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BACKSCATTERING MEASUREMENTS OF P⁺ IMPLANTED GaAs CRYSTALS

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Implantation of phosphorus and aluminium ions into GaAs is important in the investigation of the transformation processes which can take place during ion implantation and in the fabrication of heterojunctions.

In this paper profiles of phosphorus, implanted into GaAs at different energies, temperatures, doses and dose rates and depth distributions of damage are discussed. For room temperature implantations, the range of the defect peak exceeds $\overline{R}_{p,\mathrm{theor}}$ by [illegible] 30% and can extend to depths of several times higher than $R_{p,\mathrm{theor}}$ for implantation at high temperatures. The profiles of implanted phosphorus are characterized by a complicated distribution. Using the RBS technique the estimated depth of phosphorus profiles ranges up to hundreds of nanometers.

A discussion of the recently observed effect of high ion beam current density on damage and the distribution of implanted atoms is presented.

1. Introduction

The implantation of GaAs with P⁺ and Al⁺ is interesting to study from the point of view of damage formation, appearance of new phases (like $GaAs_{1-x}P_x$ and $Al_xGa_{1-x}As$) and structural transformations occurring during ion implantation because these are important in the fabrication of heterojunctions.

From studies performed by optical techniques it is known that room temperature P⁺ implantation into GaAs with a subsequent high-temperature anneal or P⁺ implantation into warmed-up GaAs crystals results to the formation of ternary compounds, such as $GaAs_{1-x}P_x$, which are capable of luminescence in the visible range of the spectrum [1–3].

Our experimental studies have also shown that implantation of P⁺ into GaAs is characterized by a number of peculiarities in the distribution and behaviour of the defects and in the profiles of the implanted component when the fluence, ion current density and temperature are varied.

In this report some new results about damage and P-atom profiles in P⁺ implanted GaAs are given. A discussion of the recently observed effect of high ion beam current density on damage and the distribution of implanted atoms is presented.

2. Experimental details

Crystals of GaAs having (111) orientation were implanted with $^{31}P^+$ at energies of 30, 40 and 60 keV. Implant doses ranged from 3×10^{15} 7×10^{17} ions cm^{-2}. The crystal temperature during the bombardment was close to T_{room}, 150, 300, 350, 400 and 450°C. The ion current densities for different sets of samples were in the intervals 5–7, 10 15, 30–40 mkA cm^{-2}.

The crystals were examined in the room temperature chamber of the F. Schiller University (GDR) 2 MeV Van de Graaff accelerator, using backscattering of 1.4 MeV $^4He^+$. The energies of the backscattered ions were measured using a surface barrier detector at a scattering angle of 160°, together with the usual electronic means for pulse height analysis. The energy resolution was 15 keV full width at half-maximum. In converting to the depth scale the tabulated values of the stopping cross sections in ref. (4) were used. The depth profiles were extracted after applying the dechannelling correction obtained using an iterative technique based upon the plural scattering approximation [5]. The effect of the changing atom concentration in the surface layers of the implanted crystals was taken into account.

3. Experimental results and discussion

Figure 1 shows typical spectra for backscattered He ions from the original (curves 1 and 2) and implanted (curves 3 to 6) cyrstals. Room temperature implantation leads to the formation of a damaged layer whose magnitude exceeds (by 20 to 30%) the theoretically estimated projected range of P⁺ in GaAs

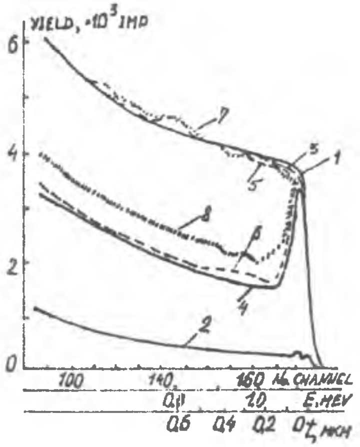

Fig. 1. Backscattering spectra of GaAs using 1.4 MeV He$^+$ for random – 1, and (111)-channelling – 2; before implantation and after 3×10^{15} ions cm^{-2} – 3 and 4; 3.2×10^{16} ions cm^{-2} – 5 and 6; 8×10^{16} ions cm^{-2} – 7 and 8. E_{P^+} = 60 keV.

[6]. The axial spectra exhibit defect "tails" extending to depths of some hundreds of nanometers. With increasing fluence (over the interval investigated) a slight increase in the defect concentration occurs due to a depth extension of the damaged layer.

The damage profiles in P$^+$ implanted at T_{room} GaAs crystals are shown in fig. 2 (curves 1 and 2). The amorphous layers begin at the very surface, their thickness is estimated to be 30–35 nm and increases with dose.

The distribution of the phosphorus implanted under such conditions is characterized by two main peaks, fig. 3. Its range is estimated to be some hundreds of nanometers, that is several times higher than $\bar{R}_{p,theor}$. Table 1 shows the theoretical estimates of $\bar{R}_p$ and $\Delta\bar{R}_p$ for comparison with the experimental data.

Table 1
Theoretically estimated projected range of P$^+$ ion in GaAs ($\bar{R}_p$), straggling ($\Delta\bar{R}_p$), and the projected range in the axial (111) channelling (R_{max})

E (keV)	30	30	60	Ref.
$\bar{R}_p$ nm	30.0	39.7	59.2	[6]
	34.8	32.4	47.6	[7]
$\Delta\bar{R}_p$ nm	23.5	30.5	42.9	[6]
	15.7	19.6	27.1	[7]
R_{max}(111), mkm	2.76	3.19	3.90	[8]

The increase with dose of the phosphorus concentration in the first peak is shown in fig. 3. The depth distribution of phosphorus was almost independent of the P$^+$ energy (at $j < 30$ mkA cm^{-2}).

With increased implantation temperatures ($T_{impl} \geqslant 150°$C) there is no amorphization of GaAs crystals during P$^+$ implantation up to fluences of 7×10^{17} ions cm^{-2}. The depth at which the peak of the defect concentration is observed is several times greater than that for the room temperature implantation, fig. 2 (curves 3 and 4). With increasing fluence the number of the defects grows due both to a slight increase in their concentrations and to the extension of the defect peak towards the surface.

The axial spectra of the crystal bombarded at higher temperatures exhibit defect "tails", with depths approaching some hundreds of nanometers

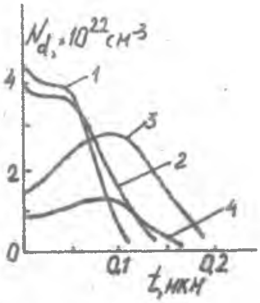

Fig. 2. Defect distribution profiles in P$^+$ ion implanted GaAs. T_{impl} = 20°C, E = 30 keV, $D = 1.6 \times 10^{16}$ ions cm^{-2} – 1; $D = 7 \times 10^{16}$ ions cm^{-2} – 2; T_{impl} = 300°C, $D = 8.2 \times 10^{16}$ ions cm^{-2} – 3; T_{impl} = 350°C, $D = 3.3 \times 10^{16}$ ions cm^{-2} – 4.

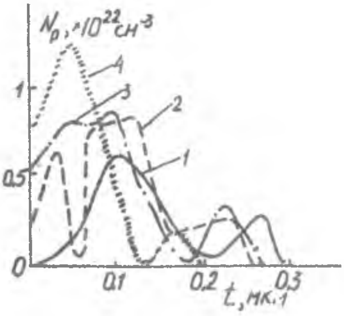

Fig. 3. Distribution profiles of phosphorus implanted into GaAs. T_{impl} = 20°C, E = 30 keV, j = 5–7 mkA cm^{-2}, $D = 1.6 \times 10^{16}$ ions cm^{-2} – 1; $D = 7 \times 10^{16}$ ions cm^{-2} – 2; E = 60 keV, j = 5–10 mkA cm^{-2}, $D = 8 \times 10^{16}$ ions cm^{-2} – 3. E = 40 keV, j = 30–40 mkA cm^{-2}, $D = 4 \times 10^{17}$ ions cm^{-2} – 4.

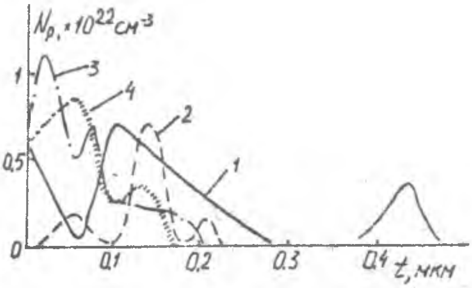

Fig. 4. Distributions profiles of phosphorus implanted into GaAs. $E = 30$ keV, $T_{impl} = 300°C$, $j = 5–7$ mkA cm^{-2}, $D = 8.2 \times 10^{16}$ cm^{-2} – 1; $T_{impl} = 400°C$, $D = 2 \times 10^{16}$ cm^{-2} – 2 $T_{impl} = 450°C$, $j = 10–15$ mkA cm^{-2}, $D = 2.7 \times 10^{17}$ cm^{-2} – 3; $E = 60$ keV, $T_{impl} = 450°C$, $D = 4 \times 10^{17}$ cm^{-2} – 4.

(which is somewhat higher than that for the room temperature implantation).

The distribution profiles of the phosphorus implanted at high temperature are also characterized by numerous peaks, moreover, the range of phosphorus is considerably higher than at T_{room}. Some of the phosphorus profiles in the GaAs crystals implanted at high temperature are presented in fig. 4. The number and the depth of the phosphorus peaks increases with the dose of ions and decreases with the temperature of implantation.

On increasing the current density of the ion beam of 30–40 mkA cm^{-2} the profiles for the defects and implanted phosphorus acquire characteristics different from those discussed above. For illustration, figs. 5 and 6 present the spatial distributions of the defects and the phosphorus when phosphorus was implanted into GaAs at different temperatures.

The phosphorus profiles at each implantation temperature exhibit a well defined peak which lies almost at same depth as that predicted theoretically [6], though straggling is somehow larger. These results correlate well with the profiles in ref. [9], obtained by studying the distribution of radioactive phosphorus using the technique of successively removing thin layers. The profiles of the defects obtained by the backscattering technique (fig. 5) were found to be at the depth corresponding to the range of the implanted phosphorus.

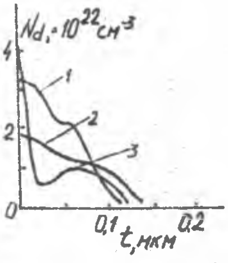

Fig. 5. Defect distribution profiles in P$^+$ ion implanted GaAs. $E = 40$ keV, $j = 30–40$ mkA cm^{-2}, $D = 4 \times 10^{17}$ ions cm^{-2}, $T_{impl} = 20°C$ – 1; 150°C – 2; 400–450°C – 3.

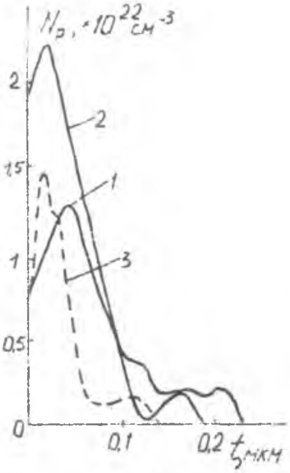

Fig. 6. Distribution profiles of phosphorus implanted into GaAs with a high current density ion beam. $E = 40$ keV, $j = 30–40$ mkA cm^{-2}, $D = 4 \times 10^{17}$ ions cm^{-2}, $T_{impl} = 20°C$ – 1; 150°C – 2; 400–450°C – 3.

The complex character of the variation in the phosphorus spatial distribution within GaAs undoubtedly indicates a competition between two counteracting processes: the synthesis reaction rate of a chemical compound like $GaAs_{1-X}P_X$ and the dissociation rate of the chemical bonds formed. The authors of ref. [10] in studying the synthesis of silicon nitride and silicon carbide by means of N$^+$ and C$^+$ ion implantation into Si have shown the importance of accounting for the basic processes affecting structural transformations in implanted crystals in order to better understand experimental results.

4. Conclusions

Some of the main experimental results which were obtained during the present investigation can be summarized as follows:

for room temperature implantations, the range of the defect peak exceeds the phosphorus ion projected range in non-oriented GaAs by 20–30%.

the damage profiles extend to depths of nR_p (n can range from 1 to 5) for implantation at high temperatures.

Defect "tails" can exist in the crystals extending to depths of some hundreds of nanometers for implantation both at room and at high temperatures.

The profiles of implanted phosphorus are characterized by a complicated distribution and the number of peaks increase with dose and increasing implantation temperature. Using the RBS technique the estimated depths of phosphorus profiles range up to hundreds of nanometers.

The use of high P^+ ion beam current density ($J \geqslant$ 30 mkA cm^{-2}) is an effective technique for reducing the level of damage and depth of damage and to achieve an implanted phosphorus range close to that predicted by LSS theory.

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