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Zn^+/P^+ and Zn^+/As^+ co-implantation in InP single crystals

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ABSTRACT

The activation efficiency of zinc impurity co-implanted with P^+ and As^+ ions in InP was studied by Hall-effect measurements. Both P^+ and As^+ 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 $T_{ann} > 600$ °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^+ host-component ions as well as of P^+ 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^+ and P^+ 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^+ and As^+ co-implantations upon activation efficiency of Zn^+ impurity in InP single crystals. For the purpose of comparison the effect of ordinary P^+ 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^{16} cm^{-3} and 3550 cm^2/(V×s) respectively. Dual implantation at doses 5×10^{13}, 5×10^{14} and 5×10^{15} cm^{-2} was performed at room temperature. The ion energies used (150, 75 and 163 keV for Zn^+, P^+ and As^+ correspondingly) provided an overlap of the implant-depth profiles. Ordinary P^+ 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_2 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 consider the results [illegible] implantation in p-InP.

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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 °C < T_{ann} < 600 °C. At the same time further increase of T_{ann} leads to a fast diminution of free electron concentration and to a partial recovery of the hole conductivity.

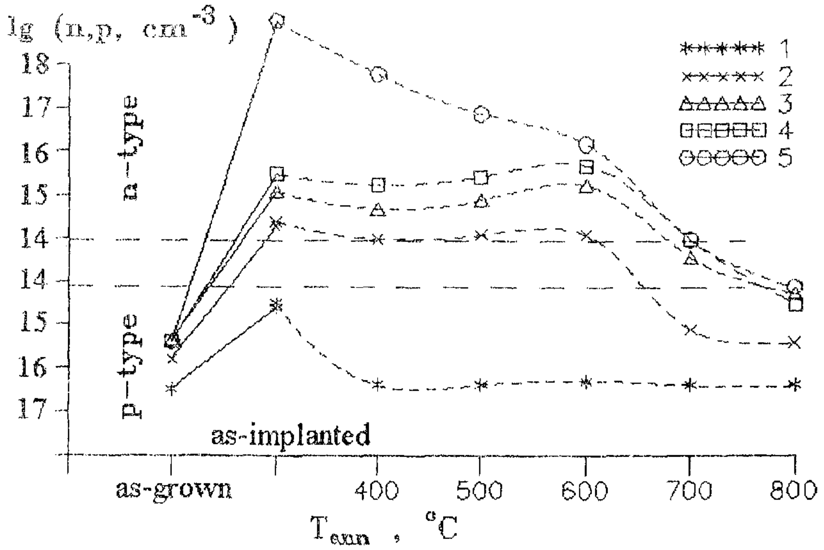

Fig. 1. Annealing curves for the InP:Zn crystals P^+-implanted at the doses: 1, 2 - $4 \cdot 10^{13}$ cm^{-2}; 3 - $7 \cdot 10^{13}$ cm^{-2}; 4 - $2 \cdot 10^{14}$ cm^{-2}; 5 - $7 \cdot 10^{12}$ cm^{-2}. Hole concentration in the substrates: 1 - $3 \cdot 10^{17}$ cm^{-3}; 2 - $6 \cdot 10^{16}$ cm^{-3}; 3, 4, 5 - $2 \cdot 10^{16}$ 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 °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_{In} antisite defects /7/. Taking into account our results, the defects responsible for n-type conductivity may be supposed to anneal at temperatures T_{ann} > 600 °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 °C does not improve the activation efficiency. Moreover, the impurity activation is diminished and semi-insulating or n-type layers are formed. In case of high doses of implantation the behaviour involved was observed at T_{ann} [illegible] as well [illegible] moderate doses of P^+ and As^+

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Table 1. Parameters of InP implanted layers

Annealing temperature, °C	Impl. dose, cm^{-3}	Implantation schedule	Sheet hole concentration, cm^{-2}	Mobility, $cm^2/(V\times s)$	Activation, %
600 °C	$5\cdot10^{13}$	Zn^+	$1.7\cdot10^{13}$	51	34
		Zn^+/P^+	*i*-type		
		Zn^+/As^+	*i*-type		
	$5\cdot10^{14}$	Zn^+	$1.4\cdot10^{14}$	44	28
		Zn^+/P^+	*i*-type		
		Zn^+/As^+	*i*-type		
	$5\cdot10^{15}$	Zn^+	$2.1\cdot10^{14}$	45	4.2
		Zn^+/P^+	*n*-type		
		Zn^+/As^+	*n*-type		
700 °C	$5\cdot10^{13}$	Zn^+	$2.3\cdot10^{13}$	72	46
		Zn^+/P^+	$1.9\cdot10^{13}$	66	38
		Zn^+/As^+	$2.0\cdot10^{13}$	91	40
	$5\cdot10^{14}$	Zn^+	$2.0\cdot10^{14}$	51	40
		Zn^+/P^+	$1.5\cdot10^{14}$	68	30
		Zn^+/As^+	$1.7\cdot10^{14}$	60	34
	$5\cdot10^{15}$	Zn^+	$2.9\cdot10^{14}$	48	5.8
		Zn^+/P^+	*n*-type		
		Zn^+/As^+	*n*-type		
750 °C	$5\cdot10^{13}$	Zn^+	$2.3\cdot10^{13}$	71	46
		Zn^+/P^+	$2.7\cdot10^{13}$	61	54
		Zn^+/As^+	$3.1\cdot10^{13}$	84	62
	$5\cdot10^{14}$	Zn^+	$2.0\cdot10^{14}$	55	40
		Zn^+/P^+	$2.4\cdot10^{14}$	46	48
		Zn^+/As^+	$2.5\cdot10^{14}$	81	50
	$5\cdot10^{15}$	Zn^+	$2.5\cdot10^{14}$	50	5
		Zn^+/P^+	*i*-type		
		Zn^+/As^+	*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^+ implantation and can be explained as follows. Unlike GaAs, there are two competitive mechanisms of defect formation in P^+ or As^+ coimplanted InP crystals. One of them is the formation of donor-like centers as in the case of ordinary P^+ 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_{ann} > 600 °C the second mechanism prevails which is responsible for the improvement of the activation efficiency.

Although the free carrier concentrations in P^+ or As^+ coimplanted layers were nearly the same, the hole mobility was found to be [illegible] case of As^+ coimplantation.

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4. CONCLUSIONS

The activation efficiency of Zn impurity coimplanted in n-type InP with P^+ or As^+ 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 $T_{ann} > 600$ °C. The values of the hole mobility were higher in the case of Zn^+/As^+ coimplantation.

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