Rapid isothermal annealing of As-, P-, and B-implanted silicon

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Single-crystal silicon wafers have been implanted with As, P, and B to doses of 1×10^{13} – 1×10^{16} /cm² and given a transient anneal using a Varian IA-200 Rapid Isothermal Annealer. The system uses infrared radiation to heat the wafers to temperatures in excess of 1000 °C for times on the order of 10 sec. Sheet resistance and Hall measurements have been used to determine the effect of the anneal on the electrical properties of the wafers. Rutherford backscattering and secondary ion mass spectroscopy have been used to measure lattice damage and dopant profiles before and after annealing. As and P are lost during the anneal unless the wafer is capped. Complete activation can be achieved with very little dopant diffusion. Residual damage is minimal in (100) oriented wafers that had been implanted with As. However, for (111) wafers damage is less in (111) wafers implanted to doses $\geq 5.0 \times 10^{15}$ /cm², than in (111) wafers implanted to doses $\leq 5.0 \times 10^{15}$ /cm². The diffusion of As during this transient anneal has been modeled using a concentration enhanced diffusion coefficient and the wafer temperature profile obtained from an optical pyrometer.

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I. INTRODUCTION

As integrated circuits increase in complexity, it becomes extremely important to reduce device dimensions in order to increase circuit speed. However, as device dimensions shrink it becomes necessary to precisely control dopant profiles. The initial profiles can be generated fairly precisely by ion implantation. However, each high temperature process step [implant activation and anneal, silicide formation, phosphosilicate glass (PSG) reflow, etc.] which occurs subsequent to the implant step can possibly cause dopant diffusion. This can increase short-channel effects in metal-oxide-semiconductor (MOS) circuits and cause emitter-collector shorts in bipolar circuits if the total diffusion length becomes comparable to the device dimensions. The desire to accurately control dopant diffusion during high-temperature process steps has led to considerable research activity in high-temperature transient annealing techniques. Several researchers have used both pulsed and cw lasers and electron beams to anneal ion implanted dopants, react silicides, and produce PSG reflow.^{1–4} For both the laser and electron beam sources, all of the energy is absorbed in the near surface region, producing a surface temperature of 900 °C or greater for times of a few milliseconds in the cw case. This is sufficient for recrystallization of implanted amorphous silicon to occur, but dopant diffusion is insignificant. The pulsed beam annealing will cause the surface layer to melt if the energy density is large enough. Any impurities in the molten layer will be redistributed by liquid phase diffusion and liquid-solid segregation effects will occur as the molten layer solidifies.⁵ These beam annealing techniques have encountered severe problems such as optical coupling with oxide layers and stresses due to thermal gradients when applied to actual devices and circuits. To overcome some of the effects of thin-

film interferences and temperature gradients, researchers have developed large area incoherent energy sources to perform rapid isothermal annealing. In this technique the entire wafer is heated to 900 °C or greater for times on the order of 10 sec.⁶ High intensity arc lamps,^{7–9} raster scanned electron beams,¹⁰ and graphite strip heaters¹¹ have been used as energy sources. Varian has developed a system for performing rapid isothermal annealing using infrared radiation from a resistively heated sheet of graphite. The anneal occurs in vacuum so that essentially all of the energy transfer is by radiation. Since infrared radiation is weakly absorbed in Si, the temperature rise is essentially uniform throughout the bulk of the wafer and thermal gradients are minimal. Due to the fact that the radiation is incoherent, the application of this technique to annealing circuits and devices is not limited by thin-film interference effects as is the case with lasers. Preliminary results using this technique to anneal ion implants and to perform other high temperature processing steps have been reported by Wilson *et al.*,^{12–14} Fulks *et al.*,¹⁵ and Downey *et al.*¹⁶ In this paper we will present additional data obtained by rapid isothermal annealing of B, As-, and P-ion implanted wafers. For completeness some results which have been presented previously^{12–14} will be repeated in this paper.

II. SAMPLE PREPARATION

Three-in. Czochralski (CZ) silicon wafers were used as substrates throughout these experiments. To evaluate isothermal annealing of ion implanted material, both (100) and (111) wafers were implanted with ⁷⁵As, ³¹P, or ¹¹B to doses ranging from 1.0×10^{13} to 1.0×10^{16} /cm². The *n*-type wafers had resistivities of 1–5 Ω cm and the *p*-type wafers had resistivities of 7–17 Ω cm.

The annealer has been described previously.¹⁶ The wafers in these experiments were annealed for exposure times

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between 5 and 30 sec. The graphite heater set point temperatures ranged from 1000 to 1350 °C. Slip lines were produced on wafers which were annealed at temperatures of 1300 °C and above if the exposure time was greater than 10 sec. The blanket implanted wafers were analyzed subsequent to annealing using sheet resistance, and Hall effect measurements to obtain carrier concentration and mobility. Boron profiles were measured by secondary ion mass spectrometry (SIMS). Arsenic profiles and residual damage were measured by Rutherford backscattering spectrometry (RBS).

III. RESULTS AND DISCUSSION

A. Wafer temperature profiles

Figure 1 presents three series of wafer temperature versus time profiles for wafers implanted with As to doses of 1.0×10^{15} , 5.0×10^{15} , and $1.0 \times 10^{16}/\text{cm}^2$. The wafer temperature is measured by an optical pyrometer located directly behind the wafer. The temperature measured at 0 sec is not indicative of the wafer but is due to radiation from the heater element passing directly through the wafer since silicon is essentially transparent to $\sim 2 \mu\text{m}$ light at room temperature. As the wafer temperature rises the transmitted radiation decreases. The reading of 875 °C between ~ 3 and ~ 7 sec is the minimum reading on the pyrometer and not the wafer temperature. After 7–10 sec the wafer temperature begins to exceed 875 °C and the temperature on the graph is now indicative of the wafer temperature. Note that the wafer temperature rises above 875 °C sooner for the higher dose implants than the low dose implants. This means the increase in dopant and damage is increasing the optical absorption at the heater wavelengths ($\sim 2 \mu\text{m}$). The wafer temperature rises rapidly between 10 and 20 sec and then remains essentially constant between 20 and 30 sec. The variations in resultant temperature are probably due to slight differences in wafer thickness, background doping, etc. or the faster heating of the wafer implanted to a higher dose. The wafer temperature exceeds the heater set point temperature because the thermocouple measuring the heater temperature is not in direct contact with the heater but is ~ 2 mm away. Therefore, the real heater temperature is higher than the set point temperature measured by the thermocouple. This data will be used to explain some of the results we observe in the following sections.

B. ^{75}As data

Initially Si wafers, (100) *p*-type, 7–17 $\Omega \text{ cm}$ were implanted with 100-keV ^{75}As to doses between 1.0×10^{13} and $1.0 \times 10^{16}/\text{cm}^2$ and isothermally annealed with heater set point temperatures between 1100 and 1300 °C. Figure 2 is a plot of sheet resistance versus exposure time for wafers implanted with As to different doses. The graphite heater set point temperature was 1150 °C. After 5-sec exposures the sheet resistances were extremely high and the wafers still had a milky appearance of amorphous silicon. Exposure times of 10 sec or longer caused the wafer to appear as single-crystal silicon, but the minimum sheet resistance was achieved only after a 15-sec anneal. Longer exposure times caused the sheet resistance to increase. Similar results were achieved with other heater temperatures, although the mini-

FIG. 1. Temperature vs time for As (100 keV) implanted Si. The anneal conditions were a heater set point of 1150 °C and exposure time of 25 sec. The implant doses were (a) $1.0 \times 10^{15}/\text{cm}^2$, (b) $5.0 \times 10^{15}/\text{cm}^2$, and (c) $1.0 \times 10^{16}/\text{cm}^2$.

um sheet resistance was obtained with shorter exposures at higher heater temperatures and longer exposures at lower temperatures. The standard deviation in sheet resistance

FIG. 2. Sheet resistance vs anneal time for ^{75}As (100 keV) implanted Si after annealing with a heater set point temperature of 1150 °C.

across the 3-in. wafers was better than 2%. The minimum sheet resistance value of 85 Ω/sq obtained on wafers implanted to a dose of $1.0 \times 10^{15}/\text{cm}^2$ can be compared to a 90 Ω/sq sheet resistance achieved by conventional furnace annealing at 1000 °C for 10 min in N_2 . A sheet resistance reading was obtained after 5 sec for the highest dose and not on lower doses, because this wafer reached a high temperature (> 900 °C) sooner. (See Fig. 1.)

Rutherford backscattering and ion channeling analysis have been used to show that complete annealing of the amorphous layer created by a $1.0 \times 10^{15}/\text{cm}^2$ As implant occurs only after a 15-sec exposure.¹² This explains the high sheet resistance readings for shorter exposure times since the dopant resides in an amorphous or heavily damaged layer. This further confirms that the wafer temperature does not exceed 900 °C for exposure times less than 10 sec. Channeling analysis on samples subjected to a 15 sec or longer exposure time showed no evidence of residual damage or defects.¹² The scattering yield ($\chi_{\min} < 5\%$) was only slightly higher than the yield obtained on virgin unimplanted silicon ($\chi_{\min} = 3\%$).

In Ref. 12 we stated that for a $1.0 \times 10^{15}/\text{cm}^2$ As implant, no loss of As occurred for exposure times of 5 or 10 sec and essentially no diffusion was observed. However, for a 15-sec exposure some diffusion occurs and ~8% of the total As was lost as determined by RBS. Longer exposure times produced greater diffusion and more dopant loss. This loss of dopant explains the rise in R_s for exposure times greater than 15 sec.

To prevent the loss of As from implanted wafers a series of experiments was performed where one half of each wafer was capped with 0.05 μm of deposited oxide subsequent to the implant and prior to the anneal. Figure 3(a) presents sheet resistance versus exposure time for wafers implanted to

doses of $1.0 \times 10^{15}/\text{cm}^2$ and annealed with a heater set point temperature of 1150 °C. The SiO_2 cap was removed in hydrofluoric acid prior to the sheet resistance readings. The minimum sheet resistance is achieved between 12.5 and 15 sec. The sheet resistance remains constant on the half of the wafer that was capped with SiO_2 . Figure 3(b) shows the As profiles, obtained by RBS, on the capped and uncapped por-

FIG. 3.(a) Sheet resistance vs exposure time for ^{75}As (100 keV, $1.0 \times 10^{15}/\text{cm}^2$) implanted Si. Half of each wafer was capped with SiO_2 prior to the anneal. The graphite heater set point was 1150 °C. (b) ^{75}As profiles measured by RBS after a 1150 °C set point, 30-sec exposure. The dashed curve was the profile obtained on the half of the wafer that was capped. The solid curve was obtained on the uncapped portion of the wafer. Approximately 30% of the As was lost from the uncapped portion.

tions of a wafer annealed for 30 sec with a heater set point temperature of 1150 °C. There is substantial diffusion toward the surface and into the bulk in both cases. As was seen in Ref. 12, the half of the wafer that was not capped lost ~30% of the implanted As. This is in good agreement with the 27% rise in sheet resistance shown in Fig. 3(a). The half of the wafer that was capped shows that no loss of As has occurred.

Both (100) and (111) Si wafers were implanted with ^{75}As (100 keV) to doses ranging from 1.0×10^{14} to $1.0 \times 10^{16}/\text{cm}^2$ to determine any effects of wafer orientation on rapid isothermal annealing. A 0.05- μm sputtered SiO_2 cap was deposited on the wafer prior to the anneal. Figure 4 compares the sheet resistance versus anneal time for As doses of 1.0×10^{15} and $1.0 \times 10^{16}/\text{cm}^2$ in (100) and (111) oriented wafers. The graphite heater set point temperature was 1200 °C in all cases. The sheet resistance for the (111) wafers implanted to a dose of $1.0 \times 10^{15}/\text{cm}^2$ is always higher than (100) wafers implanted to the same dose. After a 15-sec exposure the two orientations differ by 40% in sheet resistance. The sheet resistances differ by more than 10% after a 25-sec exposure. Comparable differences between (100) and (111) wafers were observed for implant doses of 1.0 and $5.0 \times 10^{14}/\text{cm}^2$. However, for doses of $1.0 \times 10^{16}/\text{cm}^2$, the sheet resistances for the two different orientations agree to within 10% for each exposure time. A similar trend was observed on wafers which were implanted to a dose of $5.0 \times 10^{15}/\text{cm}^2$ and isothermally annealed with a heater temperature of 1200 °C.

The RBS channeling spectra for a (111) Si wafer which was implanted with As to a dose of $1.0 \times 10^{15}/\text{cm}^2$ and isothermally annealed for 15 sec with a graphite heater temperature of 1200 °C are presented in Fig. 5(a). The scattering yield from the silicon shows that the first 0.08 μm of Si is still defective and has not completely annealed. This is in contrast to the 100 wafer shown in Fig. 2 of Ref. 12 which was implanted to $1.0 \times 10^{15}/\text{cm}^2$ and annealed for 15 sec with an

1150 °C heater temperature and no damage detectable by RBS remained. The scattering from As with the beam in the random direction [shown in Fig. 5(a)] implies minimal diffusion of the dopant has occurred. In addition, the reduction in scattering yield from the As with the beam in the aligned direction is so slight as to imply that less than 40% of the As is located on a substitutional lattice site. A (100) wafer annealed under the same condition showed ~97% of the As was located on a substitutional lattice site. This difference is residual defects and percent of substitutional arsenic explains the differences we observed in sheet resistance (Fig. 4) for the two orientations.

The RBS data for a (111) wafer implanted to $1.0 \times 10^{16}/\text{cm}^2$ with As and annealed for 15 sec with a 1200 °C heater temperature is presented in Fig. 5(b). The scattering yield from the arsenic with the He^+ beam in a random direction indicates significant diffusion of the As has occurred both toward the surface and into the bulk of the wafer. This is considerably different from the $1.0 \times 10^{15}/\text{cm}^2$ sample where only minimal movement of the dopant occurred. This rapid diffusion will be discussed further in the next section. The scattering yield from both the As ($\chi_{\min} = 7.3\%$) and the Si ($\chi_{\min} = 3.5\%$) indicates that essentially all of the defects have been annealed and the As is 96% substitutional in the Si lattice. These results compare favorably with those obtained on (100) Si wafers which were implanted and annealed under identical conditions ($\chi_{\min} \text{ Si} = 2.6\%$ and $\chi_{\min} \text{ As} = 4.5\%$).

In summary we have seen that the anneal quality of (100) As implanted wafers is quite good independent of the dose. However, the crystal quality after annealing of (111) wafers is highly dependent upon the dose. Good anneals were obtained for doses $\geq 5.0 \times 10^{15}/\text{cm}^2$. Similar results have been reported by Chu *et al.*¹⁷ for conventional furnace anneals at 1100 °C in N_2 . They observed better anneals for (111) wafers implanted to doses of $1.0 \times 10^{16}/\text{cm}^2$ than for wafers implanted to $1.0 \times 10^{15}/\text{cm}^2$. The low growth velocity of (111) Si relative to (100)¹⁸ is probably the reason for the poor anneals of the $1.0 \times 10^{15}/\text{cm}^2$ implanted wafers. However, this growth velocity can be enhanced at high dopant concentrations by the impurity enhanced self-diffusivity of silicon.¹⁹ This may explain why the wafers implanted to $1.0 \times 10^{16}/\text{cm}^2$ have better crystal quality after annealing.

As mentioned in the previous paragraphs, the As diffusion is dependent upon the As concentration. As profiles, after rapid isothermal annealing, with a heater temperature of 1200 °C, are shown in Figs. 6(a) and 6(b) for As implant doses of $1.0 \times 10^{15}/\text{cm}^2$ and $1.0 \times 10^{16}/\text{cm}^2$, respectively. The $1.0 \times 10^{15}/\text{cm}^2$ implants show a decrease in the peak concentration of ~50% after a 15-sec exposure with some As having diffused into the bulk. The peak concentration decreases further and the depth of diffusion into the bulk increases with increasing exposure time. After a 30-sec exposure the dopant concentration is relatively constant to a depth of ~0.2 μm and then decreases more than an order of magnitude between 0.2 and 0.3 μm . However, the wafers which were implanted to a dose of $1.0 \times 10^{16}/\text{cm}^2$ and annealed with a 1200 °C heater temperature [Fig. 6(b)] show a substantial diffusion of the As toward the surface and into the bulk after 15 sec. After 30 sec. the As concentration is

FIG. 4. Sheet resistance vs exposure time for As implanted (100) and (111) Si annealed with a heater set point temperature of 1200 °C.

FIG. 5.(a) Channeling spectra for As (100 keV, $1.0 \times 10^{15}/\text{cm}^2$) implanted (111) Si annealed for 15 sec with a 1200 °C heater set point. (b) Channeling spectra for As ($1.0 \times 10^{16}/\text{cm}^2$) implanted (111) Si annealed for 15 sec with a 1200 °C heater.

essentially constant to a depth of $\sim 0.45 \mu\text{m}$ and then falls an order of magnitude between 0.5 and $0.6 \mu\text{m}$. The data presented in Figs. 6(a) and 6(b) imply that the diffusion of As in these cases depends strongly on the As concentration. The amount of diffusion observed in Figs. 6(a) and 6(b) is well in excess of what is predicted by intrinsic diffusion of As in bulk silicon. However, Tsai *et al.*²⁰ and Fair and Tsui²¹ have presented models for a concentration enhanced diffusion of As in Si. In the absence of As complexing, the expression for As diffusivity is given by²⁰

$$\frac{D}{D_i} = \frac{(1 + \beta f)}{1 + \beta}, \quad (1)$$

where

$$f = \frac{C(x,t)}{n_i} \quad (2)$$

and

$$\beta = 100. \quad (3)$$

$C(x,t)$ is the As concentration, n_i is the intrinsic carrier concentration at the anneal temperature, and D_i is the intrinsic diffusivity.

$$D_i = 22.9 \exp\left(\frac{-4.1 \text{ eV}}{kT}\right). \quad (4)$$

These are the equations we have used in our computer program to model the As profiles following rapid isothermal annealing. The computer program solves the diffusion equation

$$\frac{\partial C(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[D [C(x,t)] \frac{\partial C(x,t)}{\partial x} \right] \quad (5)$$

numerically. The temperature as a function of time was determined from plots similar to those shown in Fig. 1. The as-implanted profiles were used as initial As distributions. Figures 7(a) and 7(b) compare the As profiles measured by RBS and calculated using Eqs. (1)–(5) for samples implanted to a dose of 1.0×10^{15} and $1.0 \times 10^{16}/\text{cm}^2$, respectively. The anneal conditions were an 1150 °C heater set point and a 25-sec exposure time. As mentioned previously the diffusion is much greater for the $1.0 \times 10^{16}/\text{cm}^2$ sample than the $1.0 \times 10^{15}/\text{cm}^2$ sample. This is due in part to the faster heating of the higher dose sample and due in part to the concentration enhancement of the diffusion coefficient. The model predicts the data very well in both cases. The model predicts the data to better than 15% in the peak concentration region for both samples and to better than a factor of two in the region where the concentration is 10% of the peak concentration and decreasing rapidly. Similar agreements between calculated and measured profiles have been obtained for different anneal conditions.

FIG. 6. (a) ^{75}As profiles as determined by RBS for samples which were annealed with a 1200°C heater set point temperature. The implant dose was $1.0 \times 10^{15}/\text{cm}^2$. (b) ^{75}As profiles as determined by RBS for samples which were annealed with a 1200°C set point heater. The implant dose was $1.0 \times 10^{16}/\text{cm}^2$.

In the present model we have not found it necessary to include the effect of transient point defect populations. Fair *et al.*²² have stated that B and As diffusion are also enhanced by point defects which are present after implantation in addition to concentration dependent effects. However, the effect of point defects is less if the dopant is in an amorphous layer rather than a lightly damaged layer.²² Narayan *et al.*²³ reported an enhancement of the intrinsic diffusion coefficient of about two orders of magnitude at 1050°C . They attribute this to point defects rather than concentration dependent effects which could produce a similar increase. Hodgson *et al.*²⁴ have shown that if the implanted layer is furnace annealed prior to rapid thermal annealing, the point defects are annihilated and standard diffusion occurs. Hodgson *et al.*²⁴ also concluded that they see no more than a factor of two increase in the normal diffusivity of As implanted to doses of 1×10^{14} and $1 \times 10^{15}/\text{cm}^2$ annealed in the ~ 1 sec, $\sim 1200^\circ\text{C}$

FIG. 7. (a) Comparison of measured and calculated As profile after an 1150°C , 25-sec rapid thermal anneal. The implant dose was $1.0 \times 10^{15}/\text{cm}^2$. (b) Comparison of measured and calculated As profiles after an 1150°C , 25-sec rapid isothermal anneal. The implant dose was $1.0 \times 10^{16}/\text{cm}^2$.

temperature range. In the present case the As-implanted layers are amorphous prior to the transient anneal¹² and should reduce the effect of point defect.²² In addition, the heating rate between 800 and 1100°C of the Varian IA-200 is somewhat slower (35 – $100^\circ\text{C}/\text{sec}$) than many other rapid thermal annealers (125 – $300^\circ\text{C}/\text{sec}$) and more of the point defects may be annealed at lower temperatures prior to the onset of diffusion. However, this would not explain why Hodgson *et al.*²⁴ do not see point defect enhanced diffusion since they use a very fast heating rate.

For these heavily doped layers to be used in device fabrication, the electrical properties must be stable under subsequent thermal processing. To investigate the effects of subse-

quent heat treatments, (100) oriented Si wafers were implanted with As to doses of 1.0×10^{15} or $1.0 \times 10^{16}/\text{cm}^2$ and isothermally annealed with a 1200 °C heater and 15-sec exposure. The wafer was then split into four pieces, which were subjected to a furnace anneal for 30 min in N_2 at 600, 700, 800, or 900 °C. Figure 8 represents the sheet resistance versus anneal temperature for the two sets of samples. The samples that were implanted to a dose of $1.0 \times 10^{15}/\text{cm}^2$ show a change in the sheet resistance of less than 5% over the entire temperature range. This indicates the wafers are stable under these thermal conditions. However, the specimens which were implanted to doses of $1.0 \times 10^{16}/\text{cm}^2$ showed an increase in sheet resistance of 35% after an 800 °C, 30 min anneal. The channeling spectrum from this sample showed a slight increase in both the As and Si scattering yields. This is evidence that As was coming out of solution. The RBS data shows that the As concentration in the near surface region is $\sim 4.0 \times 10^{20}/\text{cm}^3$ [see Fig. 6(b)]. The concentration in the near surface region for the $1.0 \times 10^{15}/\text{cm}^2$ implant was less than $1.0 \times 10^{20}/\text{cm}^3$ after isothermal annealing [see Fig. 6(a)]. These results are in good agreement with our results on laser annealed films.^{25,26} In that case we observed that if the As concentration was $\leq 2 \times 10^{20}/\text{cm}^3$ the films were thermally stable but higher concentrations of As were unstable.

C. ^{11}B data

Boron was implanted into *n*-type (100) Si wafers to doses ranging from 1.0×10^{13} to $5.0 \times 10^{15}/\text{cm}^2$. The im-

FIG. 8. Sheet resistance vs furnace anneal temperature for Si wafers implanted with ^{75}As (100 keV) to doses of 1.0×10^{15} or $1.0 \times 10^{16}/\text{cm}^2$ and annealed for 15 sec with a 1200 °C heater set point.

plantation energy was 50 keV. Figure 9 shows the sheet resistance versus exposure time for wafers annealed with an 1150 °C heater temperature. In this case the wafers were not capped with SiO_2 . After a 5 or 10 sec exposure the sheet resistance was more than an order of magnitude greater than what one would expect from a completely activated implant. This implies that during the first 10 sec the wafer does not reach the temperature which is necessary for complete electrical activation. After an exposure of 15 sec or greater the resistance reaches a constant value even though the wafer was not capped. In contrast to the As case (see Fig. 2) this means boron is not being lost during the anneal. Hall effect measurements show complete activation of the implanted boron and excellent values for the hole mobilities (comparable to bulk mobilities).

Figure 10 shows the Rutherford backscattering-ion channeling spectra for a sample implanted with ^{11}B to a dose of $5.0 \times 10^{15}/\text{cm}^2$ and annealed with an 1150 °C heater temperature for 15 sec. The channeling spectrum for the as-implanted sample increases steadily from the surface to a depth of $\sim 0.2 \mu\text{m}$ indicating the Si lattice has been damaged over this depth range. However, as would be expected for this dose of B, the sample has not been turned amorphous since the channeling yield does not reach the random value. The isothermal anneal greatly reduces the scattering yield, indicating most of the lattice damage has been removed. After annealing the χ_{min} value for scattering from Si in the depth range 0.0–0.2 μm was 3.7%. This is only slightly greater than the value obtained in virgin silicon.

The boron profiles after isothermal annealing were measured by SIMS and are presented in Fig. 11. The 10-sec exposure to an 1150 °C heater causes the profile to change only slightly in the deep tail region. This fast diffusion of

FIG. 9. Sheet resistance vs exposure time for ^{11}B (50 keV) implanted and annealed (1150 °C heater set point) Si.

FIG. 10. Ion channeling data from silicon implanted with ^{11}B (50 keV, $5.0 \times 10^{15}/\text{cm}^2$) before and after rapid isothermal annealing.

boron in the tail of the implant is in agreement with the data of Hodgson *et al.*²⁴ They state that the boron atoms occupy interstitial positions and are very mobile at low temperature until they are captured by a vacancy to become substitutional and then diffuse at normal rates. There is no measurable change in the peak or near surface region. This implies that almost no boron diffusion has occurred other than in the tail, but the boron was not electrically activated since we were unable to obtain a sheet resistance reading (Fig. 9). The 20-sec exposure causes the peak boron concentration to decrease with boron moving deeper into the substrate and toward the surface. After a 30-sec exposure the boron concentration is essentially constant from the surface to a depth twice the original projected range ($R_p = 0.16 \mu\text{m}$). The concentration of boron then falls sharply for greater

FIG. 11. Boron profiles obtained by SIMS before and after rapid thermal annealing.

depths into the wafer. The total integrated counts was the same for each specimen confirming our belief that we did not lose boron. This data shows boron can be activated with minimal diffusion, but we have not achieved complete activation with no diffusion of boron occurring. Complete activation is accompanied by essentially complete removal of damage and defects.

D. ^{31}P data

^{31}P -implanted wafers were annealed with one-half of the wafer capped with $0.05 \mu\text{m}$ of sputtered SiO_2 and the other half left bare. The sheet resistance results shown in Fig. 12 are similar to those obtained on As-implanted wafers [Fig. 3(a)] in that the sheet resistance first decreases to a minimum, then increases as a function of exposure time on the uncapped portion of the wafers. This suggests that P is being lost during the anneal as was the case with As. As we saw with the As, the SiO_2 cap appears to be adequate to prevent the loss of P under these annealing conditions.

V. SUMMARY AND CONCLUSION

In this paper we have shown that As, P, and B implants can be activated and crystalline damage annealed effectively by rapid isothermal annealing using the Varian IA-200 isothermal annealer. As and P could be lost from the wafer during the anneal unless the wafers were capped with SiO_2 . On the other hand, boron was not lost during the anneal. Dopant diffusion was minimal but showed a strong dependence on the concentration at least for As. The anneal quality of (100) wafers was independent of the implanted dose. However, (111) oriented wafers showed a strong dependence on the As dose. The (111) wafers implanted to doses greater than $5.0 \times 10^{15}/\text{cm}^2$ had less residual damage than wafers

FIG. 12. Sheet resistance vs exposure time for ^{31}P (50 keV) implanted Si. The wafers were annealed with a 1200°C heater set point. $\bullet$ $1 \times 10^{14}/\text{cm}^2$, no SiO_2 cap; $\blacksquare$ $1 \times 10^{14}/\text{cm}^2$ with SiO_2 cap; $\blacktriangledown$ $1 \times 10^{15}/\text{cm}^2$, no SiO_2 cap; $\blacktriangle$ $1 \times 10^{15}/\text{cm}^2$ with SiO_2 cap; $\blacklozenge$ $1 \times 10^{16}/\text{cm}^2$, no SiO_2 cap; $\times$ $1 \times 10^{16}/\text{cm}^2$ with SiO_2 cap.

implanted to lower doses. An attempt was made to model the As profiles using a concentration enhanced diffusion coefficient and the temperature profiles obtained on the pyrometer. The calculated profiles fit the measured data quite well. Wafers that were implanted with As and isothermally annealed were thermally stable if the As concentration was less than $1.0 \times 10^{20}/\text{cm}^3$. A wafer which had a concentration in excess of $4.0 \times 10^{20}/\text{cm}^3$ was not stable.

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