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Indium Arsenide Solid Solutions: Devices Based on *InGaAs(P)*

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ABSTRACT

This paper is a review of literature and data dealing with the properties of indium arsenide-based solid solutions and several devices on *InGaAs(P)/InP* heterostructures. Possible practical applications of the III V-III$_2$VI$_3$ heterostructures are indicated.

The most interesting results obtained in the fabrication of high quality heterostructures, including modulation-doped and quantum-dimensional ones are demonstrated. The epitaxial methods used for the production of heterostructures are comparatively analised. Data about applicability of epitaxial methods for fabrication of different device structures are reported. An interesting 'cleaning' effect taking place at the *InGaAs(P)* crystallization by LPE from solutions containing rare-earth elements is described.

A review of recently published works on fabrication of effective FET is made. The HEMT technology thought to be the most promising one, is supposed to contribute to a qualitatively new development stage of large integral circuits on A_3B_5, while a combination of HEMT with the technology of quantum-dimensional lasers is expected to accelerate the creation of high speed response integral circuits.

1. INTRODUCTION

Application possibilities of semiconducting III-V compounds became much wider with the appearance of solid solutions and hetero-structures on their basis[1].

Homogeneity of the III-V compounds was thoroughly studied as early as the 50s by Goryunova[2], Wooeley[3] and others. However, great interest to these materials arose with the development of semiconductor lasers based on heterostructures[4,5] and of multilayered

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superlattices[6]. Also, creating of quantum-dimensional devices based on these compounds has become very promising[7].

A study of isovalent solid solutions on indium arsenide and its analogues can be found elsewhere[2,8,9]. Investigation of heterovalent substitution in the III V-III_2VI_3 systems at an interaction between *InAs* and In_2S_3 and In_2Te_3 also showed evidence of wide ranges of solubility[10,11].

The ever-growing necessity of device structures for the fibre optical lines of communication, for the microwave range and other applications made the specialists properly appreciate the above mentioned results. Figure 1 illustrates some possibilities to change the values of the lattice parameters and band-gaps in indium and arsenide containing multicomponent alloys. An analysis of data from Fig. 1 makes possible a choice of materials for the radiation and detection devices meant for different spectrum ranges.

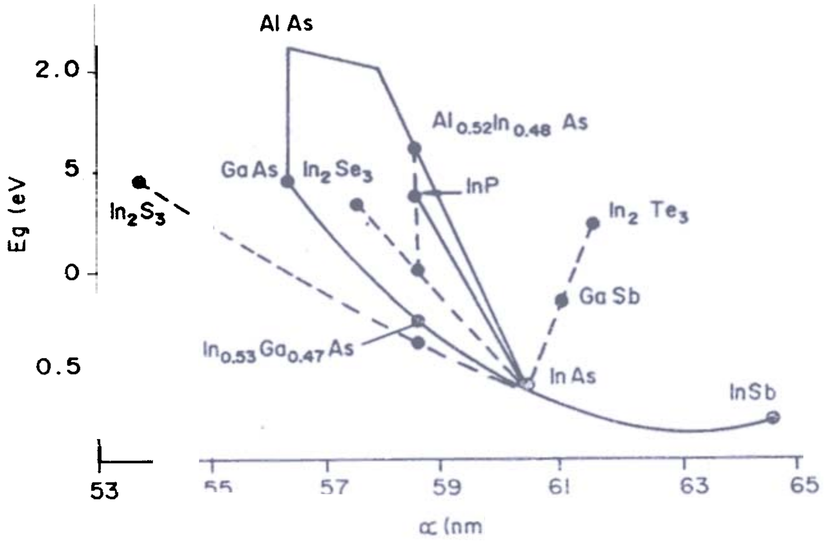

Figure 1. Energy gap as a function of lattice constant for various III V and III_2 VI_3 allo

This article reviews the investigations dealing with the yield of *InGaAs*- and *InGaAsP*-based structures, with the study of their physical characteristics and their possible applications.

The data concerning the characteristics of the *InP-InGaAs*-type alloys compared to those belonging to the starting compounds *InAs*, *InP* and *GaAs* is[12,13] summarised in Table 1. Depending on the required device characteristics, one can choose $InP^{(I)}$ or $GaAs^{(II)}$-based heterostructures as well as heterostructures based on the multicomponent $In_xGa_{1-x}As_yP_{1-y}$ alloy at different x and y values[9,14-16].

Investigations of numerous authors indicate particularly these two heterostructure types to be the most promising at present.

2. GROWTH OF HETEROSTRUCTURES AND THEIR PROPERTIES

The investigated heterostructures were obtained by liquid phase epitaxy (LPE), vapour phase epitaxy (VPE), molecular beam epitaxy (MBE) and metal organic chemical vapour deposition (MOCVD). Advantages and disadvantages of each of the above listed techniques are shown in Table 2, where most widely used heterostructures are indicated

Table 1. Several properties of binary compounds and solid solutions of the *GaInAsP* system[8,9,12,13]

Composition	InP	$GaAs$	$InAs$	$Ga_xIn_{1-x}As_yP_{1-y}$		$Ga_{0.47}In_{0.53}As$
	0		0	0.27	0.4	0.4
	0			0.6	0.85	
a (Å)	5.8694	5.6534	0.6058	5.8694	5.8694	5.8694
E_g, eV (300 K)	1.350	1.43	0.35	0.954	0.800	0.75
(77 K)	1.414	1.49	0.43	1.203	0.864	0.789
Absorption band edge, m (300 K)	0.92	0.87	3.5	1.3	1.55	1.65
Mobility of electrons	4100	8500	27000	6300	7700	10500
$T = (300/77)$ K cm^2/Vs (10^{17} cm^{-3})	44000	22000	30000	13000		28500
Coefficient of linear expansion (C^{-1})	4.56×10^{-6}	6.0×10^{-6}	5.3×10^{-6}	5.42×10^{-6}		5.72×10^{-6}
Thermal conductivity, W(cm^{-1} K)	0.67	0.54	0.26	–		0.66

Table 2. Comparable characteristics of heterostructure epitaxial crystallization technique

Technique	Advantages	Disadvantages	Types of the realised structures
LPE	Low cost and simplicity; knowledge about phase diagrams of A_3B_5 compounds and their solid solutions; realisation of multicomponent heterostructures; fabrication of modulation-doped and quantum-dimensional structures; yield of high-quality layers; ecological purity.	Low efficiency in case of multilayered structures; layer thickness nonuniformity; existence of immiscibility regions; need of large quantities of high purity metal solvents.	*InGaAsP/InP* *InGaAs/InP* *InGaAsP/GaAs* *InGaAs/GaAs*
VPE	Efficiency, uniformity and quality of layers.	Use of toxic compounds; complicated fabrication of quantum well structures.	*InGaAs/InP* *InGaAs/GaAs* *InGaAsP/InP*
MBE	Accuracy of thickness control; low temperature growth; well-controlled technique of *AlGaAs/GaAs* structure production for application in lasers and superlattices; yield of *AlInAs/GaInAs/InP* heterostructures.	Low growth rates; low efficiency; complicated crystallization of phosphorus-containing compounds and of solid solutions; complicated instrumentation of the process.	*InGaAs/InP* *AlGaAs/GaAs* *AlInAs/GaInAs*
MOCVD	Availability of instrumentation and materials for crystallization of almost all A_3B_5 compounds and their solid solutions; high purity and high control accuracy of parameters.	Relatively low growth rates; application of highly toxic gases; complicated instrumentation.	*InGaAs/GaAs* *InGaAs/InP* *InGaAsP/InP* *AlGaAs/GaAs*

including the modulation-doped and the quantum-dimensional structures. LPE turns out to be the most simple and low-cost technique. Ensuring of ecological purity makes this method rather attractive.

Disadvantages for LPE are its low efficiency and existing of immiscible regions in some A_3B_5 compounds and their solid solutions. In spite of high growth rates, LPE is very good for production of superlattices and structures generating quantum-dimensional effects. An excellent support of this method is found in the recently published works concerned with the creation of quantum-dimensional lasers on *InGaAsP/GaAs* heterostructures[16], and on *InGaAsP/InP* heterostructures[17]. These authors used an original approach which enabled them to reproducibly obtain epitaxial layers with a 30 ± 10 nm thickness. Their technique relies on an ultrarapid displacement of liquid phase on the substrate surface and is able for creation of multilayered structures with a quantum-dimensional effect.

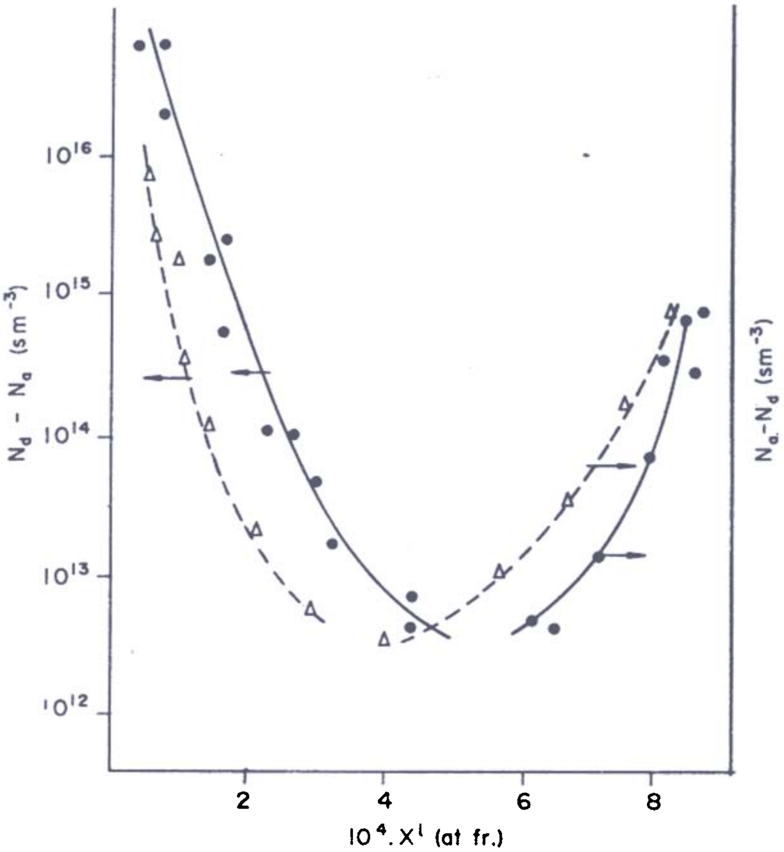

Figure 2. Dependence of the free charge carrier concentration on the yttrium concentration in the solution[24].

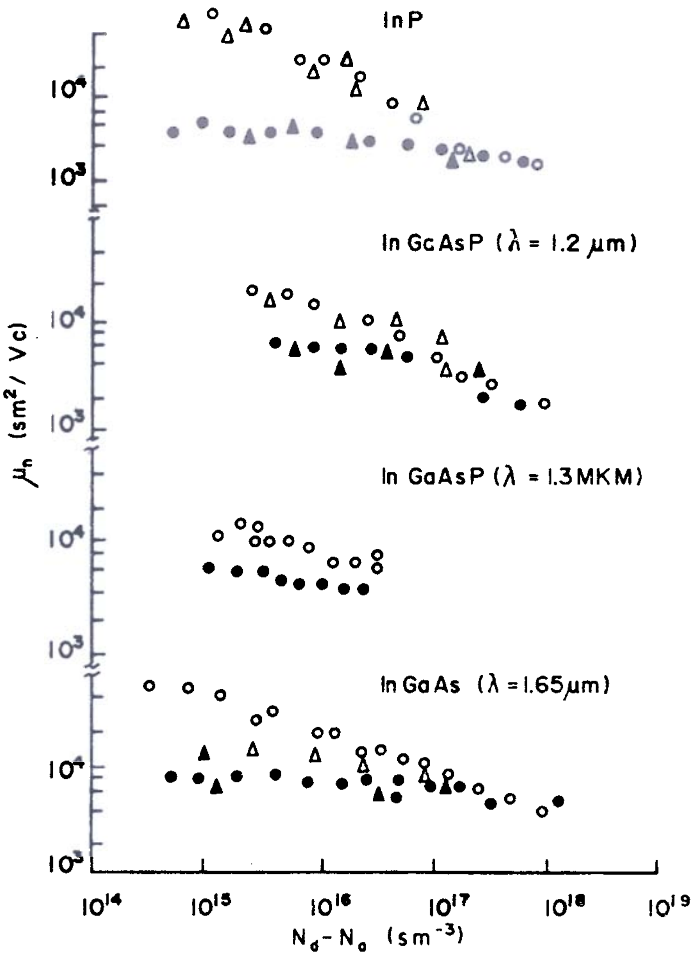

Figure 3. The general pattern of the mobility dependence on concentration of electrons in $In_xGa_{1-x}As_{1-y}P_y$ solid solutions (Δ, ▲ Bejan *et al.*[25]; ○ , ● Fidler *et al.*[28]).

Doping with *Te* and *Sn* is usually used to obtain *n*-type conductivity *InGaAsP* layers, *Sn* being accepted to be the best donor impurity. In case of LPE, the tin distribution coefficient is shown to be rather small and almost independent on the composition of the $In_xGa_{1-x}As_yP_{1-y}$ solid solution undergoing crystallization. As demonstrated by Cheng *et al.*[26], tin proved to be a convenient donor impurity also in crystallization by the MBE technique. At crystallization by the latter technique, the mobility of electrons in $In_{0.53}Ga_{0.47}As$ turned out to be higher at 77 K compared to LPE. In LPE layers, however, the mobility at 300 K is 20 per cent higher[26,27] at a 5×10^{17} cm^{-3} concentration of electrons. Probably the difference can be ascribed to the different scattering mechanisms in LPE and MBE layers.

A wider range of elements is used as acceptor impurities, including *Zn, Mn, Cd* and *Be*. Each of them possessess its own peculiarities. The activation energy of *Mn*, for instance, undergoes a severe change with the variation of the $In_xGa_{1-x}As_yP_{1-y}$ alloy composition. Thus, the activation energy of the *Mn* acceptor level makes ~ 50 meV in the $In_{0.53}Ga_{0.47}As$ ternary solution, whereas in quaternary solutions, close to *InP* with respect to E_g it will make[28] 230 MeV, i.e., doping with *Mn* is preferable only in solid solutions with a low content of phosphorus. Characteristic for zinc and cadmium is a stable shallow acceptor level (~ 22 meV for[29] *Zn*). Zinc possesses a very high coefficient of diffusion while *Cd* is characterised by a vapour pressure much higher than the one of *Mn* and *Zn*, its distribution coefficient in case of LPE being rather small[28] ~ 10^{-3}. Certain interest as an acceptor presents *Be*. It was used[30] to dope *InGaAs* and *AlInAs* epitaxial growth by MBE technique.

$In_{0.53}Ga_{0.47}As$ layers with the hole concentration from 10^{17} cm^{-3} through 10^{19} cm^{-3} were obtained with the mobilities being ~200 cm^2/Vs and ~80 cm^2/Vs respectively. Nevertheless, chemical activity and toxicity of *Be* prevent its wide application for doping of epitaxial layers.

It should be noted that undesired effects may take place during doping. For instance, during doping with *Sn* and *Cd*, there occurs a variation of the *InGaAs* lattice parameter[31], *Cd* exerting a stronger influence compared to *Sn*. This is rather important taking into consideration that an increase of mismatch leads to a shift of the band edge peak in the photoluminescence spectra[25,32]. This is shown in Fig. 4.

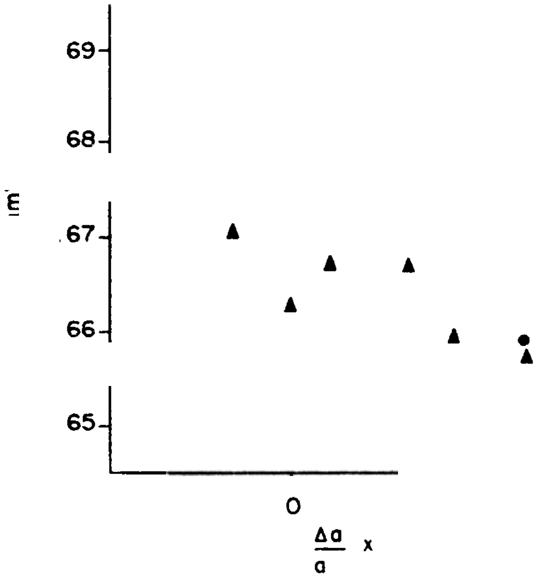

Figure 4. **Photoluminescence peak wavelength (300 K) of $In_{0.53}Ga_{0.47}As$ as a function of lattice mismatch (▲Bejan *et al.*[25], • Chen *et al.*[32]).**

3. DEVICE APPLICATION OF *InGaAsP/InP* HETEROSTRUCTURES

Table 3 demonstrates possible device applications for several A_3B_5 compounds and their solid solutions. The main tendencies of the *InGaAsP/InP* heterostructure application in optoelectronics and microelectronics are described in several reviews[6,14,19,25]. From the analysis of literature data one can conclude that works for realisation of microelectronic high speed devices, particularly FET, are being conducted according to several main approaches, namely, (a) by the use of a *p-n* junction gate, (b) by the use of a tunnel transparent oxide gate, (c) by the use of multilayered modulation-doped heterostructures, and (d) by the use of heterostructures with quantum wells.

Table 3. Several device applications of *GaAs, InP* and their solid solutions

Substrate	Structure	Device applications
GaAs	*GaAs/GaAs*	MESFETs, doped FETs, Schottky FETs, and bipolar transistors.
	AlGaAs/GaAs	HEMTs, MESFETs, low threshold lasers, quantum well lasers, solar cells photodiodes, and photo-transistors.
	InGaAsP/GaAs	Quantum well lasers
InP	*InP/InP*	Solar cells, MESFETs, and Gunn diodes.
	InGaAsP/InP	Low threshold lasers, quantum well lasers, solar cells, and photo-detectors.
	InGaAs/InP	JFETs, bipolar transistors and pin diodes.
	AlInAs/GaInAs/InP	Schottky FETs, HEMTs, integrated FETs, and photodetectors.

Before discussing FET, it is worth mentioning the perspective application of $In_xGa_{1-x}As/InP$ heterostructures for fabrication of bipolar transistors as well. An excellent example of a bipolar transistor with the current gain factor as large as 500 is reported[33]. The transistor structure was obtained by LPE. Its 0.5 μm thick base region attained a concentration of 8×10^{17} cm^{-3} with *Mn* doping.

Certain success was obtained in creating FET on *InGaAs/InP* with a *p-n* junction as a gate. Shmitt & Heine[34] described such a device where the *InGaAs/InP*-based FET with the *p-n* gate had a channel integral transconductance ~ 100 mS/mm at a 30 GHz frequency. An analogous FET is described by Selders *et al.*[35], characteristic of which is a transconductance as large as 130 mS/mm at a 20 GHz frequency, its gate dimensions being 1.6×200 μm^2. In order to make the *p-n* junction the authors[35] performed the ion doping with *Be* through an SiO_2 mask and a photoresist followed by a subsequent rapid thermal annealing.

The works dealing with the creation of multilayered heterostructures meant to ensure suitable conditions for the formation of 2-DEG present special interest. $In_{0.52}Al_{0.48}As$ turned out to be a favourable partner for the $In_{0.53}Ga_{0.47}As$ solid solution. As demonstrated by Mishra[36], the integral transconductance in HEMT-type transistors based on the *AlInAs/GaInAs/InP* hetero-composition attained high magnitudes. In case of 1.3 μm channel length transistors the channel transconductance was 460 mS/mm, it aquiring a 650 mS/mm value at a channel length up to 0.3 m. Characteristic for such transistors was a 14 dB at a 26 GHz frequency. HEMT fabricated on the basis of the extensively studied *AlGaAs/GaAs* heterostructure failed to attain such high results.

It's worth mentioning the use of the discussed heterostructures for the fabrication of highly effective photodetectors for the 0.65 to 0.9 μm range (*AlGaAs/GaAs*) and for the 1 to 1.65 μm range (*InGaAs/InP*), application of field transistor structures as high speed response photodetectors appearing to be quite realistic[19].

Much interest is also paid at present to both MOCVD and LPE *InGaAsP/GaAs* heterostructures as candidates for different device applications. Development of quantum-dimensional lasers (Fig. 5) appears[16] rather successful. These lasers emitted in the 0.86 to 0.78 μm range at a 100 A/cm^2 threshold current and had a 59 per cent efficiency. An analogous approach was used to receive quantum-dimensional lasers on the *InGaAsP/InP* heterostructure ($\lambda = 1.3$ μm). Threshold generation current magnitudes of 380 A/cm^2 seems to be the best magnitudes for injection lasers with a 1.3 μm emission wavelength[17].

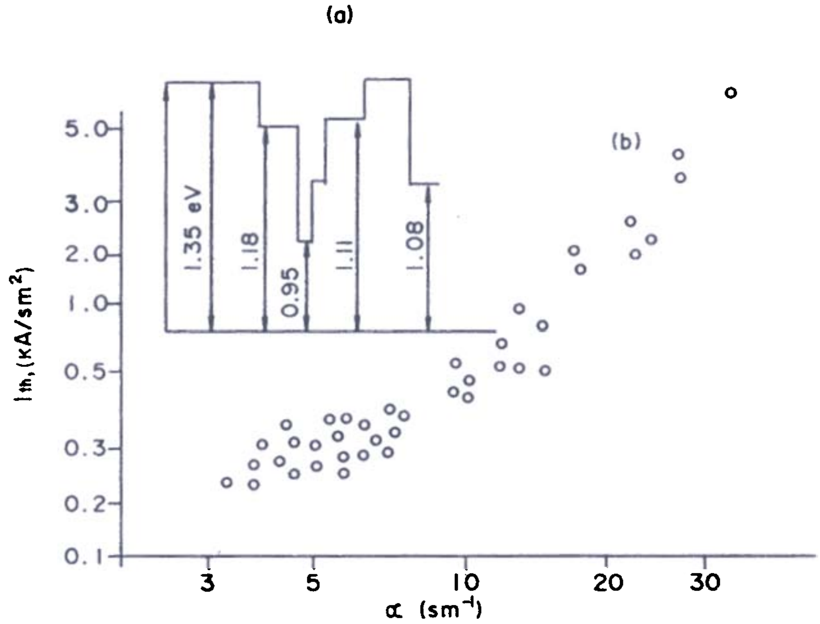

Figure 5. A schematic representation of (a) the phase diagram for a quantum well laser heterostructure, and (b) dependence of the threshold current density on the output of the mesa-band lasers[17].

Thus, data concerning the fabrication of highly effective transistors[33-36], photodetectors[19] and lasers[16,17] are available at present. Practically all these devices can be realised in an integral variant. One should expect the application of HEMT and quantum-dimensional structures in realisation of ultra high speed integral circuits to improve the high speed response and to reduce the power scattering[37,38]. A possibility to construct random-access memories with access time of the sub-nanosecond order is predicted by Abe *et al*[37].

The possibility, by use of modulation-doped structures and quantum well structures, to improve the main parameters of extensively studied devices, for instance FET, gives ground to consider these heterostructures very important for practical application. Though obtained by a considerable difficult technology the modulation-doped structures and the quantum well structures are expected to become in the near future a real basis for creation of a wide range of electronic devices, both in discrete and integral make versions[6,14,19]. At present it has been proved possible to fabricate integral optical modules on *InP* and *GaAs* substrates including the laser, Gunn diode, light diode field transistor, photodiode-amplifier, laser-modulator and other integral modules ensuring high rate information processing. For example, a 4-channel optoelectronic and integral circuit operating at 560

Mbit/s information processing rate was reported by Sakura *et al.*[38]. This suggests a tight connection between further development of the integral circuit technology and technological achievements in producing heterostructures on A_3B_5, first of all on *InP* and *GaAs*.

4. CONCLUSIONS

1. The growth technology of *InGaAsP/InP* heterostructures has attained a rather advanced stage at present to allow, by means of well-known approaches, the fabrication of compound device structures including modulation-doped and quantum-dimensional structures.

2. The trasistors, lasers and photodetectors realised in a discrete make version possess unique parameters comparable to the ones of *AlGaAs/GaAs* heterostructures, a fact that should stimulate further investigation of these heterosystems.

3. Appearance of HEMT on heterostructures opens new perspectives for further technology development of ultra high speed integral circuits.

4. The increase of the information processing rates requires an intensive development of the integral optical circuits on *InP* and *GaAs* and on their heterostructures.

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