Fast diffusion of As in polycrystalline silicon during rapid thermal annealing

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The diffusion of As in polycrystalline silicon films subjected to rapid thermal annealing has been studied using sheet resistance and Rutherford backscattering. The polycrystalline Si films were deposited on oxidized silicon wafers, implanted with As, and annealed with a Varian IA-200 isothermal annealer. Infrared radiation from a resistively heated sheet of graphite heats the wafer, in a vacuum, to temperatures >1000 °C for times on the order of a few seconds. The rate of diffusion and rate of loss of As from the polycrystalline Si is much faster than the diffusion rate and loss rate in single crystal Si annealed with identical conditions. Diffusion prior to grain growth agrees with previously reported results for As in polycrystalline Si. However, grain growth appears to enhance As diffusion.

Activating ion implanted dopants and annealing implantation damage using transient annealing has become important as device dimensions shrink to 1 μm. Better control of impurity diffusions can be obtained by transient annealing compared to conventional furnace annealing due to the short, precise time the wafer is at an elevated temperature. This will provide better control in the formation of shallow junctions, and fine geometry devices.

The use of incoherent light sources to anneal ion implanted single crystal Si has been reported in several papers,[1-5] however, very few results have been reported for annealing polycrystalline silicon with an incoherent light source. Polycrystalline Si is used both as a gate material on most metal oxide semiconductor (MOS) devices and as an interconnect material in many integrated circuits. In self-aligned implant process technology, the source, gate, and drain are all implanted in a single step and annealed in a subsequent step. Therefore, transient annealing must be applicable to both polycrystalline Si as well as single crystal silicon if it is to be used in MOS integrated circuit processing.

This letter reports on the fast diffusion of ion implanted As in polycrystalline Si during rapid thermal annealing with a Varian IA-200 annealer. This system has been described previously.[1,4] It uses infrared radiation from a sheet of heated graphite to anneal silicon wafers in a vacuum. The diffusion and loss of As have been measured by Rutherford backscattering (RBS) and are correlated with sheet resistance (R_s) measured with a four point probe.

Si wafers (7-17 Ω cm, 75 mm diam) with 0.1 μm of silicon dioxide grown on the surface were used in these measurements as substrates. Undoped polycrystalline Si, ~ 0.3 μm thick, was deposited by low pressure chemical vapor deposition (LPCVD) on the SiO_2. The polycrystalline Si films were implanted with ^{75}As (60 keV, $5.0\times 15/cm^2$). An SiO_2 cap was deposited on some of the wafers and others were left uncapped. Wafers from each group were subjected to rapid thermal annealing for exposure times ranging from 5 to 30 s. The nominal heater set point temperatures used were 1150 and 1200 °C as measured by a thermocouple, located ~ 2 mm from the heater. The actual wafer temperature was monitored by an optical pyrometer located directly behind the wafer. The wafer temperature was less than 900 °C for times <7.5 s and approached 1200 °C for times >25 s and a heater set point temperature of 1150 °C. The graphite temperature is above the set point temperature since the thermocouple is not in direct contact with the graphite and therefore the wafer temperature can exceed the heater set point temperatures for long exposure times.

Figure 1 presents sheet resistance (R_s) versus exposure time for films which were annealed without a cap. The film annealed with a 1200 °C heater set point has a higher R_s (895 $\Omega/\square$) than the film annealed with an 1150 °C heater set point (485 $\Omega/\square$) after a 10 s exposure. A 15 s exposure causes the R_s on the film annealed with an 1150 °C heater set point to rise more than a factor of 2.5 (485 to 1255 $\Omega/\square$). The R_s for the film annealed with a 1200 °C heater set point was off scale for a 15 s exposure. The peak temperatures achieved by the wafers were ~ 1150 and 1200 °C for the 1150 and 1200 °C heater set points. Longer times caused the R_s to be off scale for both heater temperatures. We previously reported a 27% increase in R_s between a 15 and 25 s, 1150 °C anneal of As implanted single crystal silicon.[4]

The total As remaining in the films annealed with an 1150 °C heater set point as determined by RBS is presented in Table I. After the 10 s exposure nearly 30% of the As has been lost. Between 10 and 15 s the As decreases by a factor of

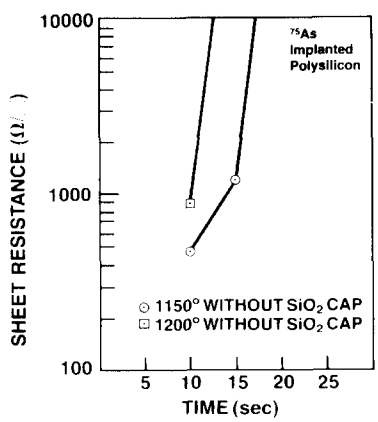

FIG. 1. Sheet resistance versus exposure time for polycrystalline Si films implanted with ^{75}As (60 keV, $5.0\times 10^{15}/cm^2$) and subsequently annealed without an SiO_2 cap.

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TABLE I. ^{75}As remaining after rapid isothermal annealing of ^{75}As (60 keV, $5.0\times10^{15}/cm^2$) implanted polycrystalline Si. The wafers were annealed without an SiO_2 cap and with an 1150 °C heater set point.

	Anneal time (s)			
	10	15	20	25
^{75}As remaining (atoms/cm^2)	3.6×10^{15}	1.4×10^{15}	7.0×10^{14}	4.7×10^{14}

~2.6 which is in excellent agreement with the increase in Rs. After 25 s, ~90% of the implanted As has been lost. This loss of dopant is substantially greater than the 29% loss of As from single crystal Si annealed with identical conditions.[4] This loss of As explains the rapid rise in R_s shown in Fig. 1.

The R_s versus exposure time for films annealed with 0.05 μm SiO_2 cap are shown in Fig. 2. The R_s decreases with increasing exposure time. The R_s for the 1150 °C data is always higher than the 1200 °C data. This is probably due to slightly larger grains in the 1200 °C annealed films.[6] The minimum R_s (98 Ω/□) achieved in the 1150 °C case (25 s) is approximately a factor of 5 lower than the minimum R_s achieved on the uncapped samples. In addition, it is a factor of 2 lower than the R_s of 199 Ω/□ achieved on a film which was furnace annealed at 950 °C for 30 min in N_2. These data plus the optical pyrometer data indicate the film temperature must exceed 1100 °C for a few seconds in order for the minimum R_s to be obtained.

The As profiles for the as-implanted and 1150 °C, 10 s annealed samples are shown in Fig. 3(a). The As profiles for the as implanted and a 12.5 s exposure are shown in Fig. 3(b). The sample was capped prior to anneal. No loss of As was measured for any of the SiO_2 capped samples. No movement of the As is detected by RBS after the 5 or 7.5 s exposure. After the 10 s exposure the As has begun to move. The peak concentration has decreased by a factor of 2 and the profile has spread ~0.05 μm. The peak temperature was 1050 °C as measured by the pyrometer on this sample. After 12.5 s the temperature reaches 1120 °C and the As has uniformly distributed throughout the 0.3 μm polycrystalline Si film. The As concentration in the film is $\sim1.6\times10^{20}/cm^3$. A similar anneal produced essentially no movement of As in single crystal Si,[4] which implies that As diffuses much faster in polycrystalline Si than in single crystal Si. This agrees with furnace diffusion results, which report faster diffusion in larger grain polysilicon (produced by cw laser annealing) than in single crystal Si.[7] However, the present data indicate a much larger diffusion coefficient than was reported by Baumgart *et al.*[8] for diffusion in polycrystalline Si. The optical pyrometer indicates the wafer temperature is less than 875 °C for the first 7.5 s. Between 7.5 and 10 s, the temperature rises from 875 to 1050 °C and reaches 1120 °C after 12.5

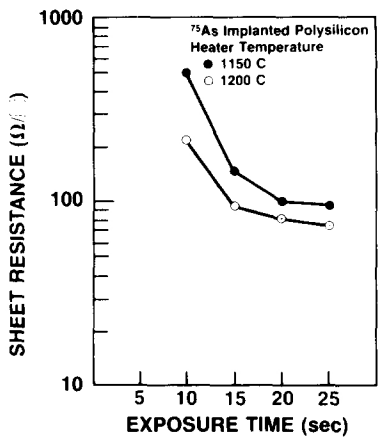

FIG. 2. Sheet resistance versus exposure time for polycrystalline Si films implanted with ^{75}As (60 keV, $5.0\times10^{15}/cm^2$) and subsequently annealed with an SiO_2 cap.

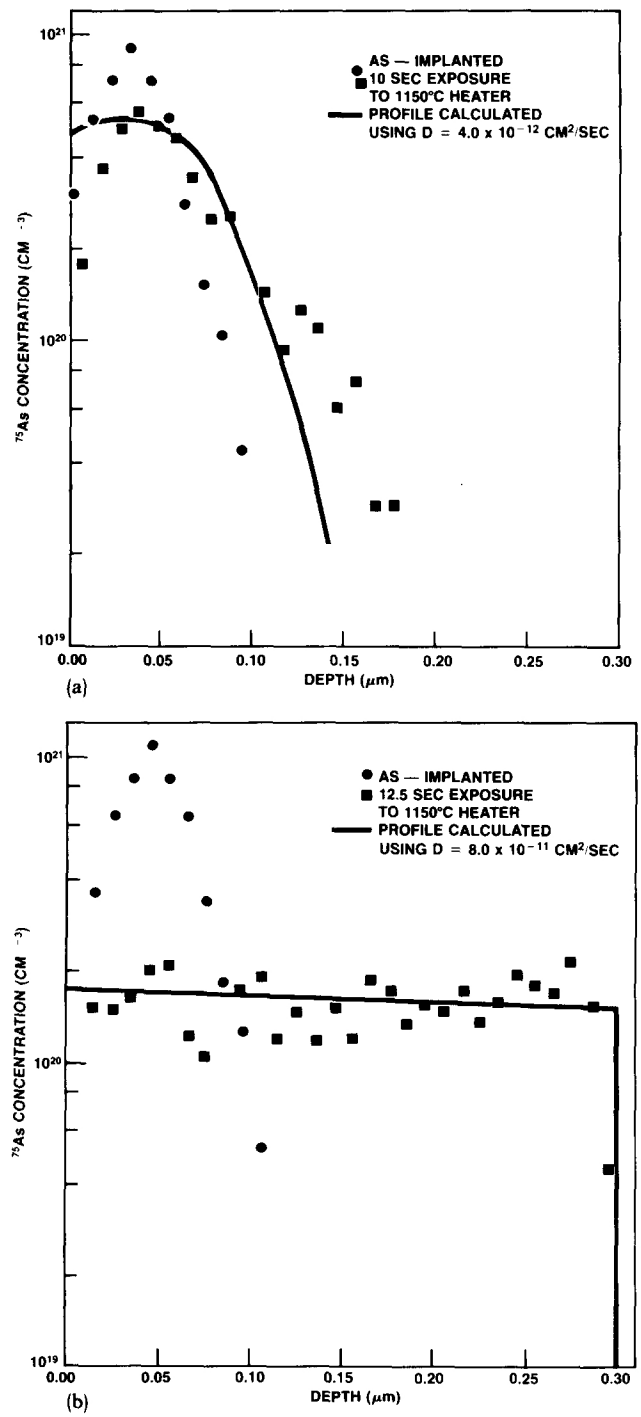

FIG. 3. (a) ^{75}As (60 keV, $5.0\times10^{15}/cm^2$) concentration profiles before and after a 10 s exposure. (b) ^{75}As (60 keV, $5.0\times10^{15}/cm^2$) concentration profiles before and after a 12.5 s exposure.

s. To determine a diffusion coefficient we have modeled the profiles by solving the diffusion equation

$$\frac{\partial}{\partial t} C(x,t) = D \frac{\partial^2}{\partial x^2} C(x,t) \quad (1)$$

numerically. $C(x,t)$ is the As concentration and D is the diffusion coefficient which is adjusted to fit the data. D is assumed to be constant independent of concentration. The as-implanted profile is used as the initial distribution and we have applied the boundary conditions that no As leaves the film at either SiO_2 interface. We have calculated an effective time at the peak temperature,[8] using the temperature versus time profiles obtained with the optical pyrometer and an activation energy of 2.3 eV given by Baumgart *et al.*[7] The 1150 °C heater, 10 s anneal has an effective time of 1.25 s at 1050 °C. As shown in Fig. 3(a) a diffusion coefficient of 4.0×10^{-12} cm^2/s gives a reasonable fit to the data. It slightly overpredicts the diffusion at the surface and underpredicts the data in the tail. This number agrees well with the value of Baumgart *et al.*[7] at 1050 °C. However, the 1150 °C, 12.5 s anneal has a calculated effective time of 2.0 s at 1120 °C. To obtain a reasonable fit to these data requires a diffusion coefficient of 8.0×10^{-11} cm^2/s which is nearly a factor of 10 higher than the values measured by Baumgart *et al.*[7] Since implant conditions are comparable, the concentration effects should be comparable. However, in the present case the average grain size is changing significantly. After a 10 s exposure the grain size is essentially the same as that of the as-deposited material ($\sim$20 nm),[9] but the average grain size increases a factor of $\sim$2.5 between the 10 and 12.5 s exposures. The grain size in Ref. 7 is several microns and does not change during the diffusion. Therefore, the grain growth which occurs during the rapid thermal annealing of As implanted polycrystalline Si may be enhancing the diffusion. This grain growth effect should change the activation energy which would change the effective time at temperature. If we assume the activation energy decreased by a factor of 2 the effective time would increase to 4 s. However, a diffusion coefficient of greater than 5.0×10^{-11} cm^2/s would still be necessary to fit the data. Swaminathan *et al.*[10] reported a substantially different activation energy of 3.9 eV for grain boundary diffusion of As in polysilicon. Using this activation energy requires a minimum diffusion coefficient of 2.0×10^{-10} cm^2/s to fit the data in Fig. 3(b). This is a lower diffusion coefficient than the 6.7×10^{-10} cm^2/s that would be predicted by Swaminathan *et al.*[10] However their[10] higher diffusion coefficient would be consistent with the data presented here. This rapid diffusion explains how large amounts of As can be lost unless films are capped.

In summary, we have shown that As implanted polycrystalline Si over SiO_2 can be activated by rapid isothermal annealing. Significant amounts of As are lost during the anneal unless the films are capped. The As diffuses very rapidly throughout the film in very short times. A similar anneal produced no movement of As in single crystal Si.[7] An effective diffusion coefficient has been calculated which is $\sim$1 order of magnitude greater than the coefficient previously reported for large grain polycrystalline Si. This rapid diffusion occurs at the same time as we see grain growth occurring. We conclude that the enhancement in the diffusion coefficient may be due to the grain growth.

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