Compensating impurity effect on epitaxial regrowth rate of amorphized Si

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The epitaxial regrowth of ion-implanted amorphous layers on ⟨100⟩ Si with partly compensated doping profiles of ^{11}B, ^{75}As, and ^{31}P was studied. Single implants of these impurities are found to increase the regrowth rate at 475 and 500 °C. The compensated layers with equal concentrations of ^{11}B and ^{31}P or ^{11}B and ^{75}As show a strong decrease of the regrowth whereas for the layers with overlapping ^{75}As and ^{31}P profiles no compensation has been found.

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The epitaxial regrowth of ion-implanted amorphous Si layers on Si crystalline substrate has been a subject of intense research in the past. It has been established that the regrowth of self-ion-implanted layers has strong orientation dependence and is a thermally activated process with an activation energy of 2.3 eV[1,2] in the temperature range 500–600 °C.

The regrowth kinetics is also strongly influenced by the presence of impurities. For example, O, C, N, and Ar in concentrations of 0.5–1.0 at. % implanted into amorphous Si layers significantly reduce the regrowth rate.[3] On the other hand, 0.5–1.0 at. % of groups III and V elements (B, P, and As) enhances the regrowth rate for annealing temperature of about 500 °C by a factor up to 20–30.[4] To offer further insight we have studied the regrowth rate of amorphous layers in ⟨100⟩ oriented Si crystals with overlapping implantation profiles of both n- and p-type impurities.

Silicon ⟨100⟩ substrates with a p-type resistivity of 1–10 Ω cm were implanted with ^{75}As, ^{31}P, and ^{11}B at the temperature of liquid nitrogen to concentrations of $\lesssim 0.5$ at. %. Combinations of partly overlapping implantation profiles were achieved by multiple energy implants of one of the impurities and a single energy implant of another. The doses and energies for the various implantations are listed in Table I. To give an idea of the resulting profiles, we have plotted in Figs. 1–3 the superposition of simple gaussians with parameters tabulated in Ref. 5. More sophisticated calculations of the distributions could be performed following the procedures of Hofker[6] or Ryssel.[7]

With ^{75}As and ^{31}P the multiple implantations produced a 6000–7000-Å-thick amorphous layer. In the case of multiple boron implantation an additional ^{28}Si implantation was performed to amorphize the ^{11}B-doped layer. The dose of the single energy implantation was calculated to give a peak concentration of 2.5×10^{20} cm^{-3}. This concentration was high enough to compensate parts of the profile of the multiple energy implantations when two types of ions were implanted. The samples were vacuum annealed in a sequence of short periods of time at temperatures of 475 and 500 °C. For comparison, reference samples with the initial multiple energy implantations of a single impurity were annealed simultaneously with samples having double impurity implantations. To evaluate the regrowth rates, the thicknesses of the amorphous layers were determined after each annealing step by using backscattering and channeling of 1.5-MeV ^{4}He$^+$ ions. This method is described in detail by Csepregi *et al.* in Ref. 4.

The effect of impurities on the growth rate is shown in Fig. 1 for an ^{75}As-doped reference sample. At both 475 and 500 °C, the growth rate is strongly enhanced compared to the intrinsic growth of Si given by the dashed lines. The relatively fast regrowth during the first annealing step can be explained by the rapid reordering of a highly disordered crystalline region at the initial amorphous-crystalline interface which cannot be distinguished from the amorphous region by the channeling technique. Our numerical values for the average regrowth rates corresponding to the highly doped ($\sim 2 \times 10^{20}$ cm^{-3}) regions of ^{75}As, ^{31}P, and ^{11}B implanted samples are shown in Table II which also gives the activation energies derived from the growth rates at 475 and 500 °C. The corresponding values for Ref. 4 are given in parentheses. With the exception of phosphorous, which in our case shows a faster regrowth and a lower activation energy, the results are in good agreement.

The effect of an additional single energy implantation of ^{31}P or ^{11}B on the regrowth at 475 °C of the initially arsenic-implanted amorphous layer is shown in Fig. 2. The addition of the ^{31}P profile [Fig. 2(b)] produces an increase of the growth rate at a depth where the initial regrowth rate is slightly reduced with the decreasing As concentration, resulting in a fairly constant regrowth rate over the whole amorphous layer thickness. The effect of the ^{11}B implantation is drastically different [Fig. 2(a)]. The regrowth rate drops to the level of 1 Å/min, where the amorphous, crystalline interface penetrates the region where the concentration levels of the two implanted impurities are equal. The combinations of a ^{75}As or ^{31}P impurity profile with boron-doped amorphous layers show similar behavior (Fig. 3). In both cases, the regrowth is strongly retarded by the n-type implant.

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TABLE I. Implantation energies employed for ^{11}B, ^{28}Si, ^{31}P, and ^{75}As.

	Multiple energy implants		Single energy implants	
Dopant	Dose (10^{15} cm^{-2})	Energy (keV)	Dose (10^{15} cm^{-2})	Energy (keV)
^{11}B	3.3	70	3.5	80
	4.25	140		
	4.85	240		
^{28}Si	1.6	100	...	...
	4.0	300		
^{31}P	4.3	160	6.25	200
	7.35	360		
^{75}As	2.7	260	5.62	570
	5.45	600		

Allowing for the uncertainties in our knowledge of the actual profiles, and generalizing, we conclude from these experimental results that shallow impurities of the same dopant type mutually enhance their effect on the regrowth, while impurities of the opposite dopant type compensate their effect on the regrowth. The data further shows that nearly exact compensation is achieved when the impurity concentrations are closely similar, even though the individual effect on regrowth enhancement of the two impurities differs substantially (see Table III).

For crystallization far below the melting temperature the regrowth will obey an Arrhenius-type equation, which is controlled by an activation energy for an atom to leave the amorphous phase, cross the interface, and attach itself to the crystalline lattice.[8] For an interface between two different phases of a single element, no large scale transport is required and the recrystallization occurs primarily through a bond rearrangement at the interface. Studies of Si at higher temperatures (in the range of ~ 1000 °C) have shown that the self-diffusivity is strongly affected by electrically active impurities at high concentration levels. Enhanced diffusion is found in both heavily doped *p*- and *n*-type silicon as compared to undoped crystals.[9] Mismatch of atomic size between the impurity and lattice atoms introduces strain surrounding each impurity atom. Accumulation of these local strains develops into a macroscopic strain in the lattice contributing to the thermodynamical force of transport.[10] Stresses may also directly affect the regrowth through a relaxation process at the growing interface.[11] Table III gives the covalent radii and the size mismatch of impurities in Si at 1200 °C. It is obvious that a stress relief mechanism could

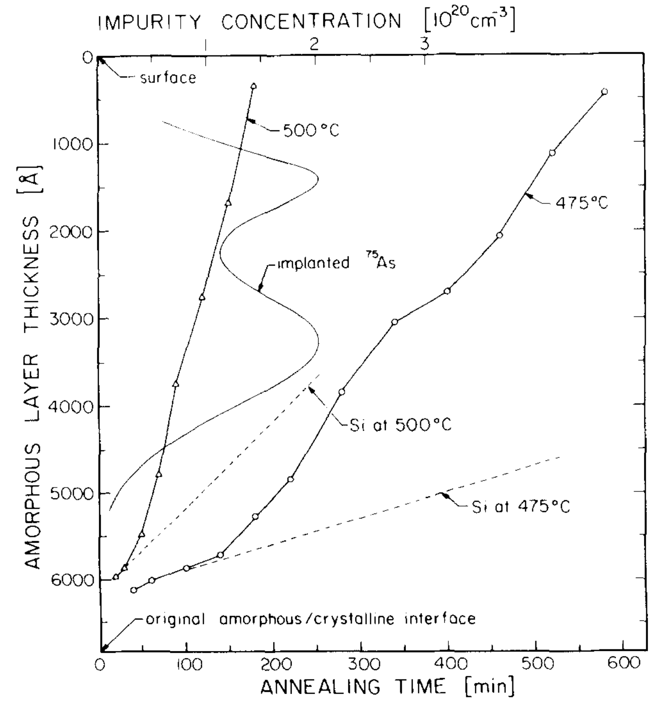


FIG. 1. Amorphous layer thickness vs annealing time for ^{75}As implanted ⟨100⟩ Si at 475 and 500 °C. The dashed lines show the regrowth rates for ^{28}Si implanted, undoped Si. The calculated ^{75}As profile is superimposed on the data.

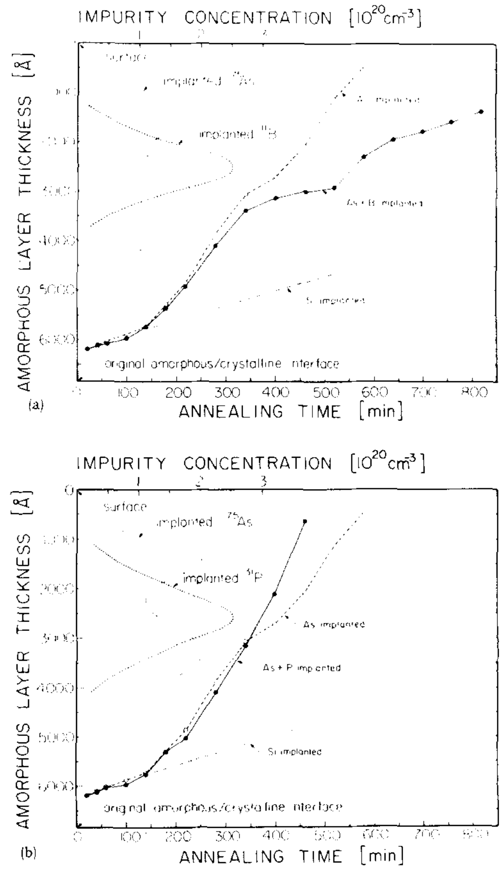


FIG. 2. Amorphous layer thickness vs annealing time at 475 °C for (a) ^{75}As and ^{11}B implanted, and (b) ^{75}As and ^{31}P implanted ⟨100⟩ Si with calculated impurity profiles superimposed on the data. The dashed line shows the regrowth characteristics of a reference sample implanted with ^{75}As only. The regrowth rate of undoped Si is given as a straight line.

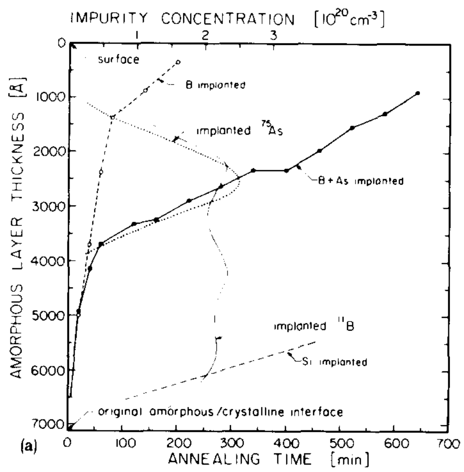
TABLE II. Rates and activation energies for the regrowth of ion-implanted amorphized Si ⟨100⟩.

		Implanted atom							
		^{75}As		^{31}P		^{11}B		^{28}Si	
Rate (Å min^{-1})	475°C	12.2	(17)[a]	31.7	(12.5)[a]	68	(80)[a]	···	(3)[a]
	500°C	39.4	(55)[a]	88.0	(60)[a]	177	(200)[a]	7	(10)[a]
Activation energy (eV)		2.3	(2.3)[a]	2.0	(2.3)[a]	1.9	(1.9)[a]	···	(2.3)[a]

[a] Values in the parenthesis are as given by Csepregi *et al.* (Ref. 4).

account for enhanced regrowth especially in the case of boron. However, a simple stress relaxation model fails to explain the observed low regrowth rates for compensated, heavily doped layers.

It is known that diffusion in silicon takes place through the motion of lattice defects. A direct relationship has been found between the carrier density and the concentration of charged defects.[13,14] The amount of electrically active impurities, therefore, plays an important role in the diffusion process. If the regrowth rate of the amorphous silicon is controlled by atomic diffusion at the amorphous-crystalline interface, it should be strongly dependent on the local doping level.



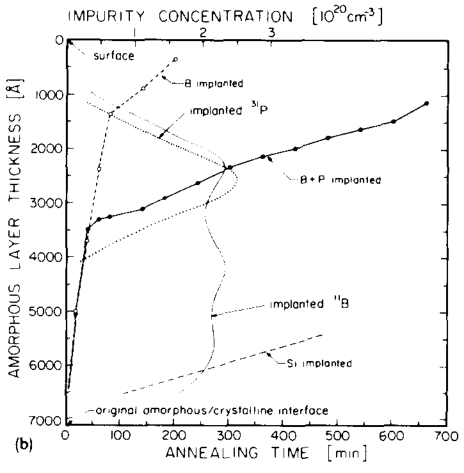


FIG. 3. Amorphous layer thickness vs annealing time at 475 °C for (a) ^{11}B and ^{75}As implanted, and (b) ^{11}B and ^{31}P implanted ⟨100⟩ Si with calculated impurity profiles superimposed on the data. The dashed line shows the regrowth characteristics of a reference sample implanted with ^{11}B only. The regrowth rate of undoped Si is given as a straight line.

TABLE III. Size effect for impurities in Si at a temperature of 1200°C, $\epsilon = (r_i - r_0)/r_0$, r_i and r_0 are the radii of impurity and Si, respectively, after Bullough and Newnan (Ref. 12).

Element	r_i(Å)	ϵ
B	0.88	− 0.25
P	1.10	− 0.06
As	1.18	0.009
Si	1.17	···

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