Silicon Incorporation in InP During LP-MOCVD using Disilane

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Silicon doped epitaxial layers of InP have been prepared by low pressure metalorganic chemical vapour deposition, using disilane as the source of silicon. Trimethylindium and phosphine were used as the source reactants for the growth. The doping characteristics for the epitaxial growth were investigated at substrate temperatures in the range 525–750 °C and for doping levels in the range $4 \times 10^{16}$–$2 \times 10^{19}$ cm$^{-3}$. The results indicated that the Si doping level is proportional to the disilane flow rate. The Si incorporation rate increases with temperature, but becomes temperature-independent for $T > 620$ °C. Comparison between Si concentrations determined by Secondary Ion Mass Spectroscopy, donor levels determined by Hall effect measurements, and optical measurements at 7 K indicates that approximately 50% of the Si in the InP is in the form of electrically inactive species. Uniform doping over 5 cm wafer dimensions has been obtained for growth at $T = 625$ °C.

Key words: MOCVD, InP, doping

1. INTRODUCTION

III-V compound semiconductor epitaxial layers of InP, GaInAs and GaInAsP with compositions lattice matched to InP are increasingly being used for the fabrication of opto-electronic devices. The application of metalorganic chemical vapour deposition (MOCVD) to the growth of epitaxial layers for such devices requires controlled doping of those layers over a wide range of doping levels. Si is one of several elements (Ge, Sn, S, Se and Te) which act as donors in III-V semiconductors, and are used as n-type dopants for InP grown by MOCVD. Si is specifically suitable as a dopant for the growth of device structures where well defined doping profiles in the layers are crucial for proper device operation. The reason for this is that memory effects associated with the use of Si-based precursors have not been observed in MOCVD reactors, and the diffusivity of Si in InP and related materials is low, which makes good control of doping profiles possible.

Several papers dealing with the use of Si as a donor species in MOCVD of InP have been published.\textsuperscript{1–7} Also, its use has been reported in other III-V compound semiconductors such as GaInP,\textsuperscript{8} GaInAs,\textsuperscript{6} GaAs\textsuperscript{8–16} and GaAlAs.\textsuperscript{15} Most investigations of Si doping of MOCVD-InP have used silane as the Si doping source.\textsuperscript{1–5} Distribution coefficients were reported to be independent of the silane flow rate\textsuperscript{1–5} and to have values in the range $10^{-5}$–$10^{-2}$ \textsuperscript{3,5} depending on growth conditions. The incorporation rate was found to increase with temperature over the temperature range (500–700 °C) investigated.\textsuperscript{3,5} The low distribution coefficient and its temperature dependence are believed to be due to the low cracking efficiency of silane, and may be a drawback when it is used in situations where accurate doping levels are required. Recently, the use of disilane (Si$_2$H$_6$) has been reported for several III-V compounds.\textsuperscript{6–8,11–16} This source was reported to have the advantage, compared to silane, of a high incorporation coefficient which is independent of temperature over a large temperature interval. This characteristic can improve uniformity of doping over large areas, as inhomogeneities associated with the reactor temperature profile are minimized.

The use of disilane as a Si dopant for MOCVD-InP was reported for growth at atmospheric pressure by Woelk and Beneking\textsuperscript{7} and by Rose \textit{et al.}\textsuperscript{7} In the present work we have investigated its use in low pressure MOCVD of InP.

2. EXPERIMENTAL

The deposition of InP was carried out in a horizontal MOCVD reactor which has been described elsewhere.\textsuperscript{17,18} Of the two susceptor configurations described in,\textsuperscript{17} for the present experiments the “conventional” configuration was used, \textit{i.e.}, with the wafer surface facing upward. Substrates were (100) oriented wafers of Fe doped semi-insulating InP. Prior to loading into the reactor the substrates were polished using a Br$_2$/methanol solution, rinsed in methanol, and blown dry with filtered high purity nitrogen. Palladium diffused hydrogen was used as a carrier gas. Trimethylindium and phosphine were used as source reactants for In and P, respectively. The source of disilane was a high pressure gas cylinder containing a mixture of 100 ppm disilane in UHP hydrogen. A dilution system was used to further reduce the disilane concentration prior to its injection into the carrier stream.

Hall measurements were carried out for layers grown on semi-insulating substrates. Secondary Ion Mass Spectroscopy (SIMS) profiles of Si in the epi-layers were also obtained. The SIMS measurements were all calibrated against the same$^{28}$Si$^{-}$-implanted InP wafer. This wafer was cross-referenced.
against additional implant standards, including an implant of $^{29}\text{Si}$. The accuracy of the Si concentrations determined by SIMS was thus determined to be better than 20%. Photoluminescence spectra were obtained, at 7 K, using a 3/4 m Spex spectrometer, a Si photodiode and a 15 mW HeNe laser focussed down to a 250 $\mu$m diameter spot size.

3. RESULTS AND DISCUSSION

3.1 Silicon Incorporation Characteristics

The relationship between the disilane flow rate into the reactor and the Si concentration in the epi-layers, as determined by SIMS, for depositions carried out at $T = 610^\circ\text{C}$ and $P = 75$ Torr, is shown in Fig. 1. The data points closely follow the dashed line, which has a slope of 1, indicating that the relationship is linear over the range of doping levels investigated up to $[\text{Si}] = 2 \times 10^{19}$ cm$^{-3}$. At doping levels exceeding this value the layer morphology deteriorated. This high doping region was not further investigated.

The relationship between the substrate temperature and the Si concentration in the epilayers, at a constant disilane flow rate and a reactor pressure of 75 Torr, is shown in Fig. 2. The Si incorporation increased with temperature up to $T = 620^\circ\text{C}$ but remained constant at higher deposition temperatures. This temperature dependent behaviour of the incorporation is similar to that observed for Si incorporation in GaAs$^{13-16}$ and GaInP.$^6$ The rate limiting factor for the Si incorporation is generally believed to be the dissociation of disilane.

$$\text{Si}_2\text{H}_6 \rightarrow \text{SiH}_2 + \text{SiH}_4 \quad (1)$$

$$\text{SiH}_4 \rightarrow \text{SiH}_2 + \text{H}_2 \quad (2)$$

The SiH$_2$ radical is extremely reactive and Si in this form is thought to react at the epilayer surface and be incorporated in the layer. Because the decomposition rate of disilane is much higher than that of silane,$^{19-21}$ Eq. (1) dominates the temperature dependence of the Si incorporation. In Fig. 2 we can distinguish a high temperature mass transport limited region and a low temperature dissociation rate limited region, which will be discussed in more detail in sections 3.2 and 3.3, respectively.

The effect of reactor pressure on the Si incorporation was determined for depositions at $T = 625^\circ\text{C}$ in the mass transport limited region, and at $T = 575^\circ\text{C}$ in the dissociation rate limited region. During each deposition, the reactor pressure was held, for 30 min each, at pressures of 75, 225 and 675

![Graph](image1.png)

![Graph](image2.png)

Fig. 1 — The disilane flow rate vs the Si concentration, determined by SIMS, for layers of MOCVD-InP grown at $T = 610^\circ\text{C}$ and $P = 75$ Torr. The dashed line corresponds to Si incorporation with a constant distribution coefficient.

Fig. 2 — The inverse susceptor temperature versus the Si concentration, determined by SIMS, for layers of MOCVD-InP grown at a disilane flow of $6 \times 10^{-5}$ sccm and $P = 75$ Torr. The horizontal dashed line corresponds to the calculated Si concentration for mass transport limited Si incorporation from SiH$_4$ radicals as discussed in the text. The sloped line corresponds to an activation energy of 2.6 eV.