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# Properties of silicon pulse doped InGaP layers grown by LP-MOCVD

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**Abstract**

Silicon doped $In_{0.49}Ga_{0.51}P$ layers were grown at 560°C and 50 mbar by low pressure metal organic chemical vapour deposition (LP-MOCVD). A delta-doping technique was used for the doping of the InGaP layers. The sheet carrier concentration increases linearly with the silane mole fraction in the feed gas. The highest value of the sheet concentration obtained was $5.9 \times 10^{12} cm^{-2}$, which corresponds to a 3D-concentration of $1.5 \times 10^{19}$ $cm^{-3}$. The width of doping profiles ranges between 3 and 6 nm, indicating low diffusion of silicon in the InGaP. The Hall electron mobility at 300 K was only slightly dependent on the doping level, and it was between 680 and 480 $cm^2$ $V^{-1}$ $s^{-1}$. The low electron mobility is due to a high concentration of native background acceptors originating from growth gases. A strong band-acceptor (e-$A^0$) transition, appearing in the photoluminescence (PL) spectra, confirms the presence of acceptors at a high density. © 1997 Elsevier Science S.A.

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## 1. Introduction

The $In_{0.49}Ga_{0.51}P$ (hereafter InGaP) ternary lattice-matched to GaAs offers an attractive alternative to AlGaAs as a barrier layer material in GaAs based quantum devices. One key feature of InGaP is the band gap dependence on the growth temperature, V/III ratio, gas pressure and velocity in a pressure metal organic chemical vapour deposition (MOCVD) reactor. This phenomenon is already understood and its origin in a spontaneous ordering of GaP/InP sublattices [1,2] is widely accepted. Electrical properties of InGaP layers are also affected by the presence of ordering [3]. Advanced electronic and photonic devices need highly doped InGaP barrier layers. N-type layers have previously been obtained by silicon, sulphur and selenium doping [4–7]. An electron concentration of $1 - 10^{19}$ $cm^{-3}$ was the highest value achieved for a silicon doped InGaP layer using disilane as a precursor [5]. Another positive effect of the doping is the so called impurity-enhanced disordering [7]. However, Liu et al. [8] have observed ordering in InGaP samples Si-doped up to $1 \times 10^{19}$ $cm^{-3}$. On the other hand, no ordering has been observed in samples grown at 730°C. Thus, an appropriately chosen growth temperature is a crucial factor for the preparation of high quality, wide band InGaP layers. Data of the electron mobility in InGaP, published in various papers, spread in a wide range between 700 and 4100 $cm^2$ $V^{-1}$ $s^{-1}$ for comparable doping levels of $10^{15}$–$10^{16}$ $cm^{-3}$. However, evaluation of the electron mobility from Hall measurements should be carried out with care because a two-dimensional electron gas (2DEG) can be formed at the GaAs/InGaP interface [6]. Thus, the true electron mobility in undoped InGaP reaches a value of about 1000–1300 $cm^2$ $V^{-1}$ $s^{-1}$. Such values were published for atmospheric-pressure MOCVD deposited layers [9] and for liquid phase epitaxy (LPE) prepared InGaP layers [10]. Pulse (also called delta) doping is a method of obtaining easily a high sheet concentration, which is required especially in high mobility electron transistor (HEMTs). This technique, in the ideal case, places doping atoms into a single plane, however they in fact extend over a distance of 2–5 nm. In this work, we report on electrical properties of pulse silicon-doped InGaP layers grown by low pressure MOCVD at the temperature of 560°C.

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## 2. Experiment

The layers were prepared in an Aixtron AIX200 equipment with a horizontal low-pressure reactor. A series of samples was grown at 560°C. Such a low temperature was chosen with the intention to prepare disordered layers [1] and minimise the out-diffusion of silicon atoms from the $\delta$-plane into the adjacent layer. The pressure in the reactor was 50 mbar. Trimethylgallium, trimethylindium, phosphine and silane (1% $SiH_4$ in hydrogen) were used as precursors. A growth rate of 1.2 μm and the V/III ratio equal to 260 were used for our experiments. The samples were prepared simultaneously on exactly oriented (001) semi-insulating and $n^+$-GaAs substrates. No GaAs buffer layer was grown between the substrate and the layer to avoid creating 2DEG on the interface. A $\delta$-plane was grown by switching off TMI and TMG flow, interrupting the growth process for 5 s, and switching on silane for 60 s. Then, after another 5 s interruption, both sources were switched on. Phosphine was kept flowing constant during the whole growth process. The doping level was adjusted by the mole fraction of silane in the carrier gas. Two different test structures were prepared for this study. In the first case, one silicon $\delta$-plane was grown in the middle of a 400 nm thick undoped InGaP layer. In the second case, a doping $\delta$-plane was sandwiched between a 400 nm thick InGaP buffer layer and a 300 nm InGaP cap layer. Whichever the test structure was measured no differences in results were observed. The layers were characterised by X-ray diffraction, photoluminescence (using an Ar laser), Hall-effect, current–voltage ($I$–$V$) and capacitance–voltage ($C$–$V$) measurements (using gold Schottky contacts).

## 3. Results and discussion

Fig. 1 shows sheet electron concentrations obtained from the Hall measurement. The sheet carrier concentration increases linearly with the silane mole fraction in the feed gas up to a level of $3 \times 10^{12}$ $cm^{-2}$, then begins to saturate. The responsive 3D carrier concentration in the InGaP layer can be precisely adjusted over four decades by varying the silane mole fraction from $2 \times 10^{-6}$ to $2 \times 10^{-4}$. The highest value of the Hall sheet concentration obtained was $5.9 \times 10^{12} cm^{-2}$, which theoretically corresponds to the 3D-concentration $n_{3D} \sim n_S^{3/2} = 1.4 \times 10^{19}$ $cm^{-3}$. Higher concentrations can be obtained simply by changing the growth temperature. Our experiments (not reported in this paper) have shown that the electron sheet concentration increases approximately 3.7–4 times at 640°C (in agreement with data reported by Wang et al. [11]) and by a factor of 11 at 720°C. However, although at 640°C an extremely sharp doping profile (full-width-half-maximum (FWHM) = 1.9 nm) was observed, the InGaP layers were strongly ordered, and in layers grown at 720°C the donor distribution peak looks like a 10–15 nm wide rectangle. An important property of $\delta$-doped layers, in comparison with homogeneously doped ones, is a significant increase of the electron mobility [12]. However, the opposite effect was observed in our samples grown at 560°C. The undoped InGaP exhibits a carrier mobility of 1190 $cm^2$ $V^{-1}$ $s^{-1}$ at 300 K and 2310 $cm^2$ $V^{-1}$ $s^{-1}$ at 77 K. Except for sample #73, doped near the background level, all other $\delta$-doped samples exhibited an approximately two times lower mobility, which was only slightly dependent on the doping level. The carrier mobility was in the range 690–485 $cm^2$ $V^{-1}$ $s^{-1}$ at 300 K and it decreases to 200–250 $cm^2$ $V^{-1}$ $s^{-1}$ at 77 K. Hai and Studart [13] have shown that the electron mobility in a $\delta$-doped semiconductor is strongly influenced by a background acceptor concentration. Therefore, a reduction of the carrier mobility (and the saturation of doping level) can be attributed to a very high concentration of native acceptors (probably carbon) in the InGaP layer originating from the low temperature growth process performed. The possibility that silicon itself can act as an acceptor in InGaP, due to its amphoteric nature, can be excluded [11]. The low Hall mobility measured and the absence of Shubnikov-deHaas oscillations in magnetic fields up to 10 T indicate that our Hall measurements were not influenced by a 2DEG at the heterointerface.

Important information about the material parameters can be extracted from photoluminescence (PL) measurements. Fig. 2 shows PL spectra of two InGaP samples with different doping level recorded at 15 K. The important peaks with corresponding energies are

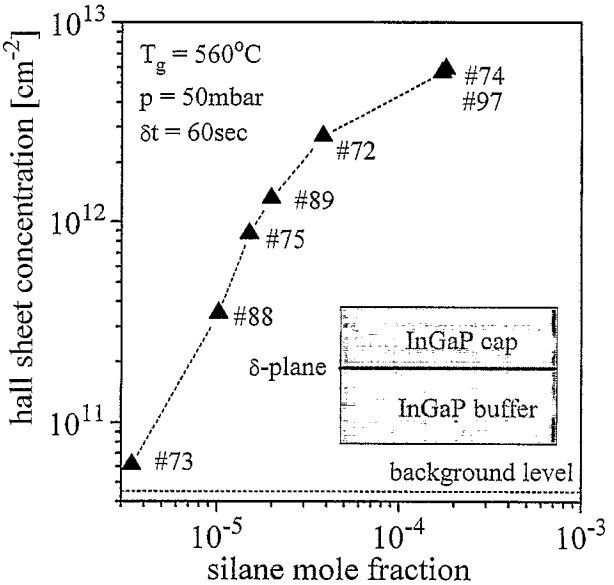


Fig. 1. Sheet carrier density vs. silane mole fraction in the growth gas.

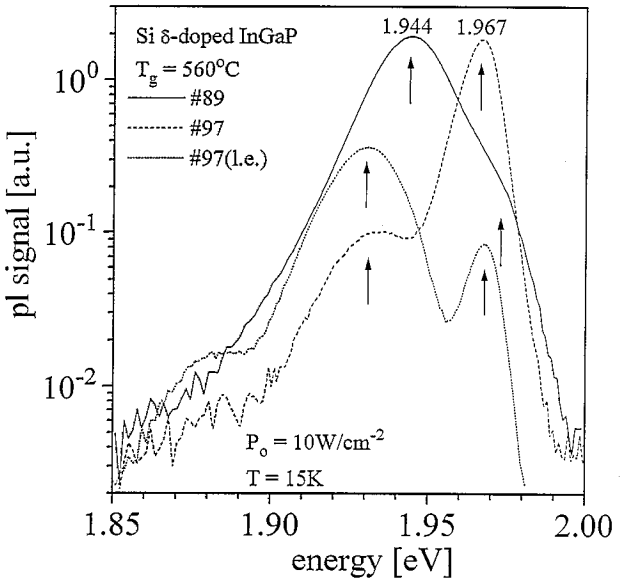


Fig. 2. Low temperature photoluminescence spectra from two samples with different doping levels.

designated by arrows. Both samples exhibit optical transitions at 1.94 and 1.97 eV. Whereas in the low doped sample, the second peak appears as a high energy cut-off of the spectra, in the case of the highly doped sample, it clearly appears as a separated peak. The distance between the peaks is 38 meV, and it is independent of the doping level. The halfwidth of the peaks is low. It is apparently 23 meV wide (for the low doped sample # 89), but a detailed analysis yields two Gauss-like peaks with a FWHM of 22 and 14 meV, respectively. The highly doped sample # 97 exhibits even narrower peaks. The FWHM is 21 meV and the high energy peak is as narrow as 9 meV, indicating good quality of the layer. Taking published data [10] into account, the intensive broad peak at 1.94 eV is due to the band to acceptor (e-$A^0$) transition, and the peak at 1.97 eV corresponds to the band to band transition (e-d). Increasing excitation power causes a blue shift of about 22 meV for the (e-$A^0$) related peak, whereas no shift was measured at the (e-d) related transition. A third peak of unknown origin appears 25–28 meV below (e-$A^0$) peak at low excitation power. The PL peak at 1.97 eV is about 30 meV lower than it was published for disordered material [14]. This indicates that InGaP layers prepared with our equipment are still weakly ordered despite high doping. This agrees with conclusions in [8]. DeLong et al. [15] have shown that the value for the InGaP band gap determined from low temperature ( < 60 K) PL is up to 30 meV lower than a true value. Therefore, the true low temperature band gap in our InGaP layers is expected to be near 2 eV. The fine energy structure of a V-shaped well caused by delta doping can not be observed in the PL spectra because holes are not present in the well. Results from PL measurements are not influenced by various compositions of individual samples, because misfit determined from X-ray measurements was in a narrow range $7 \times 10^{-4}$–$1.2 \times 10^{-3}$.

The doping distribution was derived from capacitance–voltage measurements at room temperature. Although this method has some limitations [12], it is a useful tool for the characterisation of plane doped structures. The test Schottky diodes were excellent devices for $C$–$V$ analysis (barrier height $F = 0.99$ eV, ideality factor $n = 1.04$, extremely low reverse current density of $6 \times 10^{-9}$ A cm$^{-2}$). The diode capacitance slightly decreases with increasing reverse bias. An abrupt decrease in capacitance occurs as the $V$-potential well is fully depleted [16]. Further saturation of the $C$–$V$ curve occurs at the point where the depletion layer reaches the substrate. The concentration profile was calculated from $C$–$V$ data using well-known equations $N_{CV} \sim n_{CV} = (C^3/e\varepsilon) \cdot (dV/dC)$ and $x = \varepsilon/C$, where $C$ is the capacitance per unit area. Fig. 3 shows concentration profiles obtained for three samples with various silane mole fractions. The doping profiles are narrow, indicating little diffusion of silicon. Half widths of the peaks decrease from 6.7 to 3.5 nm with increasing doping concentration due to a stronger carrier localisation in the plane. Fig. 4 shows, as an example, the $C$–$V$ concentration profile (sample # 89) scanned through the whole layer thickness and a detailed trace of concentration peak (sample # 97). The $\delta$-peak appears very close to the expected depth of 300 nm below the top surface, and it is slightly asymmetric. The slope of the upper interface (about 4.1 nm per decade) is about

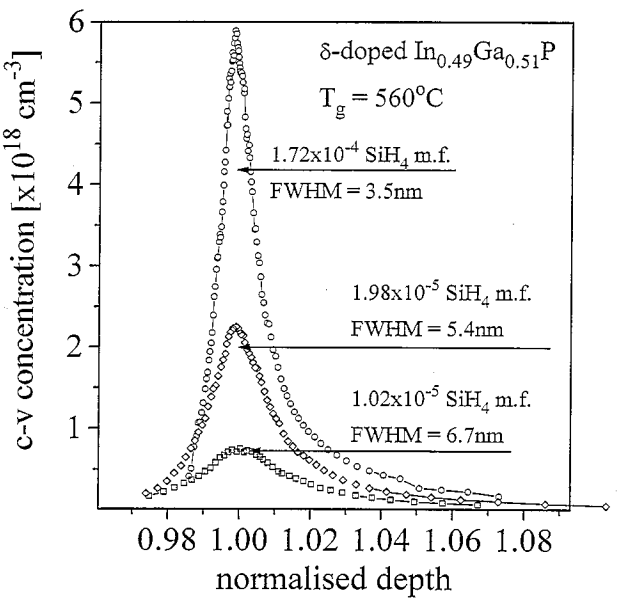


Fig. 3. Carrier concentration profiles deduced from $C$–$V$ measurements for three samples with different doping.

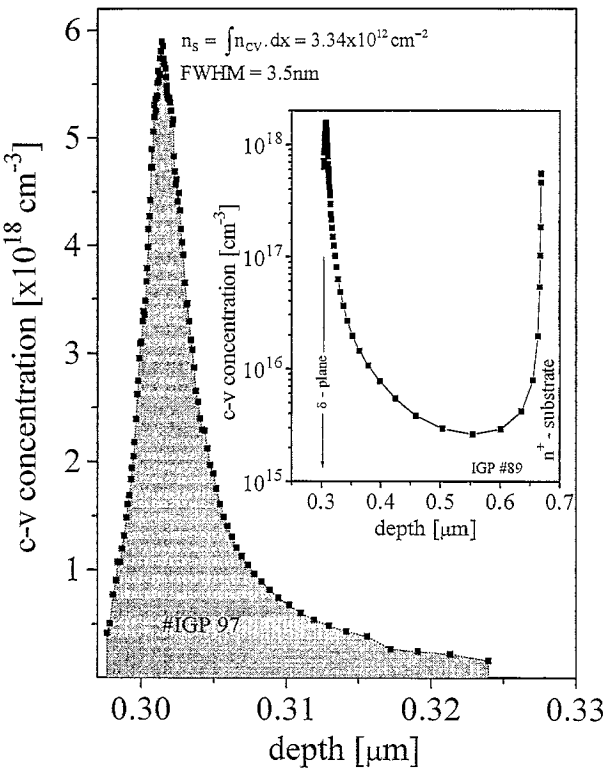


Fig. 4. Detailed free carrier distribution for the highly $\delta$-doped InGaP. The $n_{CV}$ vs. depth scan for the whole layer thickness.

two times as steep as the bottom one. The $C-V$ profile falls down to a background level at the distance 150–200 nm from $\delta$-plane. Integration of $n_{CV}$ profiles has yielded sheet concentrations that were 1.1–1.7 times lower than data observed from Hall measurements although the corrections for the influence of surface states were done [12]. This indicates that not all electrons are localised in the narrow V-shaped-well and a part of charge carriers creates a parallel channel in the InGaP layer.

## 4. Conclusion

We presented the preparation and properties of silicon delta-doped $In_{0.49}Ga_{0.51}P$ layers grown at 560°C and 50 mbar by LP MOCVD using silane for the doping. The concentration increases linearly with the silane mole fraction in the feed gas up to a level of $3 \times 10^{12}$ cm$^{-2}$. The highest value of the sheet concentration obtained was $5.9 \times 10^{12}$ cm$^{-2}$. Sharp doping profiles with FWHM between 3 and 6 nm were observed using a $C-V$ profiling technique. The Hall electron mobility was between 690 and 480 cm$^2$ V$^{-1}$ s$^{-1}$. The low electron mobility was related to a high concentration of native background acceptors originating from growth gases.

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