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**Zn<sup>+</sup>/P<sup>+</sup> and Zn<sup>+</sup>/As<sup>+</sup> co-implantation in InP single crystals**  
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**ABSTRACT**

The activation efficiency of zinc impurity co-implanted with P<sup>+</sup> and As<sup>+</sup> ions in InP was studied by Hall-effect measurements. Both P<sup>+</sup> and As<sup>+</sup> co-implantations followed by post-implantation annealing at 400 to 600 °C in InP single crystals have been found to result in a decrease of impurity activation. At the same time an improvement of activation efficiency was observed at annealing temperatures T<sub>ann</sub> > 600 °C.

**1. INTRODUCTION**

Dual implantation has been established to be a powerful tool for improving the activation efficiency of p-type dopants in GaAs /1, 2/. The co-implantation of As<sup>+</sup> host-component ions as well as of P<sup>+</sup> isoelectronic-impurity ones leads to nearly the same enhancement of the activation efficiency of implanted Zn-acceptor impurity /3, 4/. Such behaviour seems to be related with the formation of gallium vacancies in the As<sup>+</sup> and P<sup>+</sup> implanted layers, which facilitates the incorporation of impurity atoms into the cationic sublattice. As concerns InP, comparatively little attention was paid to the effect of co-implantations on the activation efficiency of p-type dopants. Moreover, the analysis of the data published on this matter /5, 6/ shows that they are rather contradictory. The goal of this work was to study the influence of P<sup>+</sup> and As<sup>+</sup> co-implantations upon activation efficiency of Zn<sup>+</sup> impurity in InP single crystals. For the purpose of comparison the effect of ordinary P<sup>+</sup> implantation on electrical properties of p-type InP has been studied as well.

**2. EXPERIMENTAL**

(100)-oriented liquid encapsulated Czochralski grown n-type crystals have been used for dual implantation. The carrier concentration and mobility in as-grown samples at 300 K were 2×10<sup>16</sup> cm<sup>-3</sup> and 3550 cm<sup>2</sup>/(Vxs) respectively. Dual implantation at doses 5×10<sup>13</sup>, 5×10<sup>14</sup> and 5×10<sup>15</sup> cm<sup>-2</sup> was performed at room temperature. The ion energies used (150, 75 and 163 keV for Zn<sup>+</sup>, P<sup>+</sup> and As<sup>+</sup> correspondingly) provided an overlap of the implant-depth profiles. Ordinary P<sup>+</sup> implantation was performed at 80 keV energy in p-type wafers possessing different hole concentrations. The post-implantation annealing was carried out in a H<sub>2</sub> atmosphere for 15 min at different temperatures from 400 to 750 °C. A face-to-face proximity was used to avoid the surface decomposition. Free-carrier concentration and mobility were determined by Hall-effect measurements using Van der Pauw method. When measuring p-type layers on p-InP substrates the hole concentration was determined by C-V techniques.

**3. RESULTS**

First we shall present the results of Zn<sup>+</sup> implantation in p-InP.



Fig. 1 illustrates the effect of ordinary  $P^+$  implantation and subsequent annealing on free-carrier concentration in InP:Zn single crystals. The drawing is divided into three parts. The middle part corresponds to semi-insulating material while the upper and lower parts represent  $n$ - and  $p$ -types regions respectively. One can see that  $P^+$  implantation leads to  $n$ -type layer formation in InP:Zn. The higher the  $P^+$  ion dose, the higher the electron concentration. On the other hand, the critical dose necessary to reach a conductive-type conversion depends upon the hole density in the as-grown samples, it being higher in heavily doped substrates. A rather weak dependence of electron concentration upon annealing temperature was observed in the range  $400\text{ }^\circ\text{C} < T_{\text{ann}} < 600\text{ }^\circ\text{C}$ . At the same time further increase of  $T_{\text{ann}}$  leads to a fast diminution of free electron concentration and to a partial recovery of the hole conductivity.

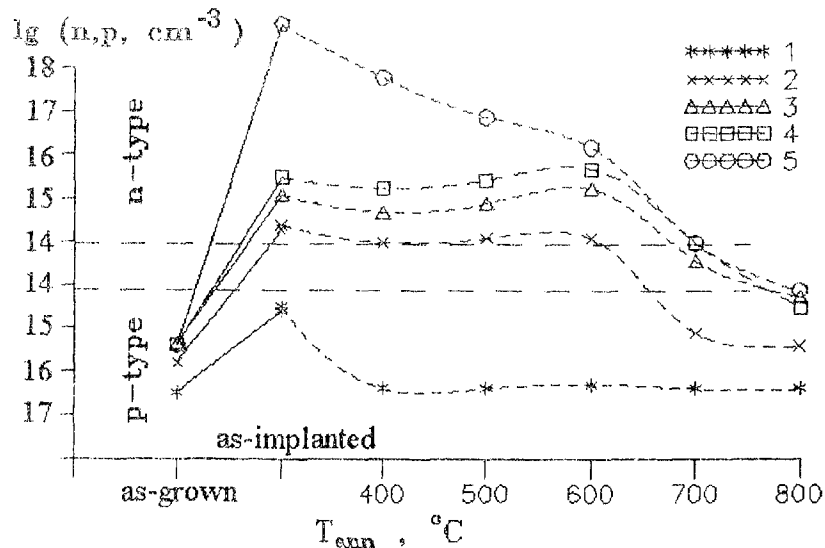


Fig. 1. Annealing curves for the InP:Zn crystals  $P^+$ -implanted at the doses: 1, 2 -  $4 \cdot 10^{13}\text{ cm}^{-2}$ ; 3 -  $7 \cdot 10^{13}\text{ cm}^{-2}$ ; 4 -  $2 \cdot 10^{14}\text{ cm}^{-2}$ ; 5 -  $7 \cdot 10^{12}\text{ cm}^{-2}$ . Hole concentration in the substrates: 1 -  $3 \cdot 10^{17}\text{ cm}^{-3}$ ; 2 -  $6 \cdot 10^{16}\text{ cm}^{-3}$ ; 3, 4, 5 -  $2 \cdot 10^{16}\text{ cm}^{-3}$ .

The observed behaviour of conductivity may be explained by the predominant formation of donor like centers as a result of  $P^+$  implantation. Activation of these centers turns out to take place in the interval of annealing temperatures from 400 to 600  $^\circ\text{C}$ . One can note, in this regard, that high electron conductivity was observed recently in low-temperature molecular-beam-epitaxy-grown InP, it being attributed to the autoionization of the  $P_{\text{In}}$  antisite defects [7]. Taking into account our results, the defects responsible for  $n$ -type conductivity may be supposed to anneal at temperatures  $T_{\text{ann}} > 600\text{ }^\circ\text{C}$ .

Let us pass now to the discussion of results on dual implantation in  $n$ -InP single crystals. Table 1 summarizes the electrical parameters for  $Zn^+$ ,  $Zn^+/P^+$  and  $Zn^+/As^+$  implanted layers. One can see that the implantation of  $P^+$  or  $As^+$  with subsequent annealing at 600  $^\circ\text{C}$  does not improve the activation efficiency. Moreover, the impurity activation is diminished and semi-insulating or  $n$ -type layers are formed. In the case of high doses of implantation the behaviour involved was observed at  $T_{\text{ann}}$  by moderate doses of  $P^+$  and  $As^+$ .

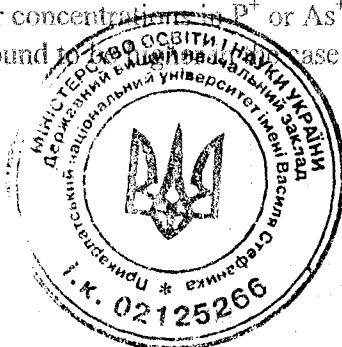


Table 1. Parameters of InP implanted layers

Annealing temperature, °C	Impl dose, cm <sup>-3</sup>	Implantation schedule	Sheet hole concentration, cm <sup>-2</sup>	Mobility, cm <sup>2</sup> /(V×s)	Activation, %
600 °C	5·10 <sup>13</sup>	Zn <sup>+</sup>	1.7·10 <sup>13</sup>	51	34
		Zn <sup>+</sup> /P <sup>+</sup>	<i>i</i> -type		
		Zn <sup>+</sup> /As <sup>+</sup>	<i>i</i> -type		
	5·10 <sup>14</sup>	Zn <sup>+</sup>	1.4·10 <sup>14</sup>	44	28
		Zn <sup>+</sup> /P <sup>+</sup>	<i>i</i> -type		
		Zn <sup>+</sup> /As <sup>+</sup>	<i>i</i> -type		
	5·10 <sup>15</sup>	Zn <sup>+</sup>	2.1·10 <sup>14</sup>	45	4.2
		Zn <sup>+</sup> /P <sup>+</sup>	<i>n</i> -type		
		Zn <sup>+</sup> /As <sup>+</sup>	<i>n</i> -type		
700 °C	5·10 <sup>13</sup>	Zn <sup>+</sup>	2.3·10 <sup>13</sup>	72	46
		Zn <sup>+</sup> /P <sup>+</sup>	1.9·10 <sup>13</sup>	66	38
		Zn <sup>+</sup> /As <sup>+</sup>	2.0·10 <sup>13</sup>	91	40
	5·10 <sup>14</sup>	Zn <sup>+</sup>	2.0·10 <sup>14</sup>	51	40
		Zn <sup>+</sup> /P <sup>+</sup>	1.5·10 <sup>14</sup>	68	30
		Zn <sup>+</sup> /As <sup>+</sup>	1.7·10 <sup>14</sup>	60	34
	5·10 <sup>15</sup>	Zn <sup>+</sup>	2.9·10 <sup>14</sup>	48	5.8
		Zn <sup>+</sup> /P <sup>+</sup>	<i>n</i> -type		
		Zn <sup>+</sup> /As <sup>+</sup>	<i>n</i> -type		
750 °C	5·10 <sup>13</sup>	Zn <sup>+</sup>	2.3·10 <sup>13</sup>	71	46
		Zn <sup>+</sup> /P <sup>+</sup>	2.7·10 <sup>13</sup>	61	54
		Zn <sup>+</sup> /As <sup>+</sup>	3.1·10 <sup>13</sup>	84	62
	5·10 <sup>14</sup>	Zn <sup>+</sup>	2.0·10 <sup>14</sup>	55	40
		Zn <sup>+</sup> /P <sup>+</sup>	2.4·10 <sup>14</sup>	46	48
		Zn <sup>+</sup> /As <sup>+</sup>	2.5·10 <sup>14</sup>	81	50
	5·10 <sup>15</sup>	Zn <sup>+</sup>	2.5·10 <sup>14</sup>	50	5
		Zn <sup>+</sup> /P <sup>+</sup>	<i>i</i> -type		
		Zn <sup>+</sup> /As <sup>+</sup>	<i>i</i> -type		

co-implantation and annealing temperatures higher than 600 °C lead to an increase of zinc activation efficiency. This behavior is consistent with the results obtained in the case of ordinary P<sup>+</sup> implantation and can be explained as follows. Unlike GaAs, there are two competitive mechanisms of defect formation in P<sup>+</sup> or As<sup>+</sup> coimplanted InP crystals. One of them is the formation of donor-like centers as in the case of ordinary P<sup>+</sup> implantation. The other is the formation of indium vacancies in the crystal lattice which are easily filled in by impurity atoms during the post-implantation annealing, like gallium vacancies in GaAs crystals. In the range of annealing temperatures up to 600 °C the formation and activation of donor-type defects is predominant giving rise to the n-type conductivity observed. At T<sub>ann</sub> > 600 °C the second mechanism prevails which is responsible for the improvement of the activation efficiency.

Although the free carrier concentrations in P<sup>+</sup> or As<sup>+</sup> coimplanted layers were nearly the same, the hole mobility was found to be lower in the case of As<sup>+</sup> coimplantation.



#### 4. CONCLUSIONS

The activation efficiency of Zn impurity coimplanted in n-type InP with P<sup>+</sup> or As<sup>+</sup> ions was established to decrease in the interval of annealing temperatures from 400 °C to 600 °C. At the same time an improvement of activation efficiency was observed after dual implantation and annealing at T<sub>ann</sub> > 600 °C. The values of the hole mobility were higher in the case of Zn<sup>+</sup>/As<sup>+</sup> coimplantation.

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