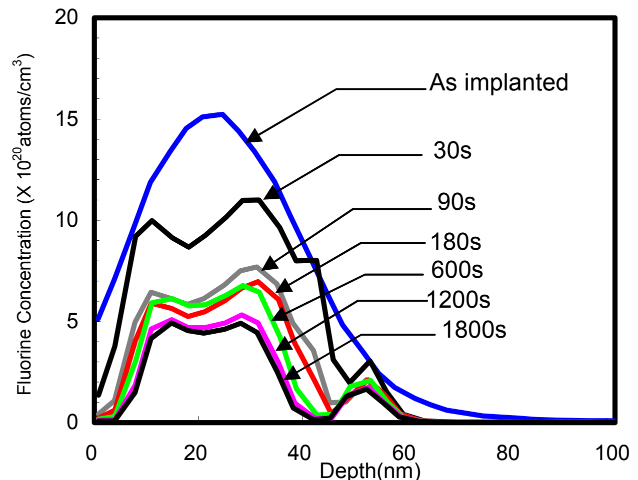

Figure 4. Dependence of F depth profile on annealing time ($^{49}BF_2^+$, 30keV, 3E15 atoms/cm^2, implanted wafers annealed at 900°C)

To determine the behavior of the dopant at high temperatures, SIMS analysis was carried out for the wafers annealed at 1100°C. Figure 5 shows boron depth profiles and each sheet resistance value with anneals at 1100°C for different annealing times.

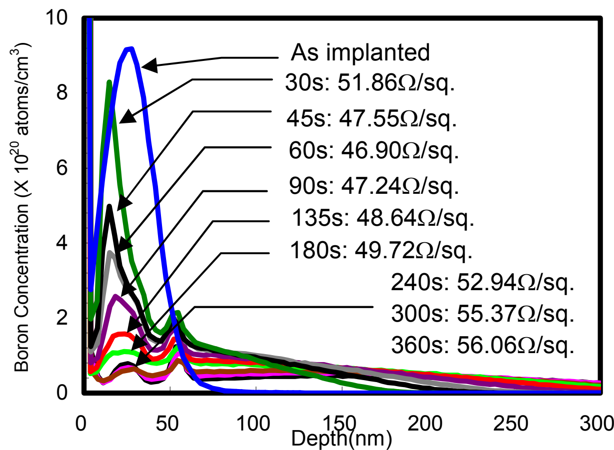

Figure 5. Dependence of B depth profile and sheet resistance on annealing time ($^{49}BF_2^+$, 30keV, 3E15 atoms/cm^2, implanted wafers annealed at 1100°C)

As seen in Figure 5, the boron peak concentration is decreased as annealing time increases. The obvious concentration peaks at 15 nm and 53 nm are observed. The boron atom re-distribution occurred even at a 1100°C annealing as well as at 900°C. As long as this is the boron re-distribution profile, it should be same regardless of annealing temperature. As annealing time increased, the concentration peak at 15nm is decreased. The boron atoms diffused to a deeper layer as seen in Figure 5 with a boron concentration at 15 nm after annealed at 1100°C for 240, 300 and 360 sec was comparable to that of a deeply diffused layer (~8E19 atoms/cm^3). As a result of this, the sheet resistance had a minimum value at the 60 sec annealing time.

The dependence of fluorine concentration profiles annealed at 1100°C for different annealing times is shown in Figure 6. As seen in Figure 6, the fluorine concentration was drastically reduced as annealing time increased. Higher temperature annealing was effective in terms of fluorine desorption, but it requires some amount of time even at 1100°C. So, it is questionable if fluorine of a wafer annealed with short time processing like lamp-based RTP is entirely desorbed.

$^{49}BF_2^+$ is attractive for shallow junction formation due to its matrix amorphization effect during implantation. Fluorine atoms are, however, localized at certain depths and the fluorine atoms should have a bonding structure with silicon and boron atoms due to its electro affinity. Furthermore, the fluorine atoms are retained even after 1100°C annealing. To fabricate stable and shallower junctions, a minimum amount of $^{49}BF_2^+$ dosage with proper energy needs to be used.

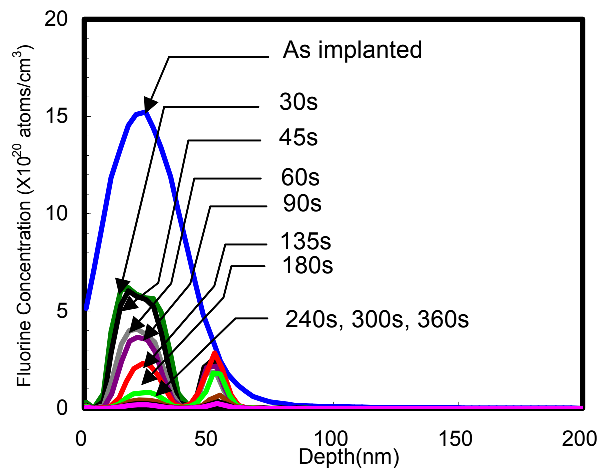

Figure 6. Dependence of F depth profile on annealing time ($^{49}BF_2^+$, 30keV, 3E15 atoms/cm^2, implanted wafers annealed at 1100°C)

Estimation of Electrically Activated Dopant Concentration at Junction Layer

The junction depth annealed at 900°C for each condition was estimated from Figure 3 as 42 nm (for 30 sec and 90 sec) ~38 nm (for 1200 sec and 1800 sec). Based on the observed junction depths and sheet resistances, the activated dopant concentration in the formed junction was also estimated as 2.5E20 atoms/cm^3 for 30 sec and 90 sec ~ 4E20 atoms/cm^3 for 1200 sec and 1800 sec [2]. This assumes a uniform and abrupt concentration profile referred to as a 'box profile'. The contribution from the deeply diffused layer was not considered in these calculations, but the values can be treated as the possible maximum concentration of the electrically activated dopant. 1E21 atoms/cm^3 of boron were initially implanted, but the calculations show that only one third or less of boron is activated in the junction annealed at 900°C. The excess boron atoms exist in the silicon and are not electrically activated.
In the case of the wafers annealed at 1100°C, the deeply diffused layer cannot be neglected. As seen in Figure 1 and Figure 5, the sheet resistance

annealed at 1100°C increased at a 90 sec annealing time and longer. The same calculation for 900°C will have a larger error because of the deeply diffused layer. It is, however, meaningful to know that limitation in calculating the activated dopant concentration for 1100°C. The junction depth annealed at 1100°C was roughly estimated as 35 nm (for 30 sec and 45 sec) ~ 300 nm (for 240 sec, 300 sec and 360 sec). It gives the activated dopant concentration calculation of 7E20 atoms/cm^3 (for 30 sec and 45 sec) ~ 1.8E19 atoms/cm^3 (for 240 sec, 300 sec and 360 sec). Since the deeply diffused layer cannot be neglected, the above 7E20 atoms/cm^3 would be in error. That means, there is not big difference about the electrically activated dopant concentration annealed at 900°C (2.5~ 4E20 atoms/cm^3) and 1100°C (<7E20 atoms/cm^3).

The solid solubility of boron in silicon at 1200°C was evaluated as about 5E20 atoms/cm^3 in the past. So, 2.5~4.0E20 atoms/cm^3 for 900°C is considered as a good estimation for the solid solubility of boron into silicon at 900°C. Even in case of 1100°C annealing, this is a fair estimation.

It is possible to activate boron contained to the solid solubility limit into silicon even when annealing at 900°C. If the required carrier concentration for the junction layer from the device performance point of view is well-estimated, the amount of dosage could be reduced.

SUMMARY

$^{49}BF_2^+$ implanted wafers were annealed using the single wafer rapid thermal furnace in the temperature range of 900°C and 1100°C from 30 sec to 1800 sec under a N_2 ambient at atmospheric pressure.

The sheet resistances of the wafers annealed below 1000°C decreased with increasing annealing time. In the range of the annealing time at each temperature, that is, <1800 sec at 900°C, <1200 sec at 950°C and <360 sec at 1000°C, both processes of dopant activation and junction depth broadening occur because of thermal diffusion. The sheet resistance of the wafers annealed with a longer annealing time increased above the minimum sheet resistance. It is explained as the electrically activated dopant concentration in the formed junction layer was decreased by thermal diffusion during longer annealing times than 240 sec at 1050°C and 60 sec at 1100°C.

Good uniformity with reasonable productivity was obtained. At 900°C, the uniformity is better than 1% (1σ) for times shorter than 180 sec. At 1000°C, the minimum sheet resistance 67.46 Ω/sq. with uniformity of 0.57% (1σ) was achieved at 90 sec annealing time.

Boron and fluorine depth profiles of the wafers annealed at 900°C and at 1100°C were analyzed using SIMS. Regardless of annealing temperature and time, boron and fluorine had concentration peaks at specific depths of 15 nm and 53 nm. Annealed at 900°C, the peak concentration at 15 nm in depth was growing as annealing time increased and saturated. It was predicted that a boron re-distribution mechanism other than thermal diffusion must exist. Annealed at 1100°C, the peak concentration was decreased when the annealing time increased. The peak concentration depth was the same as that annealed at 900°C. It appears that there was no big difference about the boron re-distribution mechanism at 900°C and 1100°C. Fluorine has come out of the wafer as annealing temperature and time increased. Even after annealing at 1100°C, fluorine was retained in the junction layer.

An approximate calculation of the electrically activated dopant concentration was carried out. The calculation showed that there was no significant difference about the electrically activated dopant concentration at 900°C and 1100°C. The concentration was 2.5~4E20 and <7E20 atoms/cm3 at 900°C and 1100°C. It appears that even annealing at 900°C the boron can be activated to the solid solubility limit.

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