DEFECTS AND AMORPHIZATION IN ION-IMPLANTED SILICON

By

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Defect formation in boron and phosphorus implanted silicon was investigated by infrared spectroscopy, X-ray topography and mechanical surface analyzer. Anneal characteristics are given; an increase in volume after implantation was detected.

Ion-implantation is a very efficient technique for doping materials, first of all semiconductors, but suffers from a side-effect, namely defect formation. Numerous methods were elaborated to study these defects with the aim to eliminate their undesired effect. As today infrared spectroscopy, nuclear backscattering, electron and X-ray diffractography are the widely used methods [1—3]. In the present paper we are going to present results summarizing our work on this matter.

1. *Infrared spectroscopy*

Both transmission and reflection methods were applied to study the damage structure of implanted silicon. The absorption band at 1.8 μm is connected with the presence of divacancies, so-called V—V centers [4]. The thickness of the amorphous layer was determined from the interference structure of the reflection spectrum [5].

A Unicam SP-270 spectrophotometer was used for these experiments. For reflection measurements, a simple mirror system was built. In order to enhance absorption, both surfaces of the sample were implanted with equal dose and energy.

Divacancy absorption. On Fig. 1 the transmission spectrum of an implanted silicon crystal is to be seen, compared with that of a non-implanted wafer. The boron dose was 10^{15} cm^{-2}, the energy 80 keV on each surface. The absorption band at 1.8 μm is very well expressed. In the figure the transmission is to be seen. In the calculations, the difference in αd values (α being the absorption coefficient in cm^{-1}, d the layer thickness) between the implanted and non-implanted case was attributed to the presence of divacancies. In order to restore crystal perfectness, an annealing cycle must be used. The changes in difference of αd for an isochronal anneal* process

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* "Isochronal" denotes a series of annealing processes in an inert atmosphere with 50 °C steps and 30 minutes duration each.

are shown on Fig. 2. Implantation was made using 80 keV boron ions with 10^{15} and 4×10^{15} cm^{-2} dose. Most of the lattice defects anneal at 500 °C. It is to be noted that the factor four in dose does not mean an increase with the same ratio for the concentration of divacancies. With this relatively high dose, we are getting closer to the limit where the defects are forming clusters or complexes. This process sat-

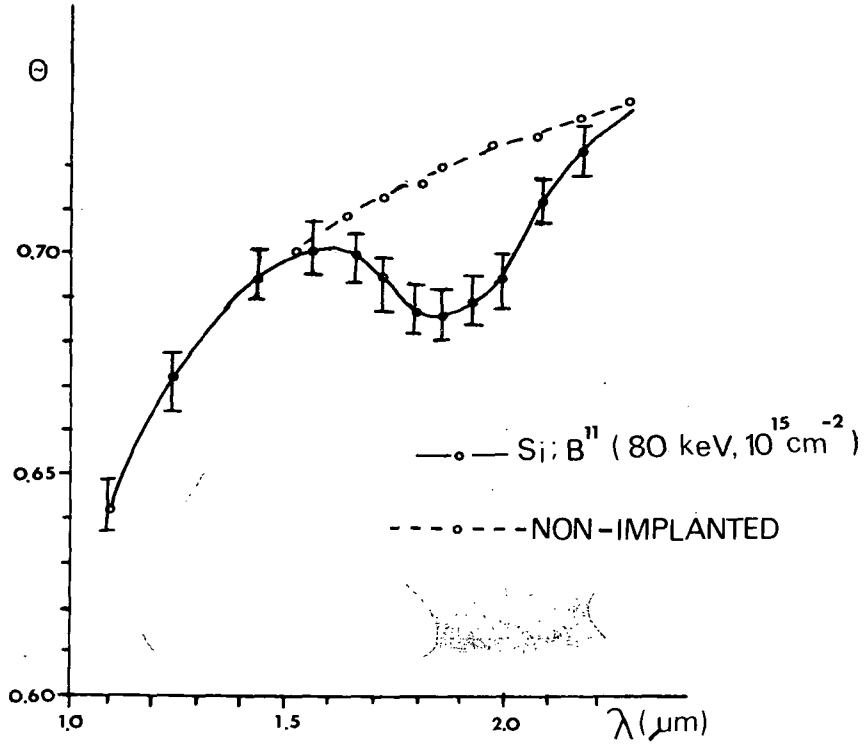

Fig. 1. Optical transmission spectra for boron implanted and non-implanted silicon

urates when the surface is fully amorphous. As Fig. 3 shows, for phosphorus implantation the effective decrease of the N^{vv} divacancy concentration is clear above doses of $2—3\times10^{14}$ cm^{-2}, *i.e.* the concept "divacancy" looses its meaning above this limit. For 80 keV boron implant, this limit is higher in dose; as boron is a light atom the limit does not fall into the range of our measurements.

In cases, when the amorphous phase has been reached, the infrared spectroscopy offers another possibility, which may give an account on the thickness of this layer.

Interference structure of infrared reflection. For amorphous layers, the dielectric constant differs from that of undamaged silicon. In other words, a sandwich of two layers with different optical properties is present. For the thicknesses $d\cong\lambda/4\bar{n}$ of the layer ($\bar{n}$ is the refraction index of the amorphous layer), the reflection spectrum has interference structure [5]. In Fig. 4, the spectra both for 80 keV phosphorus and

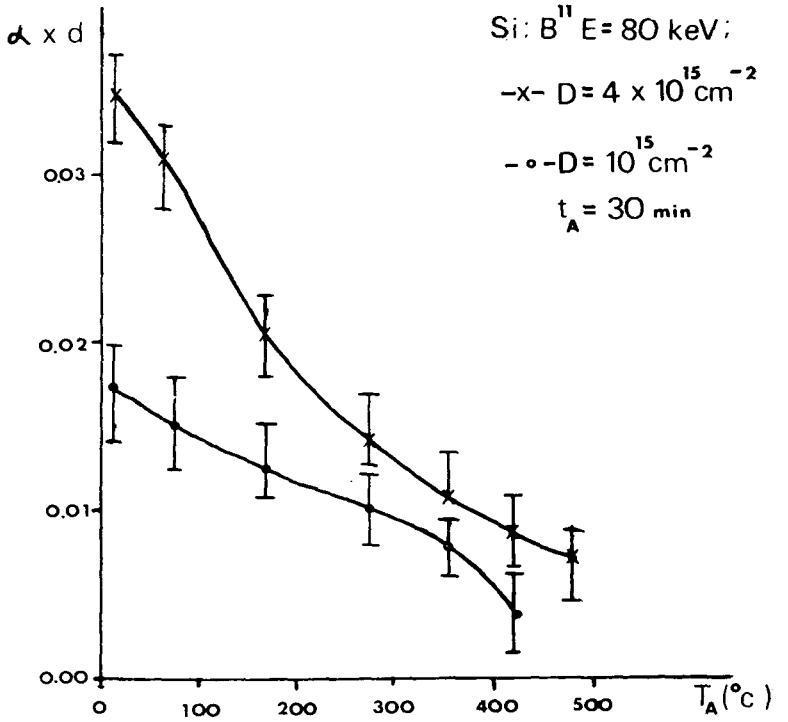

Fig. 2. Anneal characteristics of N^{vv} centers through the values of absorption peaks at 1.8 μm. On the horizontal scale, T_A, the temperature of isochronal anneal sequences is given

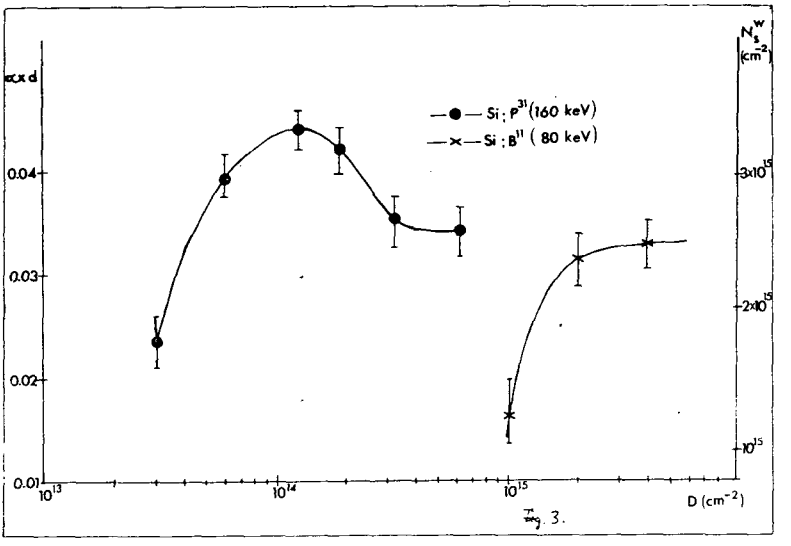

Fig. 3. Dose dependence of N^{vv} and αd for phosphorus and boron implants

boron implants and doses of 1.25×10^{16} and 3.1×10^{16} cm^{-2}, respectively, are shown. It is obvious that the interference structure for phosphorus is more pronounced, as the layer is fully amorphous from optical point of view, while for boron, this is not the case. Another characteristic difference is the distance of the minima, showing that the phosphorus layer is shallower.

In Table I, the examined implants and the corresponding calculated thicknesses of the amorphous layers are listed.

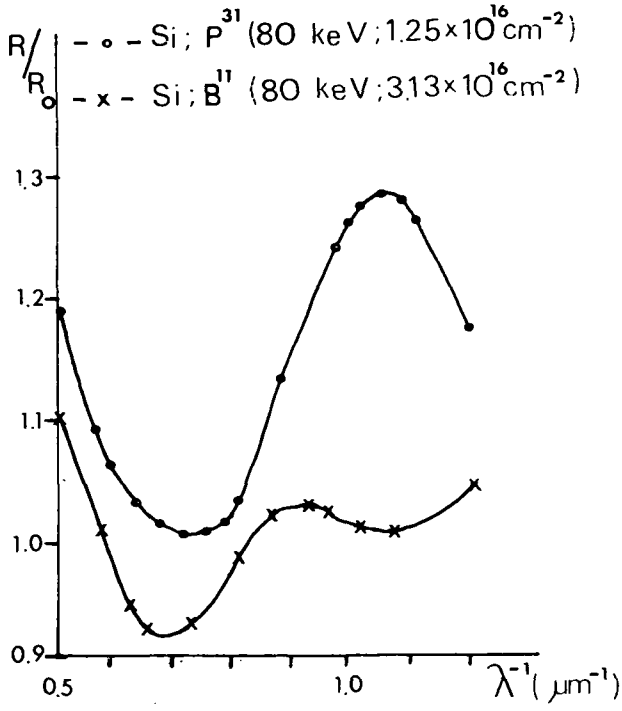

Fig. 4. Interference in reflection spectra, R/R_0, for phosphorus and boron implants

Table I

	Si:P^{31}	Si:B^{11}		
	$E = 80$ keV	$E = 40$ keV	$E = 60$ keV	$E = 80$ keV
1.25×10^{16}	$d = 0.2280\,\mu$m			
2.5×10^{16}	$d = 0.2325\,\mu$m	$d = 0.1850\,\mu$m	$d = 0.2850\,\mu$m	$d = 0.4050\,\mu$m
3.13×10^{16}	$d = 0.2100\,\mu$m			
4.37×10^{16}	$d = 0.2230\,\mu$m	$d = 0.1847\,\mu$m		
6.25×10^{16}	$d = 0.2630\,\mu$m	$d = 0.1855\,\mu$m		

The infrared spectroscopy as a method for measuring layer thicknesses has some specific properties. It gives some kind of average as if a rectangular distribution were present. In case of boron, the thickness of the disordered layer determined by optical method is

$$d_{opt} = R_p + \Delta R_p,$$

where R_p is the projected range and ΔR_p the standard deviation. For phosphorus, the experiments gave a somewhat different result

$$d_{opt} = R_p + 4\Delta R_p.$$

This can be explained qualitatively as follows. The interference structure is connected with the existence of two layers with different optical refraction. Only the amorphization of the silicon will cause sufficient changes in the refraction index, therefore, the measured values may be clarified by calculating the surface concentration (in cm^{-2} units) of atoms penetrating through the effective layer thickness d_{opt}. This concentration appears just below the amorphous limit. For phosphorus, 2×10^{13} cm^{-2} atoms penetrate deeper than $d_{opt}=0.21$ μm. This value is somewhat lower than the amorphous limit which is around 10^{14} cm^{-2}. The same can be said for boron. The more exact solution of the problem is a future task.

2. *X-ray topography*

Changes in lattice constant due to implantation were investigated with X-ray topography. The so-called Berg—Barrett type reflection was used. In this case a monochromatic X-ray produces the diffraction, the information on inhomogeneities or lattice defects can be calculated therefrom [3]. This can be performed with high accuracy by photographing the pattern. According to Bragg's formula, the reflection angle from portions with different lattice constant is somewhat different. Therefore, using a divergent beam, a shift between images of non-irradiated and irradiated portions is found, the shift being proportional to the change in lattice constant.

Photographs were made using the Cu $K_{\alpha 1}$ radiation, with reflection from the (333) plane, parallel with the surface. Photometry was used to determine the shift. The changes in reflection angle, $\Delta\vartheta$, can be determined from the known geometry of the system and the relative change in lattice constant $\Delta a/a_0=(a-a_0)/a_0$, depends on the angles as follows:

$$\frac{\Delta a}{a_0} = -\operatorname{ctg}\vartheta\cdot\Delta\vartheta,$$

where ϑ is the reflection angle for the undamaged surface.

A conventional diode structure was used for this measurement. The thick oxide (SiO_2) was used as a mask and $^{11}B^+$ ions (energy 80 keV, dose 6×10^{15} cm^{-2}) were implanted through the square windows covered by 1200 Å thermal oxide. Measurements were made on as-implanted samples, and after 30 minutes anneal at 600 and 800 °C respectively.

Table II

	$\Delta a/a_0$
as-implanted	$1.6\times10^{-3}\pm10\%$
$T_A = 600$ °C	$0.9\times10^{-3}\pm10\%$
$T_A = 800$ °C	0.6×10^{-3}

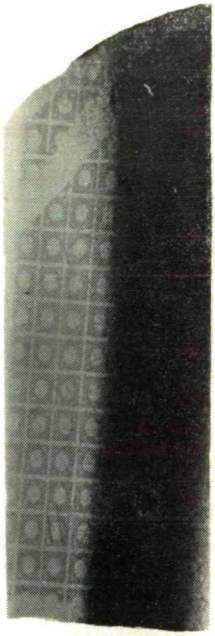

Fig. 5. A (333) X-ray topogram for a boron-implanted diode structure. Implanted are the square portions

In Fig. 5, the reflection topogram of the as-implanted crystal is to be seen. The dark portion on the right is the diffraction maximum from the deep undamaged part of the crystal with dislocation lines visible at the edge. The contrast on the left is due to the implanted squares ($6\times$ magnification).

The calculated changes in lattice constant are given in Table II.

During annealing, the original lattice structure is restored by an epitaxial regrowth.

3. *Mechanical measurement of volume changes*

In order to clarify changes in crystal structure, a series of measurements were made using a mechanical probe to detect volume changes of implanted crystals. In order to get more pronounced effect, we omitted the 1200 Å thick silicon dioxide, *i.e.* all ions were implanted into the silicon. The volume changes were measured by a Talystep equipment (Rank Precision Industries). This equipment used a diamond stylus travelling along the surface, sensing steps on it (Fig. 6). The step height for an as-implanted crystal (boron ions, 80 keV, 6×10^{15} cm^{-2}) was 30 Å. Comparing this value with $\Delta a/a_0$ in the previous section, it is clear that the changes in lattice constant in the deeper portion of the implant layer do not explain this relatively big value. This indicates that the amorphous layer lying above the partly disordered layer is responsible for most of the volume changes. In X-ray measurements, this amorphous part does not play a role in "changes" of the lattice constant.

The correlation between defect production and changes in volume is of great interest. As a first result, in Fig. 7 we present step height values for 80 keV boron, silicon and arsenic implant, showing a decrease in step height with increasing mass. The dose was 3×10^{16} cm^{-2} for all samples. This result correlates with results measured by a cantilever technique [6]. A more complex study of the question is going on.

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It is a distinguished honour to one of the authors (J. G.) to express sincere gratitude to the memory of his first master, Professor A. BUDÓ.

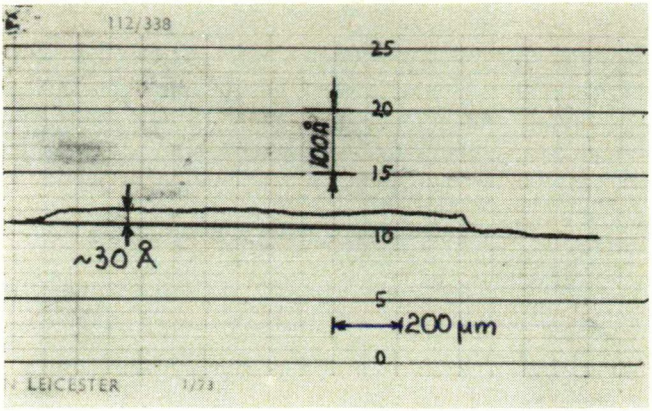

Fig. 6. Step height of an 80 keV, 6×10^{15} cm^{-2} dose boron implant measured with a Talystep. On the vertical scale one small division is 20 Å, horizontal magnification is given in the figure

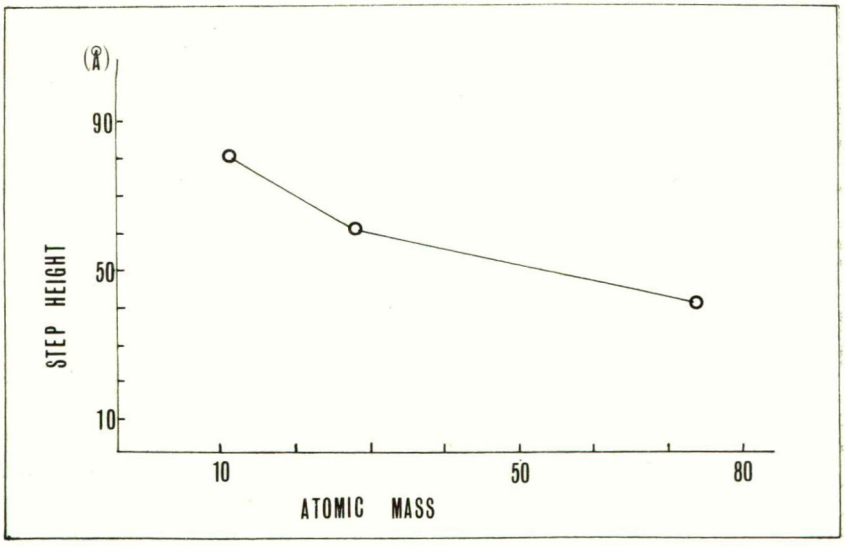

Fig. 7. Step height, *i.e.* volume increase for 3×10^{16} cm^{-2}, 80 keV implants into silicon

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ДЕФЕКТЫ И АМОРФИЗАЦИЯ В ИОННО ЛЕГИРОВАННОМ КРЕМНИИ

Й. Дьюлаи, П. Ревес, Л. Жолдош, Г. Вертеши, Й. Дьимеши

Исследовано образование дефектов в слоях кремния, легированных ионами бора и фосфора, методами ИК-спектроскопии, рентгено топографии а также механическим анализатором поверхности кристалла. Получены характеристики отжига дефектов и обнаружено увеличение объёма после ионного легирования.