phys. stat. sol. (a) **202**, No. 4, 590–592 (2005) / **DOI** 10.1002/pssa.200460434

# Terahertz investigation of high quality indium nitride epitaxial layers

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Received 28 May 2004, revised 10 July 2004, accepted 1 September 2004
Published online 1 March 2005

**PACS** 72.30.+q, 76.40.+b, 78.20.Ls, 78.30.Fs

We report on the optical characterization of InN layers in the THz range and magnetic fields up to 13 T. The results are interpreted using the dielectric function formalism, with contributions of cyclotron resonance, phonons, plasmons and helicon wave excitations. We show how THz radiation transmission measurements can provide an optical contactless method of determining the quality (carrier density and momentum scattering rate) in the InN layers.



## 1 Introduction

InN is of great potential interest for the realization of hyperfrequency/terahertz devices since it has been theoretically established that its electron velocity peaks at a higher value than GaAs and GaN, under rather moderate electric fields. Interest in this material has been recently renewed by the discovery that its band gap was more probably around 0.7 eV [1, 2] than close to 1.9 eV, as earlier studies reported [3]. It appears now that this material has a huge potential for optoelectronic devices, where a band gap around 0.7 eV would allow for applications at the telecommunications wavelength of 1.55 µm, but also in hyperfrequency devices, since calculations have predicted a hot electron velocity peak at a much higher value than in GaN and GaAs [4, 5]. In the present work, we investigate transmission and reflectivity of Indium Nitride (InN) in THz range. Transmission measurement at low temperature (2 K) and high magnetic fields (up to 13 T) was interpreted in the formalism of complex Dynamic Dielectric Function (DDF).

## 2 Results

The growth of InN layers is extremely difficult, due to both a low dissociation temperature (around 700 °C) and the lack of a matched substrate. A lot of progress has been made by Molecular Beam Epitaxy [1, 2], but recent advances in Metal organic Vapor Phase Epitaxy (MOVPE) [6] have allowed us to grow mirror-like layers on 2 inches diameter sapphire substrates, with a reproducible mobility of 800 $cm^2$/V.s, the highest value obtained by MOVPE up to date. The growth is realized under nitrogen carrier gas, using Trimethyl Indium (TMIn) and ammonia ($NH_3$) as precursors. We found that the use of a low V/III molar ratio of 5000 is essential for the obtention of high quality material, and the growth pressure is 200 mBar. The growth temperature is 550 °C. The layers were characterized by Atomic Force Microscopy (AFM), and they exhibit a two dimensional growth mode, with a surface constituted of bi-monolayer steps, resulting in a rms roughness of 0.6 nm. Table 1 present characteristics of our samples.

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**Table 1** Characteristics of samples.

| samples | structure |
|---|---|
| 377 | InN(0.732)/GaN(0.063)/sapphire |
| 390 | InN(0.535) doped Si(7.1 × $10^{-2}$ μmol/min)/InN/sapphire |

The measurements were performed using a Bruker 113V FIR Fourier transform spectrometer (1–50 THz) connected via an outcoupling optic to a superconducting 13 T magnet. All measurements were done in the Faraday geometry with unpolarized light, using a bolometer detector mounted close to the sample.

Figure 1 present reflectivity spectra of all samples at ambient temperature and reflectivity for sample 377 at two temperatures $T = 290$ K and $T = 20$ K. It shows the existence of a plasma edge and invariance of reflectivity as a function of temperature.

Obtained transmission data for sample 377 at two values of magnetic field are shown in Fig. 2. At low energy, we observe increase of transmission as function of magnetic field.

## 3 Analysis and discussion

The far infrared transmission was analysed using a complex dynamic dielectric function in the form:

$$\varepsilon(\omega) = \kappa_\infty + \frac{\omega_{\mathrm{TO}}^2(\kappa_0 - \kappa_\infty)(\omega_{\mathrm{TO}}^2 - \omega^2)}{(\omega_{\mathrm{TO}}^2 - \omega^2)^2 + \gamma^2\omega^2} + i\,\frac{\omega_{\mathrm{TO}}^2(\kappa_0 - \kappa_\infty)\,\gamma\omega}{(\omega_{\mathrm{TO}}^2 - \omega^2)^2 + \gamma^2\omega^2} - \frac{\kappa_\infty\omega_p^2}{\omega(\omega \pm \omega_{\mathrm{C}} + i\Gamma)}\,. \tag{1}$$

Here $\kappa_0$ and $\kappa_\infty$ are the static and optical dielectric constants, $\omega_{\mathrm{TO}}$ is the frequency of the transverse optical phonon, $\gamma$ is the phonon damping parameter, $\omega_p$ is the plasma frequency, $\omega_{\mathrm{C}}$ is the cyclotron resonance frequency and $\Gamma$ is the inverse of the electronic scattering time. The second and third term are the real and imaginary parts of the lattice dielectric function, while the fourth corresponds to electronic contributions. The plus/minus sign depends on the sign of the circular polarisation of the incident radiation, giving the responses of the cyclotron resonance inactive (CRI) and cyclotron resonance active (CRA) polarisations, respectively. For a review of this formalism see e.g. [7]. The transmission is then calculated in terms of plane waves

$$\Psi = \mathrm{e}^{i\eta(\omega)\,x}\,, \quad \text{where} \quad \varepsilon(\omega) = |\eta(\omega)|^2\,.$$

The changes in transmission caused by the magnetic field will be given by the last term of Eq. (1), where the magnetic field enters through the cyclotron resonance frequency $\omega_{\mathrm{C}} = eB/m_0m^*$, where $e$ is

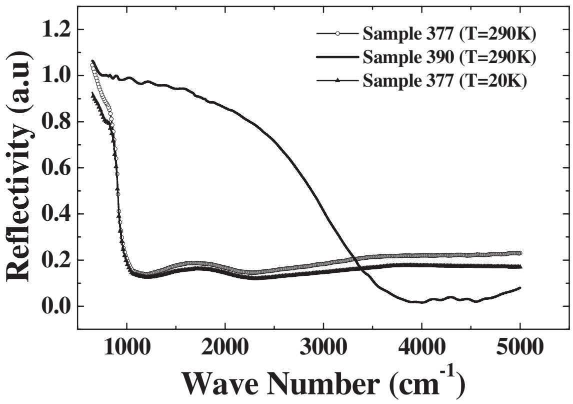


**Fig. 1** Reflectivity measurements performed on all samples at $T = 290$ K and $B = 0$ T.

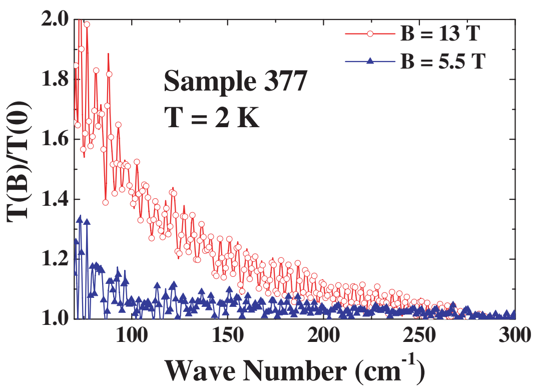


**Fig. 2** (online colour at: www.pss-a.com) THz spectroscopic measurement performed on sample 377 at $T = 2$ K and for different magnetic field values.

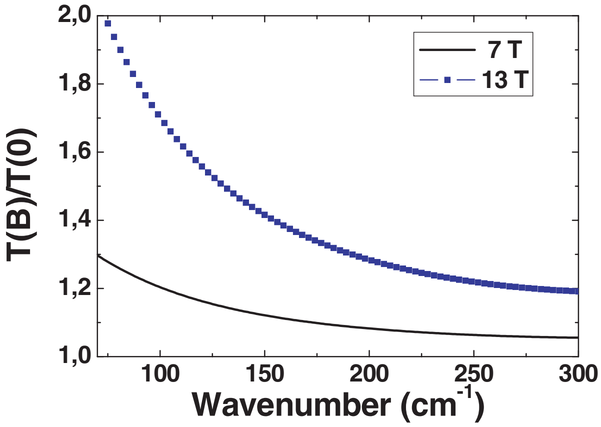


**Fig. 3** (online colour at: www.pss-a.com) Theoretical results of transmission for sample 377 at $T = 2$ K and for two values of magnetic fields. The results were obtained by using DDF formalism.

the electron charge, $B$ is the magnetic field, and $m_0 m^*$ is the electron effective mass. Figure 3 shows simulated changes of transmission with magnetic field, $T(B)/T(0)$ as function of the measured values (Fig. 2). Thelow energy transmission of the sample is seen to increase when a magnetic field is applied; this effect is well reproduced in the simulation. Given the metallic character of the sample (carrier concentration $n \sim 10^{19}$ cm$^{-3}$, plasma frequency $\omega_p \sim 1000$ cm$^{-1}$), it is expected to be opaque to electromagnetic radiation for frequencies $\omega$ such that $\omega_p > \omega > \omega_C$. When a magnetic field is applied, however, we approach the so-called helicon limit:

$$\frac{\omega_p^2}{\omega} \gg \omega_C \gg \omega$$

where CRA radiation may propagate. Such helicon waves are well known from studies of metals as well as strongly doped semiconductors (e.g. [8]). The simulations shown in Fig. 1 were performed with the following sample parameters: $m^* = 0.15$, $\omega_{TO} = 460$ cm$^{-1}$, $\kappa_0 = 15.3$, $\kappa_\infty = 8.4$, $\omega_p = 951$ cm$^{-1}$, $\gamma = 20$ cm$^{-1}$ and $\Gamma = 60$ cm$^{-1}$. The large values of the damping parameters $\gamma$ and $\Gamma$ make it difficult to use the present measurements to determine sample parameters such as the effective mass.

## 4 Conclusion

Results of transport and optical experiments performed in a wide temperature range (2–300 K) show that the InN layers have a metallic character with carrier density between $5 \times 10^{18}$ cm$^{-3}$–$5 \times 10^{19}$ cm$^{-3}$ that stays constant even at lowest temperatures and highest magnetic fields. In the THz experiments, we observe an increasing of transmission as function of magnetic field. This effect is well reproduced in the simulation using complex dynamic dielectric function. We have demonstrated the importance of helicon waves in InN.

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