Carrier-induced change due to doping in refractive index of InP: measurements at 1.3 and 1.5 mm

Citation for published version (APA):

DOI:
10.1063/1.116837

Document status and date:
Published: 01/01/1996

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.
Carrier-induced change due to doping in refractive index of InP: Measurements at 1.3 and 1.5 μm

Laurent Chusseau, a Patrick Martin, Céline Brasseur, and Claude Alibert
Centre d’Electronique et de Micro-optoélectronique de Montpellier, UMR 5507 CNRS-MEN, Université de Montpellier II, 34095 Montpellier, France

Philippe Hervé
Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

Philippe Arguel and Françoise Lozes-Dupuy
Laboratoire d’Analyse et d’Architecture des Systemes du CNRS, 7 Avenue du Colonel Roche, 31077 Toulouse, France

E. V. K. Rao
France Télécom CNET, Centre Paris B, 196 Avenue Henri Ravera, 92220 Bagneux, France

(Received 2 July 1996; accepted for publication 11 September 1996)

Accurate measurements of the InP refractive index as a function of free-carrier doping are reported at 1.3 and 1.5 μm, the two strategic wavelengths for optical communications. A total of 21 samples with different N- and P-doping levels have been measured using a novel and simplified grating-coupling technique. In contrast to the conventional method, this only involves the use of a directly etched diffraction grating on the sample surface, thereby avoiding the necessity of a specific guiding layer. The measured index, in agreement with earlier predictions, decreases by more than 0.05 when the N doping is increased from below 10^{15} to about 10^{19} electrons per cubic centimeter. This effect, however, is much less pronounced with P doping than with N doping.

Indium phosphide is the basic semiconductor material for long-wavelength optoelectronic and photonic device fabrication devoted to future optical communication systems. Several modern applications in this field such as, wavelength-division multiplexing, design of Bragg reflectors, or modal calculations require an accurate knowledge of InP refractive index in the 1.3–1.5 μm wavelength range. Such considerations have revived the field of InP refractive index experimental determination with the goal of increasing the accuracy of previously available reference data up to, at least, 10^{-3}. Evidently, such accuracy necessitates a thorough knowledge of free-carrier induced change in refractive index due for instance to voluntary impurity doping. Unfortunately, the few available experimental data show marked discrepancies. One frequently resorted in a theoretical model to evaluate doping influence.

One of the most accurate techniques for refractive index measurements employs a grating coupler etched on the surface of a guiding layer. It provides the effective guided-mode indices, \( n_{\text{eff}} \), of allowed propagating modes within a planar waveguide. Very sharp peaks are observed either on the reflected or guided signals as the input angle of incidence, \( \theta \), is varied. Effective guided-mode indices, \( n_{\text{eff}} \), are determined from the resonant-coupling angles according to the formula \( n_{\text{eff}} = \sin(\theta + m\lambda/L) \), where \( \lambda \) is the wavelength in vacuum, \( L \) the grating period, and \( m \) the grating order. The range of \( \lambda \) and \( L \) are kept so that \( m = 1 \) in our experiments. This procedure has been employed to determine the refractive index of a thin nonintentionally doped InP layer grown by molecular beam epitaxy (MBE). 1

In the present work, the InP substrate index is obtained from a slightly different scheme which in fact is implicit in our earlier work. For example, as we have remarked in Ref. 1, a **guiding layer is not required** to observe a sharp peak, the substrate index, \( n \), then being given by \( n = \sin(\theta_0 + \lambda/L) \), where \( \theta_0 \) is the angle of peak position. The physical origin of this somewhat unexpected peak resides in the experimental setup (see the inset of Fig. 1) used for guided-mode observation. 11 Clearly, rays having incidence angles between \( \theta_0 - \Delta \theta \) and \( \theta_0 \) can only give rise to an optical signal detected by the photodiode. Provided that the detector aperture \( d \) is small compared to its distance \( L \) to the sample exit edge, the angle straightforwardly follows from grating diffraction theory and Snell’s law according to

![FIG. 1. Measured optical intensity in the \( m=+1 \) diffracted order with the experimental arrangement given in the inset. Sample under test corresponds to No. 7 of Table I, grating period and working wavelength are \( \Lambda=510.2 \) nm and \( \lambda=1.3159 \) μm.](image)
Using Moharam’s formalism without absorption ($k = 2 \times 10^{-4}$, thick line and $k = 0$, thin line, respectively). Bell shape curves account for a Gaussian apparatus response centered at $\theta_0$ with a $\sigma = 0.02^\circ$ standard deviation. Calculations are performed at $\lambda = 1.5577 \, \mu m$, assuming a semi-infinite InP substrate whose real part of the refractive index is $n = 1.553$. Grating period and depth are $\Lambda = 530.1$ and $250$ nm, respectively.

$$\sin(\theta_0 - \Delta \theta) \approx n \left(1 - \frac{d^2}{2n^2\Lambda^2}\right) - \frac{\lambda}{\Lambda}. \tag{1}$$

A first-order expansion yields an estimate of $\Delta \theta$ (Fig. 1),

$$\Delta \theta \approx \frac{\sin \theta_0 - \sin(\theta_0 - \Delta \theta)}{\cos \theta_0} \approx \frac{d^2}{2 \cos \theta_0 n \Lambda L^2}. \tag{2}$$

Applying Eq. (2) to our experimental conditions, i.e., $d = 0.5$ cm, $L = 20$ cm, and with the InP substrate of Ref. 1 at $\lambda = 1.5577 \, \mu m$, we obtain $\Delta \theta \approx 6 \times 10^{-3}$ degrees. In practice, the measured peaks are wider as seen in Fig. 1 for a typical measurement at $\lambda = 1.3159 \, \mu m$ with sample No. 7. The measured peak extends over $\Delta \theta \approx 0.05^\circ$, corresponding to five steps of the motorized rotating sample holder. Accordingly the standard derivation is $\sigma \approx 0.02^\circ$. This value is about three times greater than the $\Delta \theta$-value calculated from Eq. (2). Such a broadening of the response comes from the beam divergence of our illuminating laser, which is of about the same order of magnitude. This $0.02^\circ$ angle uncertainty corresponds to a $3 \times 10^{-4}$ uncertainty on the substrate refractive index.

Because of the novelty of our measurement technique, we had to ensure that the above crude ray analysis agrees well with the rigorous electromagnetic theory. Therefore, we calculated the optical intensity in the $m = +1$ diffracted order using Moharam’s formula $^{12}$ without ($k = 0$) and with ($k = 2 \times 10^{-4}$) absorption. The results are given in Fig. 2 together with their convolution with a Gaussian experimental apparatus response having the standard deviation $\sigma = 0.02^\circ$. Without absorption, the optical intensity reaches zero with an infinite slope exactly at $\theta_0 = 12.521^\circ$. This angle is directly related to the prescribed substrate index $n = 3.1553$, grating period $\Lambda = 530.1$ nm, and wavelength $\lambda = 1.5577 \, \mu m$. Consequently, there is no path for a light ray emerging exactly parallel to the grating surface. The resulting signal accounting for the apparatus response exhibits in that case a maximum noticeably shifted from $\theta_0$. However, with a realistic absorption of $k = 2 \times 10^{-4}$, the optical intensity decreases smoothly without the previous singular point occurring at $\theta_0$. Accounting for a Gaussian apparatus response yields a signal with a nearly Gaussian shape whose maximum occurs at $12.513^\circ$. The systematic error made by assuming that the substrate index corresponds to this $0.008^\circ$-shifted peak maximum is much smaller than the angle accuracy of $0.02^\circ$ quoted above. Consequently, this method appears to be the best tradeoff between accuracy and simplicity.

Gratings were defined on each substrate sample by means of a holographic technique using calibrated fringes obtained with an argon laser. They were further etched in a Plasmalab 80 chamber with SiCl$_4$. Resulting grating profile was therefore nearly square. Calibration procedures either in gas flow and rf power have allowed a perfect control of grating depth that was always kept close to $\approx 100$ nm. Owing to this low value, we could eliminate any secondary effect resulting from deep gratings. Experiments were conducted with two distributed feedback (DFB) semiconductor lasers emitting at 1.5577 and 1.3159 $\mu m$. Both these devices were operated at a $\approx 1$ mW output power that corresponds to the calibrated wavelength given above. The sample temperature was stabilized at 300 K using a thermoelectric cooler, ensuring a negligible sample heating. As is well known, this is required for accurate index measurements.$^{1,2}$

Experimental results are listed in Table I and plotted in Fig. 3. The data of sample No. 1, shown in Table I for comparison, are taken from Ref. 1. This value, in fact, has been measured using the conventional grating coupling technique and belongs to the previously mentioned unintentionally doped MBE grown InP layer on an $N = 3.2 \times 10^{18}$ cm$^{-3}$ doped substrate. The mean accuracy of our refractive index data from the modified grating-coupler method described here is estimated to be $\approx 5 \times 10^{-4}$ when all contributions are considered. The doping level was measured from the Hall effect on all samples. The typical accuracy on this measurement being estimated to be of the order of $\approx 20\%$. For the three unintentionally doped samples No. 1–3, we have as-

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Doping type</th>
<th>Doping level ($\times 10^{18}$ cm$^{-3}$)</th>
<th>$n = 1.3159 , \mu m$</th>
<th>$n = 1.5577 , \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>n.i.d.</td>
<td>$N = 0.0001$</td>
<td>3.2081</td>
<td>3.1722</td>
</tr>
<tr>
<td>2</td>
<td>Fe</td>
<td>$N = 0.001$</td>
<td>3.2052</td>
<td>3.1683</td>
</tr>
<tr>
<td>3</td>
<td>Fe</td>
<td>$N = 0.001$</td>
<td>3.2046</td>
<td>3.1679</td>
</tr>
<tr>
<td>4</td>
<td>n.i.d.</td>
<td>$N = 0.0042$</td>
<td>...</td>
<td>3.1701</td>
</tr>
<tr>
<td>5</td>
<td>n.i.d.</td>
<td>$N = 0.0054$</td>
<td>...</td>
<td>3.1769</td>
</tr>
<tr>
<td>6</td>
<td>n.i.d.</td>
<td>$N = 0.0061$</td>
<td>3.2041</td>
<td>3.1688</td>
</tr>
<tr>
<td>7</td>
<td>...</td>
<td>$N = 0.074$</td>
<td>3.2050</td>
<td>3.1685</td>
</tr>
<tr>
<td>8</td>
<td>Sn</td>
<td>$N = 1.1$</td>
<td>...</td>
<td>3.1624</td>
</tr>
<tr>
<td>9</td>
<td>...</td>
<td>$N = 1.2$</td>
<td>...</td>
<td>3.1622</td>
</tr>
<tr>
<td>10</td>
<td>...</td>
<td>$N = 2.0$</td>
<td>...</td>
<td>3.1585</td>
</tr>
<tr>
<td>11</td>
<td>...</td>
<td>$N = 3.1$</td>
<td>3.1909</td>
<td>3.1530</td>
</tr>
<tr>
<td>12</td>
<td>...</td>
<td>$N = 3.2$</td>
<td>3.1940</td>
<td>3.1553</td>
</tr>
<tr>
<td>13</td>
<td>S</td>
<td>$N = 4.0$</td>
<td>...</td>
<td>3.1430</td>
</tr>
<tr>
<td>14</td>
<td>...</td>
<td>$N = 4.4$</td>
<td>...</td>
<td>3.1461</td>
</tr>
<tr>
<td>15</td>
<td>...</td>
<td>$N = 5.2$</td>
<td>...</td>
<td>3.1455</td>
</tr>
<tr>
<td>16</td>
<td>S</td>
<td>$N = 8.2$</td>
<td>3.1671</td>
<td>3.1251</td>
</tr>
<tr>
<td>17</td>
<td>S</td>
<td>$N = 8.5$</td>
<td>...</td>
<td>3.1268</td>
</tr>
<tr>
<td>18</td>
<td>S</td>
<td>$N = 10$</td>
<td>...</td>
<td>3.1170</td>
</tr>
<tr>
<td>19</td>
<td>S</td>
<td>$N = 12$</td>
<td>3.1638</td>
<td>...</td>
</tr>
<tr>
<td>20</td>
<td>Cd</td>
<td>$P = 1.7$</td>
<td>3.2062</td>
<td>3.1634</td>
</tr>
<tr>
<td>21</td>
<td>Zn</td>
<td>$P = 3.6$</td>
<td>3.2021</td>
<td>3.1616</td>
</tr>
</tbody>
</table>

*Epitaxial layer grown by MBE (see Ref. 1).
FIG. 3. Measured InP refractive index as a function of doping level and type for the two wavelengths used in experiments. Square: \(\lambda=1.3159\ \mu m\), circles: \(\lambda=1.5577\ \mu m\), filled symbols: \(N\) doping, open symbols: \(P\) doping. Dark and gray solid lines are guidelines to the eyes for \(N\) and \(P\) doping, respectively.

Assumed a doping level of \(N=10^{15}\ \text{cm}^{-3}\). It appears from Table I that InP samples having very similar doping levels exhibit the same refractive index values to within a few times \(10^{-3}\). This discrepancy is probably a consequence of substrate manufacturing conditions and/or the nature of dopant atoms and/or different densities of growth-induced defects. One can expect that a more accurate determination of the free-carrier concentration together with a thorough knowledge of the sample crystalline quality would further reduce data dispersion. Nevertheless, the most important conclusion of our study is the large decrease of the \(n\)-value, \(~4.5 \times 10^{-2}\) at \(~1.3\ \mu m\) and \(~5.5 \times 10^{-2}\) at \(~1.5\ \mu m\), when the \(N\)-doping is increased from a low level (non-intentionally doped, \(~10^{15}\ \text{cm}^{-3}\)) up to about \(~10^{19}\ \text{cm}^{-3}\). Also worth indicating is the reduced effect in the case of \(P\) doping.

A simple comparison of our results with those previously published, both experimental5–7 or calculated,8 show a general agreement. The overall tendency for a rapid decrease of \(n\) as soon as doping level exceeds \(10^{18}\ \text{cm}^{-3}\) can be clearly evidenced from Fig. 3. Its origin is mainly the intra-band free carrier absorption also known as the plasma effect.5,6,8 From a quantitative point of view, we can compare our measurement results to calculations. For instance at \(\lambda=1.5577\ \mu m\), the mean measured decreases of \(n\)-values are \(7 \times 10^{-3}\), \(3 \times 10^{-2}\), and \(5.5 \times 10^{-2}\) for \(N=10^{18}\ \text{cm}^{-3}\), \(N=3 \times 10^{18}\ \text{cm}^{-3}\) and \(N=10^{19}\ \text{cm}^{-3}\), respectively. At the same doping levels, the calculations reported in Ref. 8 predict \(7 \times 10^{-3}\), \(3 \times 10^{-2}\), and \(8 \times 10^{-2}\), respectively. Although a slight discrepancy appears at the highest doping level, this very good agreement comforts the model proposed in Ref. 8.

In conclusion, accurate measurements at 1.3159 \(\mu m\) and 1.5577 \(\mu m\) of InP refractive indices have been performed as a function of doping type and level. A new measurement method derived from the grating coupler technique has been applied to 21 samples. This large number of samples covering a wide range of free-carrier concentrations must be of great use to those involved in the design of InP-based photonic devices operating in the 1.3–1.5 \(\mu m\) wavelength range.

This work was supported by France Telecom CNET under Contract No. 95 6B 021. The authors wish to acknowledge the fruitful discussions with E. M. Skouri and J. Arauda. They are also grateful to P. Petit for performing Hall effect measurements on most of the samples studied here.