

## Si- and Zn-doping of lattice matched $B_xIn_zGa_{1-x-z}As$ - and $In_xGa_{1-x}N_yAs_{1-y}$ -layers

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### Introduction

$In_xGa_{1-x}N_yAs_{1-y}$ -alloys have attained great attention in the past few years due to the possibility of lattice matched or strained growth on GaAs substrates in combination with a large reduction of the band-gap energy with increasing nitrogen incorporation [1]. Highly strained  $In_xGa_{1-x}N_yAs_{1-y}$ -layers with large In contents have been used as active material in 1.3–1.5  $\mu m$  laser diodes [2]. Lattice matched layers are of high interest for high-efficiency multi-junction solar cells [3]. The new  $B_xIn_zGa_{1-z}As$ -material system, which is largely unknown, offers new possibilities in band-gap engineering and strain reduction [4,5]. The growth of lattice matched  $B_xIn_zGa_{1-z}As$ -layers on GaAs has also been demonstrated introducing the material as another candidate for solar-cell applications [4,5]. Systematic doping studies are prerequisite for application of both materials in solar cells or detector structures. However, systematic doping investigations of  $B_xIn_zGa_{1-z}As$  and  $In_xGa_{1-x}N_yAs_{1-y}$  using metalorganic vapour-phase epitaxy (MOVPE) are either absent or very rare, respectively [6]. In this work, we investigate the Si- and Zn-doping of lattice matched  $B_xIn_zGa_{1-z}As$ - and  $In_xGa_{1-x}N_yAs_{1-y}$ -layers using MOVPE and disilane and diethylzinc as doping precursors. All layers were characterized with high-resolution x-ray diffraction, photoluminescence (PL), Hall-measurements and infrared spectroscopic ellipsometry (IR-SE).

### Experimental

$B_xIn_zGa_{1-z}As$ - and  $In_xGa_{1-x}N_yAs_{1-y}$ -layers have been grown lattice matched on (001)-GaAs substrates at 550°C and 560°C, respectively using low-pressure ( $p_{tot} = 50$  mbar) MOVPE (AIX200). The total flow into the horizontal reactor amounted to 7ssl and the growth rate was  $\sim 800$  nm/min. Triethyl boron (TEB), (1,1)-dimethyl hydrazine (DMHy), trimethyl gallium (TMGa), trimethyl indium (TMIn), diethyl zinc (DEZn) and disilane (500 ppm in  $H_2$ ) were used as B-, N-, Ga-, In-, Zn- and Si-precursors, respectively. Tertiarybutyl arsine (TBAs) and arsine were used as As-precursor for the growth of  $In_xGa_{1-x}N_yAs_{1-y}$  and  $B_xIn_zGa_{1-z}As$ , respectively. The nitrogen- and indium compositions of the approximately 1  $\mu m$  thick, lattice matched  $In_xGa_{1-x}N_yAs_{1-y}$ -layers can be estimated to  $y = 0.016$  and  $x = 0.047$  and the band-gap energy is  $\sim 1.08$  eV. The compositions and the band-gap energy of the lattice matched  $B_xIn_zGa_{1-z}As$ -layers ( $d \sim 1 \mu m$ ) amount to  $x @ 0.027$ ,  $z @ 0.06$  and  $E_g = 1.36$  eV. The partial pressures of TMIn, TMGa, DMHy, and TBAs, used for the growth of  $In_xGa_{1-x}N_yAs_{1-y}$ , were  $1.158 \cdot 10^{-4}$ ,  $2.6980 \cdot 10^{-3}$ ,  $1.9 \cdot 10^{-1}$ , and  $1.293 \cdot 10^{-2}$  mbar, respectively. The partial pressures of TEB, TMIn, TMGa, and arsine, used for the growth of  $B_xIn_zGa_{1-z}As$ , amounted to  $4.95 \cdot 10^{-3}$ ,  $1.365 \cdot 10^{-4}$ ,  $2.7146 \cdot 10^{-3}$ , and  $7.117 \cdot 10^{-1}$  mbar, respectively.

### Results

Nominally undoped  $In_xGa_{1-x}N_yAs_{1-y}$ -layers were found to be  $p$ -type with free hole concentrations ranging from  $\sim 6 \cdot 10^{16} \text{ cm}^{-3}$  ( $V/III = 25$ ) to  $\sim 2 \cdot 10^{16} \text{ cm}^{-3}$  for  $V/III$ -ratios above 100. In comparison, the background-doping level was drastically reduced for the  $B_xIn_zGa_{1-z}As$ -layers, for which free electron concentrations of  $10^{10} \text{ cm}^{-3}$  ( $V/III = 41$ ) and  $5 \cdot 10^{13} \text{ cm}^{-3}$  ( $V/III = 8$ ) have been measured. These values are surprisingly low in view of the relatively large boron-carbon bondstrength.

Fig. 1 (a) shows the free carrier concentrations of the Si-doped  $In_xGa_{1-x}N_yAs_{1-y}$ - and  $B_xIn_zGa_{1-z}As$ - layers resulting from the Hall-measurements as a function of the normalized partial pressure of disilane in the gasphase. With increasing Si-incorporation, the  $p$ -type  $In_xGa_{1-x}N_yAs_{1-y}$ -layers become semiinsulating and for

$p_{\text{disilane}}/p_{\text{group-III}}$ -values above  $10^{-3}$ ,  $n$ -type conduction is obtained with a maximum electron concentration of  $\sim 6 \times 10^{18} \text{ cm}^{-3}$  for  $p_{\text{disilane}}/p_{\text{group-III}} = 0.1$ . For normalized disilane-partial pressures between 0.007 and 0.07, the increase of the electron concentration is approximately linear and a Si-distribution coefficient  $k_{\text{Si}}$  of  $\sim 0.004$  can be estimated. Please note that in this

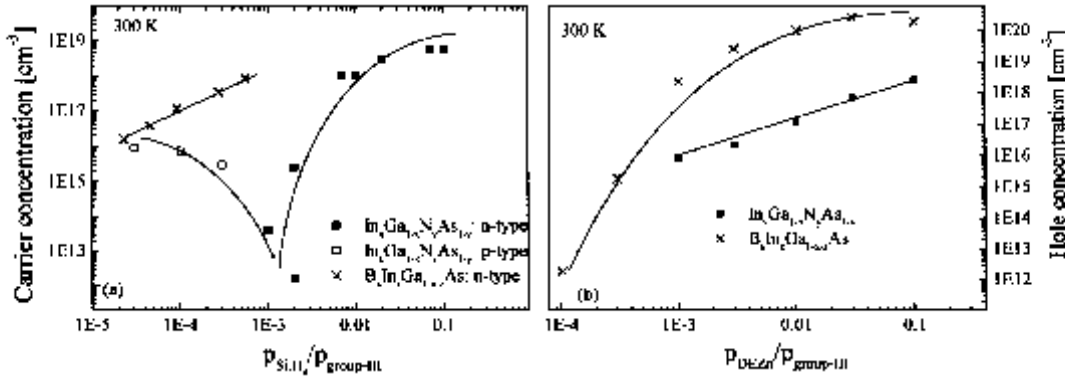


Fig. 1: (a): Free carrier concentration of Si-doped  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (squares) and  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ -layers (crosses) depending on the ratio of the partial pressure of disilane to the partial pressures of all group-III precursors. (b): Free hole concentration of Zn-doped  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (squares) and  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ -layers (crosses) depending on the ratio of the partial pressure of DEZn to the partial pressures of all group-III precursors. All lines are shown to guide the eye.

approximation autocompensation effects and the formation of Si-precipitates (both observed in Si-GaAs [7]) are neglected. For  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ , the Si-doping efficiency is clearly increased compared to  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (for  $2.2 \times 10^{-5} < p_{\text{disilane}}/p_{\text{group-III}} < 5.5 \times 10^{-4}$ ), which can be understood by the smaller compensation ratio in  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ . The electron concentration increases linearly with increasing  $p_{\text{disilane}}/p_{\text{group-III}}$ -ratio and a Si-distribution coefficient  $k_{\text{Si}}$  of 0.075 can be estimated under the same assumptions as for  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ . This value is significantly enhanced compared to  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  ( $k_{\text{Si}} \sim 0.004$ ), which might be partly due to the increased autocompensation ratio and/or tendency for formation of Si-precipitates for higher Si-concentrations [7].

Incorporation of Zn resulted in  $p$ -type conduction for both materials,  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  and  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$  (Fig. 1 (b)). In Ref. 6,  $n$ -type conduction was obtained for Zn-doped  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  using MOVPE under similar growth conditions. The origin of this puzzling difference remains unsolved and needs further clarification. For  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ , we obtain linearly increasing hole concentrations with increasing  $p_{\text{DEZn}}/p_{\text{group-III}}$ -ratio up to the highest obtained value of  $p \sim 3 \times 10^{18} \text{ cm}^{-3}$  and a Zn-distribution coefficient  $k_{\text{Zn}}$  of  $\sim 0.012$  can be estimated. In comparison, the Zn-doping efficiency is drastically enhanced in  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ . Assuming that all Zn-atoms are incorporated on group-III lattice sites, a Zn-distribution coefficient  $k_{\text{Zn}}$  of  $\sim 0.4$  can be estimated for  $p_{\text{DEZn}}/p_{\text{group-III}}$ -ratios between 0.001 and 0.03, where the incorporation behaviour is approximately linear. Different surface reconstructions and the higher As/group-III-ratio in  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$  leading to a higher number of group-III vacancies might explain the observed differences between the two materials.

Fig. 2 shows the Hall-mobilities of the Si- (a) and Zn-doped (b)  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (squares) and  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ -layers (crosses) as a function of the carrier concentration. Generally, the mobilities of the  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ -layers are clearly enhanced (by a factor 2–5) compared to the corresponding values for  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ , which can be explained by the lower compensation ratio in  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$ . For  $n$ -type layers, there is a trend of increasing mobilities with decreasing electron concentrations for high Si-compositions (Fig. 2 (a)). This can be understood by the decreasing number of ionized impurities with decreasing Si-concentration. The saturation or even decrease of the mobilities in the low-concentration region hints at a second process, possibly the

interaction of the Si-dopants with other defects, which may

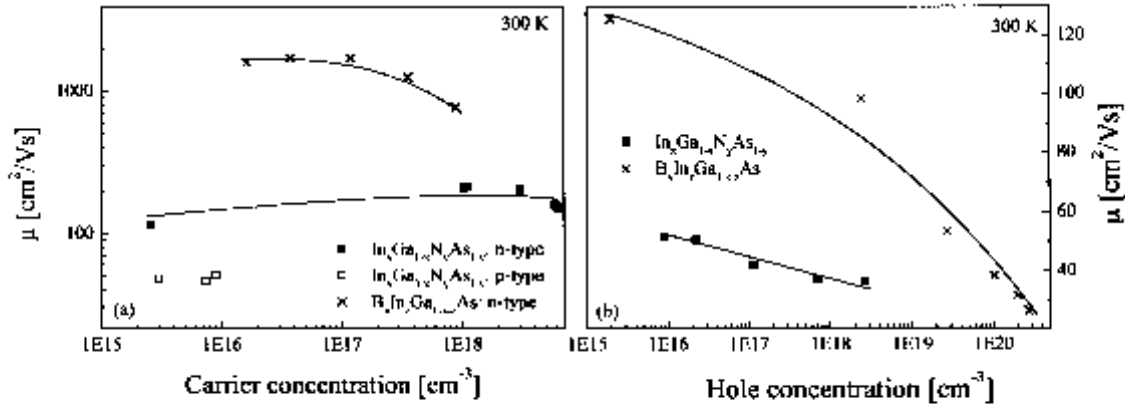


Fig. 2: (a): Hall-mobility of Si-doped  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ - (squares) and  $\text{B}_x\text{In}_2\text{Ga}_{1-x}\text{As}$ -layers (crosses) depending on the carrier concentration. (b): Hall-mobility of Zn-doped  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ - (squares) and  $\text{B}_x\text{In}_2\text{Ga}_{1-x}\text{As}$ -layers (crosses) depending on the hole concentration. All lines are shown to guide the eye.

also be concluded from PL-experiments (see below). The mobilities of both types of Zn-doped layers decrease with increasing Zn-concentration due to enhanced ionized-impurity scattering and are generally lower than the mobilities of the Si-doped samples, which is due to the higher valence-band effective masses (Fig. 2 (b)).

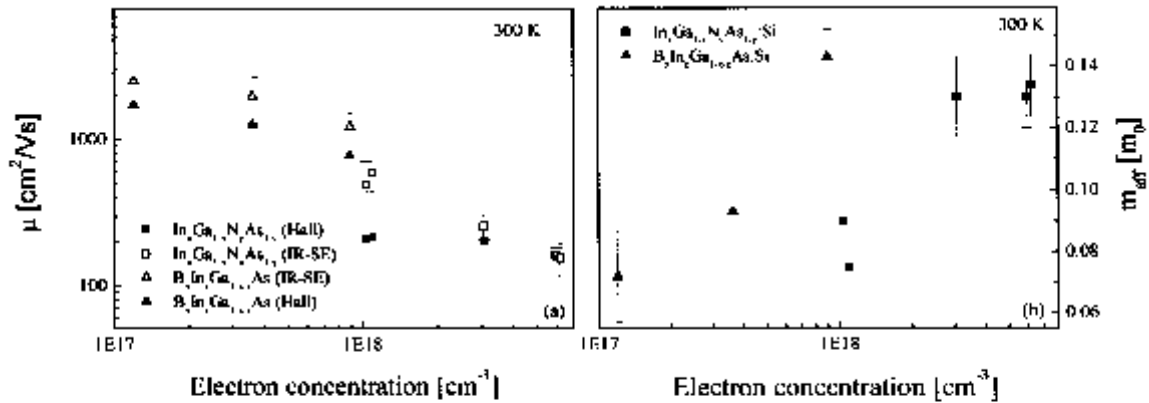


Fig. 3: (a): Mobilities of  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (squares) and  $\text{B}_x\text{In}_2\text{Ga}_{1-x}\text{As}$  (triangles) derived from Hall-measurements (solid symbols) and ellipsometry (open symbols). (b): Effective electron masses of  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (squares) and  $\text{B}_x\text{In}_2\text{Ga}_{1-x}\text{As}$  (triangles).

For the Si-doped layers, infrared spectroscopic ellipsometry was used to derive mobilities and effective masses using the Hall-concentrations as input parameter. Hall-mobilities and optically determined mobilities show in general the same trends (Fig. 3 (a)) and the effective masses increase for both materials with increasing carrier concentration (Fig. 3 (b)), which is an indicator of the nonparaboly of the conduction bands.

The room temperature PL-spectra of both materials are largely influenced by Si-doping as shown in Fig. 4. For  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (a) and  $\text{B}_x\text{In}_2\text{Ga}_{1-x}\text{As}$  (b), the maximum PL-intensities increase with increasing doping level up to  $\sim 10^{18} \text{ cm}^{-3}$ . This effect is possibly caused by the interaction of the Si-dopants with other defects. For higher doping levels, the PL-intensities decrease in  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$ , which can be explained by defect creation due to

formation of Si-precipitates as observed in Si-GaAs [7].

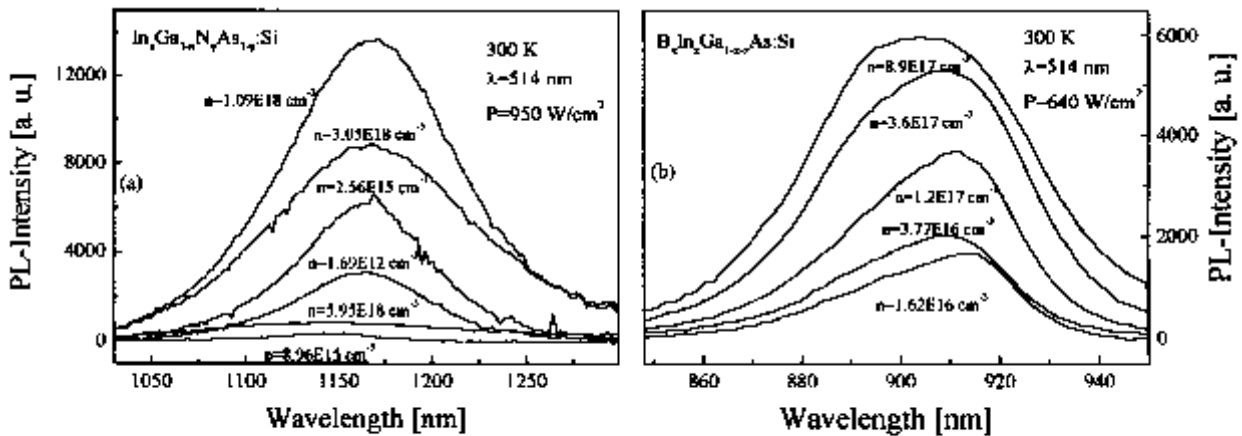


Fig. 4: Room temperature PL-spectra of  $\text{In}_x\text{Ga}_{1-x}\text{N}_y\text{As}_{1-y}$  (a) and  $\text{B}_x\text{In}_z\text{Ga}_{1-z}\text{As}$  (b).

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