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## PULSED ELECTRON BEAM ANNEALING OF As AND B IMPLANTED SILICON

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**RESUME**

Des échantillons de Si (100) implantés avec  $10^{16}$  ions/cm<sup>2</sup> As ou B sous 20 et 200 keV ont été recuits par faisceau d'électrons pulsés (50 ns). Les fluences utilisées étaient 1,1 et 1,4 J/cm<sup>2</sup> avec des électrons d'énergie moyenne 15 keV. L'effet de recuit a été étudié par rétrodiffusion de particules  $\alpha$  en position canalisée ou décanalisée. Les profils de redistribution ont été obtenus par mesure à la sonde ionique.

Le mécanisme de recuit est l'épithaxie en phase liquide, la vitesse moyenne de l'interface liquide-solide étant de 400 et 250 cm/s respectivement pour les deux fluences utilisées. On observe une bonne recristallisation et une activation élevée des dopants sauf dans le cas de l'implantation Bore 200 keV. Une importante redistribution d'impuretés est observée. Les profils expérimentaux sont en bon accord avec les profils calculés sur la base des données obtenues par simulation thermique au moyen d'un modèle de diffusion en phase liquide. Celui-ci utilise une solution sous forme de fonction de Green modifiée. Aucun effet de ségrégation n'apparaît. Les coefficients de diffusion déduits du modèle sont de l'ordre de  $5 \cdot 10^{-5}$  cm<sup>2</sup>/s pour le bore et de  $2 \cdot 10^{-4}$  cm<sup>2</sup>/s pour l'arsenic.

**ABSTRACT**

p-type (100) silicon wafers have been implanted either by As or B ions at 20 and 200 keV energies and doses of  $10^{16}$  cm<sup>-2</sup>. Pulsed electron beam annealing has been performed with fluences of 1.1 and 1.4 J/cm<sup>2</sup> using a mean electron energy of 15 keV. The pulse duration was 50 ns. The annealed layers have been investigated by Rutherford backscattering under random and channeling conditions and by S.I.M.S. profiling.

Good crystal regrowth and high dopant activation occur in all cases except for the 200 keV Boron implant. Impurities redistribution is observed but no significant segregation effects appear. The experimental profiles are in good agreement with a diffusion model using a modified green function solution and taking into account dopant diffusion in liquid phase and the computed melt front location. The deduced diffusion coefficient are in the  $5 \cdot 10^{-5}$  cm<sup>2</sup>/s range for boron and  $2 \cdot 10^{-4}$  cm<sup>2</sup>/s range for arsenic.

**I. INTRODUCTION**

Since a few years, it has been demonstrated that a short duration pulsed electron beam can be used to remove implantation damage in silicon by liquid phase epitaxial regrowth from the undamaged substrate /1,2/. In a previous work /2/, pulsed electron beam annealing (PEBA) has been used to recrystallize p-type silicon implanted with As in concentration lower than the equilibrium limit solubility. In this work, we investigate the annealing conditions of a very high dose of As and B for superficial (20 keV) and deeper (200 keV) implantation. Crystal quality of the regrowth layer and dopant activation are studied by Rutherford backscattering (RBS) and the redistribution profiles are obtained by SIMS profiling.

2. PULSED ELECTRON BEAM ANNEALING

Thermal effects such as maximum molten layer thickness, liquid phase duration and melt front velocity are determined by both the electron beam parameters (energy deposition profile energy density) and the surface crystal structure of the irradiated material.

A description of the pulsed electron beam processor and a study of the beam parameters are reported elsewhere [2,3]. Fig.1 shows the diode current and voltage waveforms with the field emission diode parameters used in this work. These are selected to obtain an electron energy deposition profile convenient for surface melting of silicon [2]. Monte-Carlo

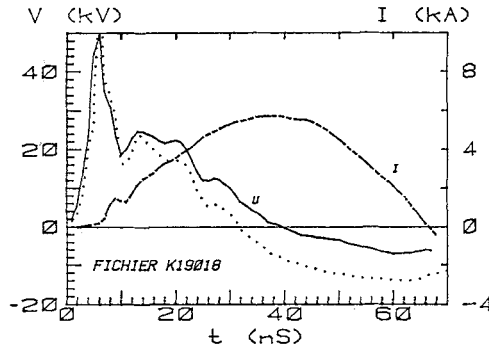


Fig. 1 - Diode current (I) and voltage (U) waveforms for a electron beam pulse of  $1.4 \text{ J/cm}^2$ . Storage voltage : 68 kV ; cathode diameter : 19 mm ; anode-cathode gap : 3 mm.

calculation of the normalized time-integrated energy deposition profile is shown on Fig.2. Implanted silicon wafers were annealed using two typical fluence values : 1.1 and  $1.4 \text{ J/cm}^2$ . These values are chosen to obtain melting depths compatible with amorphous layer thicknesses.

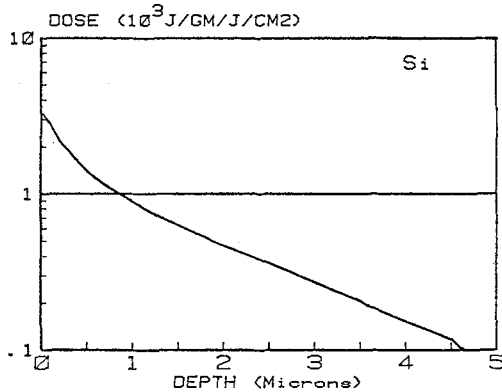


Fig. 2 - Monte-Carlo calculation of normalized time-integrated polykinetic electron energy deposition profiles in silicon. The mean electron energy is 15 keV.

Thermal effects of the pulses have been determined by numerical solution of the one-dimensional heat flow equation. A detailed description of this calculation can be found in ref.4. The melting depth  $x_M$  and the liquid phase duration are plotted in table 1. The melt front velocity is 400 cm/s and 250 cm/s for  $1.1$  and  $1.4 \text{ J/cm}^2$  respectively.

3. ANNEALING EFFECTS

Annealed samples were first characterized by RBS performed under random and channeling-conditions with a  $^4\text{He}^+$  ion beam of 1-2 MeV energy. The silicon residual disorder

$\chi_{min}$  and the dopant substitutional fraction are given table 1. The results indicate a good re ordering of the amorphous layer except for the 200 keV boron implant, and reveal a high dopant activation.

Implant (dose $10^{16} \text{cm}^{-2}$ )	PEBA ( $\text{J}/\text{cm}^2$ )	$\chi_{min}$ (%)	Subst. Fraction (%)	Duration (ns)	Melting depth (micron)	$x^*$ (nm)	Diffusion coefficient ( $\text{cm}^2/\text{s}$ )
As 20 keV	1.15	5.0	90	150	0.62	18	$2.2 \pm 0.1 \cdot 10^{-4}$
	1.45	5.2	91	400	0.95	23	$1.7 \pm 0.1 \cdot 10^{-4}$
As 200 keV	1.1	-	-	140	0.59	25	$2.7 \pm 0.3 \cdot 10^{-4}$
	1.4	5	91	370	0.90	-	-
B 20 keV	1.1	9	99	140	0.56	1.8	$6 \pm 0.2 \cdot 10^{-5}$
	1.4	9.5	100	370	0.90	2.5	$5 \pm 0.2 \cdot 10^{-5}$
B 200 keV	1.15	23	0	150	0.62	-	-
	1.45	30	12	400	0.95	7.5	$1.5 \pm 0.3 \cdot 10^{-4}$

Table 1 - Results on Si PEBA processed samples.  $\chi_{min}$  substitutional fraction obtained from RBS measurements. Molten depth and liquid phase duration obtained from thermal simulation. Values of the diffusion coefficient obtained from best fit of experimental SIMS profiles with the diffusion model discussed in the text.  $x^*$ : characteristic length for segregation effect.

SIMS profiling was performed on as-implant and on annealed samples. The profiles are shown on Fig.3,4,5. The as-implanted profiles are in nearly convenient agreement with the LSS theory except at the end of the path because of ion channeling effects. The annealed profiles show considerable redistribution of the As and B implanted atoms toward the surface and deeper in the crystal except again for the B 200 keV implant. These results are quite coherent with liquid phase epitaxy as annealing mechanism and will be discussed below.

#### 4. DIFFUSION MODEL

Heat flow calculations combined with mass diffusion models have been satisfactorily used to explain the observed spreading of dopant profiles in ion-implanted, laser or pulsed electron beam annealed samples [2,5,6]. As in ref.2, we used a simplified numerical-analytical method in order to obtain the solution of the one-dimensional diffusion equation with a semi-infinite model. In a first approximation, Wood et al./6/ derived the final profile  $C(x,t)$  from the Green's function formulation of the mass-diffusion problem in the "instantaneous approximation" by :

$$C(x,t) = \int_0^\infty \left[ G(x,t | x_0, t_0) C_1(x_0, t_0) \right]_{t_0=0} dx_0 \quad (1)$$

in which  $C_1$  is the implanted profile. However, this approximation does not take into account the melt front motion during the regrowth process.

In our simplified method [2], the implantation profiles is divided into cells of equal thickness  $\Delta x < 20 \text{ nm}$ . For each cell of nearly constant concentration the implanted atoms were allowed to diffuse in the liquid according a constant diffusivity  $D$ . The silicon surface layer is assumed to be brought to the melt point instantaneously. Then the liquid-solid interface retreats back to the surface with an assumed constant velocity given by the thermal simulation. Then, for each cell, we have a semi-infinite diffusion problem. It is a good approximation to consider the associated modified Green's function :

$$G(x,t | x_0, t_0) = 4\pi D (t-t_0)^{-1/2} \cdot \left[ \exp \left( \frac{-(x-x_0)^2}{4D(t-t_0)} \right) + P \cdot \exp \left( \frac{-(x+x_0)^2}{4D(t-t_0)} \right) \right] \quad (2)$$

The dopant concentration at the interface inside the liquid is assumed to be frozen in the underlying solid. At the surface, the diffused profile is assumed to be reflected inward the

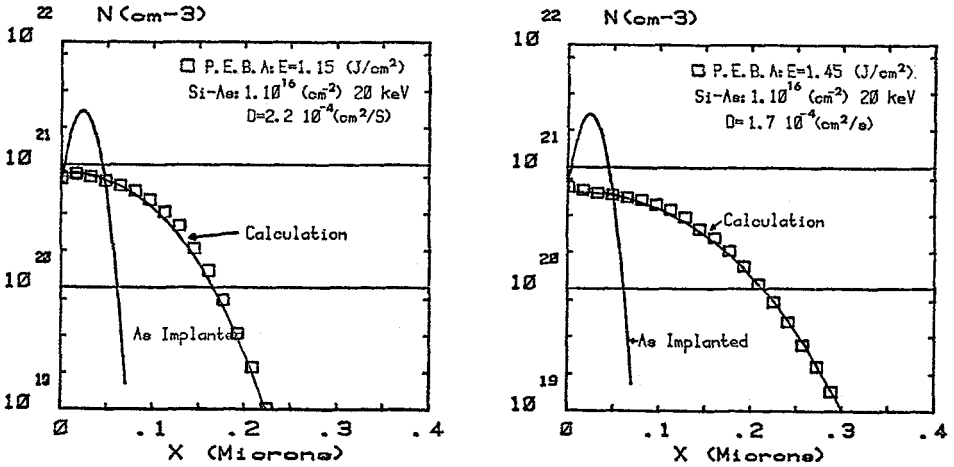


Fig. 3 - SIMS profiles of Arsenic, as implanted ( $1.10^{16} \text{ cm}^{-2}$ , 20 keV) and after PEBA ( $\square$ ) at 1.15 and 1.45  $\text{J/cm}^2$ . The solid line represents the computed diffused profiles.

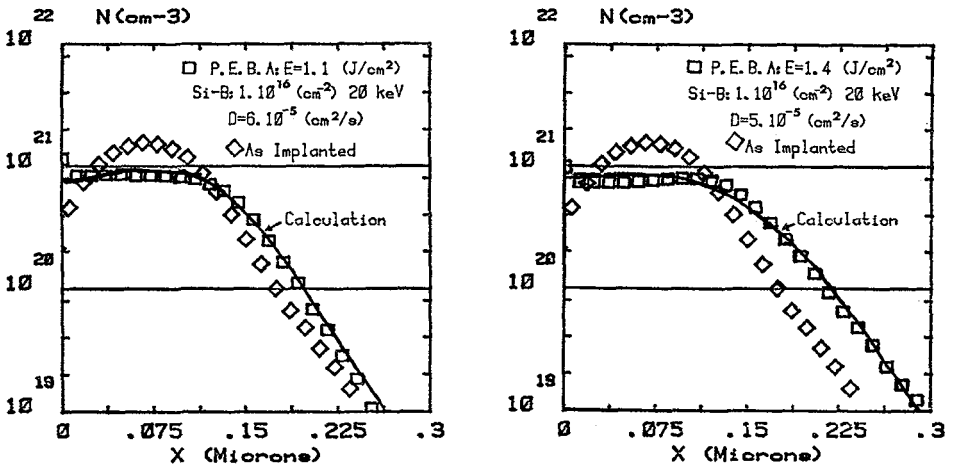


Fig. 4 - SIMS profiles of Boron, as implanted ( $1.10^{16} \text{ cm}^{-2}$ , 20 keV) ( $\diamond$ ) and after PEBA ( $\square$ ) at 1.1 and 1.4  $\text{J/cm}^2$ . The solid line represents the computed diffused profiles.

material ( $P=1$ ) or not ( $P=0$ ) if dopant losses are taken into account. Obviously, all values between 0 and 1 are possible for  $P$ . Finally, the total redistribution profile is calculated by summing up the contribution of each initial cell profile :

$$C(x,t) = \sum_{\text{cells}} C_i G \quad (3)$$

were  $G$  is given by equation (2).

5. RESULTS AND DISCUSSION

As shown on Fig.3,4,5 good matching is obtained for the annealed profiles with diffusivity  $D$  plotted on table 1 using the indicated values for the melting depth and duration.

The values for D agree with laser annealing experiments. It is interesting to note that D for As is near  $2.10^{-4} \text{ cm}^2/\text{s}$ , higher as the value obtained in the previous work /2/ for low dose implantation ( $10^{15} \text{ cm}^{-2}$ ). This suggest that D increases with the implantation dose. One can also remark that, for the 20 keV implantation, the value for D is higher for the lower fluence, both for As and B. The following explanation can be used on the basis of the thermal effect analysis of ref.4 : the melting zone is divided into two parts where the physical state of silicon differs. A superficial layer where the whole latent L is deposited and where the temperature can be higher than the melting temperature, and a deeper zone were only a part of L is deposited. In laser annealing experiment the energy deposition profile is steep as compared to the profile of Fig.2. So, this effect is not possible. Then, a mass diffusivity gradient probably occurs in the PEBA induced melting layer. In addition, the fully molten layer thickness depends on the surface crystal structure and for a given impurity and a fixed surface dose the 20 keV ion energy results in a higher surface disorder than the 200 keV ion energy. So that, the deduced mean diffusivity values are nearer the liquid phase diffusivity at  $1.1 \text{ J/cm}^2$  with the 20 keV implants because at this fluence a highly damaged layer is likely to be fully molten. A  $1.4 \text{ J/cm}^2$ , mass transport is assumed with an equal diffusivity over the whole melting layer of  $0.9 \text{ }\mu\text{m}$ , while the fully molten layer is less than  $0.3 \text{ }\mu\text{m}$ . So that a lower mean diffusivity is deduced from the SIMS profiles fitting. Our hypothesis is supported by the lower D value obtained with the B implants either at 20 keV or 200 keV because of a lower damage produced by B ions as with As ions.

The diffusion model assumes no segregation effect ( $k = 1$ ). This hypothesis is reasonable for As and B in silicon and can be discussed on the basis of the following relation :

$$C_s(x) = k C_l(x) = C_0 \left( 1 - (1-k) \exp\left(-\frac{x}{x^*}\right) \right) \quad (4)$$

giving the concentration in the solid  $C_s$  versus the concentration in the liquid  $C_l$ , the interface segregation coefficient  $k$  and  $x^* = D/kv$ .

Equation (4) was derived by Wood et al. /6/, in the case where the initial concentration  $C_0$  is constant. With  $k = 0.3$  for As and  $0.8$  for B respectively the calculated value for  $x^*$ , the segregation characteristic length, plotted on table 1, are lower than 25 nm. This value is noticeably lower than the molten depth and, so, the segregation effect can be ignored. In addition, no noticeable losses of B are observed. In a previous work As losses increasing with the fluence were also assumed /2/. However, the amounts of As losses were overestimated. The present results are more credible because the dopant concentrations allow more accurate profiling as in the case of our previous work /2/ and because SIMS is more sensitive than RBS.

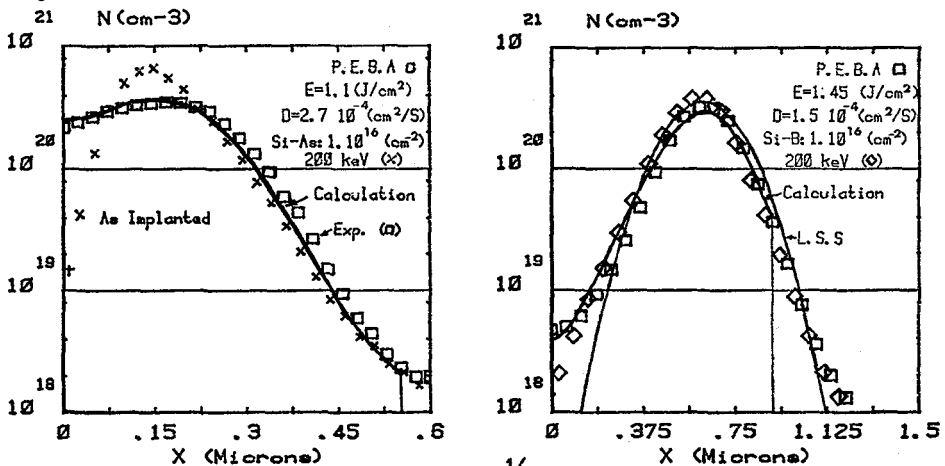


Fig. 5 - SIMS profiles of As and B, as implanted ( $1 \cdot 10^{16}$ , 200 keV) and after PEBA (□)  $1.1 \text{ J/cm}^2$  for As and  $1.45 \text{ J/cm}^2$  for B.

The As losses deduced from the diffusion model are only : 2 % for  $1.1 \text{ J/cm}^2$  and 4 % for 1.4 while the maximum theoretical losses ( $P=0$ ) can reach 41 % for the 20 keV As implants.

## 6. CONCLUSION

Pulsed electron beam annealing of a high implantation dose of As and B in silicon was studied. The poor annealing of B 200 keV is normal because the melting layer (900 nm) is thinner than the implantation damaged layer. For the other cases, good crystallization and good activation are obtained according to the liquid phase epitaxy process as annealing mechanism. The redistribution profile is well described by a simple diffusion model using a modified Green function solution. In addition no segregation appears and dopant losses are negligible in the case of boron and weak in the case of arsenic

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