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Magneto-optical studies of shallow donors in MOCVD grown GaN layers in FIR

A. M. Witowski[12], M. L. Sadowski[12], K. Paku ,a[1], B. Suchanek[1], R. Stepniewski[1], Jacek M. Baranowski [1], M. Potemski[2], G. Martinez[2] and P. Wyder[2]
[1]*Institute of Experimental Physics, Warsaw University,*
[2]*Grenoble High Magnetic Field Laboratory MPI CNRS,*

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Far infrared magnetooptical investigations of shallow donors in epitaxial MOCVD GaN layers show two types of shallow donors. In relaxed layers, a donor with an ionization energy of 35 meV was found. In strained, undoped and Si doped samples, a donor with ionization energy 32.5 meV was observed. From the p state splitting in magnetic field, the cyclotron effective mass for conduction electrons was found to be $m^*=0.222\ m_0$.

1 Introduction

Numerous attempts at investigating the shallow donor states in GaN have been made [1] [2] [3], but there is no clear conclusion about the properties and origin of such centers. The subject therefore still remains of interest. We try to investigate the problem by means of far infrared (FIR) magnetospectroscopy. The investigated samples were in the form of epitaxial MOCVD gallium nitride layers grown on an oriented (0001) sapphire substrate, with c-axis perpendicular to the sample substrate. The atmospheric pressure MOCVD technique starting from TMG, NH_3 and SiH_4 was used. The method used is described in detail elsewhere [4]. Using different substrate and buffer layer preparation methods two types of material were grown: relaxed (SAP) and strained (MAR). The strain in the layer is determined from the donor bound exciton spectra [5]. Some of the MAR type samples were intentionally doped with silicon. The thickness of the layers varied from 2 μm to 8 μm. Prior to the optical measurements, the samples where characterized using classical transport. The temperature dependence of electron concentration and mobility is presented in Figure 1. As one can see, we are able to obtain a free carrier concentration one order of magnitude lower in MAR samples than in SAP samples. The lowest investigated concentration (sample MAR51) is about $2x10^{16}$ cm^{-3} in an 8 μm layer. We have therefore been able to dope such layers with silicon donors at the level of 10^{17} cm^{-3} (see Figure 1).

We chose the following samples for magnetooptical studies:

- SAP119 (2 μm thick) with $n_{300K} = 2x10^{17}$ cm^{-3} , mobility $\mu_{300K} = 490$ cm^2/Vs;
- MAR51 (8 μm thick) with $n_{300K} = 2x10^{16}$ cm^{-3} , mobility $\mu_{300K} = 540$ cm^2/Vs;
- MAR70 (Si doped, 6 μm thick) with $n_{300K} = 2x10^{17}$ cm^{-3} ,mobility $\mu_{300K} = 740$ cm^2/Vs.

2 Experimental results

The FIR magnetophotoconductivity and magnetotransmission were measured using a Bruker FTIR 113V Fourier transform spectrometer at magnetic fields up to 13T and temperatures of 4.3K and 2K. In the SAP sample a magnetic field dependent structure was observed at about 213 cm^{-1} at zero field (see Figure 2). Other features are due to the optical properties of the sapphire and GaN, multilayer structure, and can be interpreted without the existence of shallow states. The magnetic field splitting and the energies of the lines (Figure 2) can be found after a careful recalculation of the experimental data. These suggest that it is a shallow donor, but with a quite large chemical shift (20 cm^{-1} = 2.5 meV). The estimated ionization energy is about 35 meV, in agreement with previously reported data [1]. It is worth noting that the high field slope is equal to the cyclotron resonance slope with $m^* = 0.222\ m_0$.

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A different and clearer photocurrent response can be observed for MAR samples (Figure 3). There, a sharp line is observed at 187 cm^{-1}. It splits in a magnetic field into three components, whose energy positions vs. magnetic field show a strong non-linear dependence. We assign them to inter-donor transitions from 1s to split $2p_{\pm}$ states.

The positions of the observed lines can be described using a simple model of a hydrogen-like center in a magnetic field. The splitting of $2p_{-1}$ $2p_{+1}$ states is directly related to the cyclotron energy, so one can establish the effective mass to be 0.222 m_0, which agrees very well with previously reported data [2] [3]. The high quality of the data (sharp lines) reveals a strong diamagnetic shift for all transitions, which has to be included in the description. The same behavior was measured for samples intentionally doped with silicon. The conclusion is therefore that the native donor in this group of samples has the same chemical shift (less than -0.5 meV) as a silicon donor (ionization energy of about 260 cm^{-1} = 32.5 meV).

The structure observed in the relaxed sample is probably related to a donor with a different physical origin, with a much larger chemical shift (about 2.5 meV).

3 Theoretical description

To describe the magnetic field dependence of the transitions we used a model developed by Wheeler and Dimmock [6] for excitons in CdS, which takes into account both the diamagnetic shift and a correction due to the uniaxial symmetry. In this case the energies of the levels are given by the following formulas:

$$E_{1s} = E_{cc} + E_S\left(1+\tfrac{1}{3}\alpha+\tfrac{3}{20}\alpha^2\right)+\sigma\cdot B^2$$

$$E_{2p\pm} = E_P\left(1+\tfrac{1}{5}\alpha+\tfrac{9}{140}\alpha^2\right)+12\sigma\cdot B^2 \pm \frac{1}{\mu}\mu_B\cdot B$$

where

$E_S = \dfrac{R_H\,\mu}{\varepsilon_x\varepsilon_z}$, $E_P = E_S/4$, E_{cc} – chemical shift,

$\mu = m^*/m_0$, $\alpha = 1-\dfrac{\varepsilon_x}{\varepsilon_z}$, $\sigma = 10^{-6}\dfrac{\varepsilon_x\varepsilon_z}{\mu^3}$ (in cm^{-1}/T).

We assume that the conduction band is spherically symmetric, and therefore the electron effective mass is a scalar. We allow for differences between longitudinal (ε_z) and perpendicular (ε_x) dielectric constants. For calculations we have taken values of ε_z and ε_x from reflectivity data given in [7]. With a small adjustment of the values of ε (within experimental error) we obtained an excellent description of the experimental points (Figure 2 and Figure 3).

4 Conclusions

The following conclusions can be drawn:

- The shallow donors in strained and relaxed GaN layers grown by MOCVD on sapphire have different origins, leading to different chemical shifts;
- The splitting of 2p states at higher fields is equal to the cyclotron energy, which allows to determine the effective mass as $m^* = 0.222\ m_0$.
- The energy of shallow donor states is strongly affected by the diamagnetic shift.

Some speculation can be made in this point. In strained, undoped samples the donors are silicon impurities introduced on the level of 10^{15} cm^{-3} during the growth procedure. In the case of unstrained samples another impurity is responsible for the creation of the donor centers. Due to the polarity of the layer [5] one of the possibilities is oxygen impurities.

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FIGURES

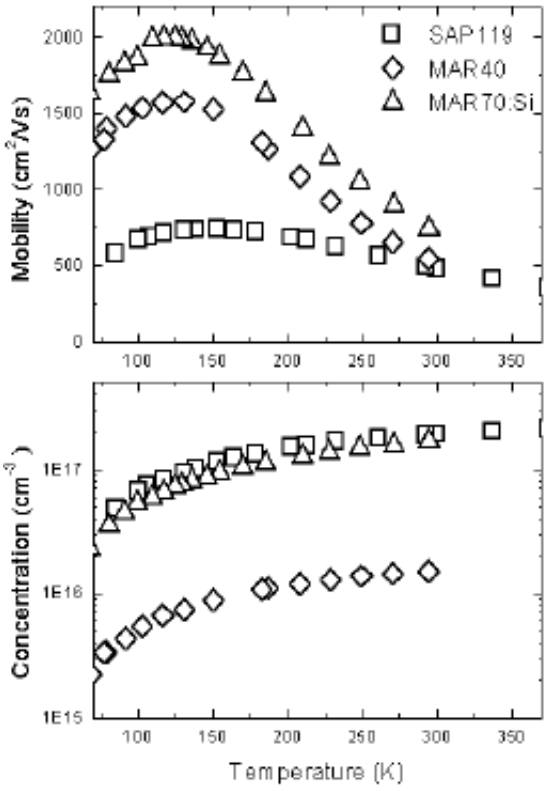

Figure 1. Temperature dependence of concentration and mobility for GaN epilayers grown on sapphire.

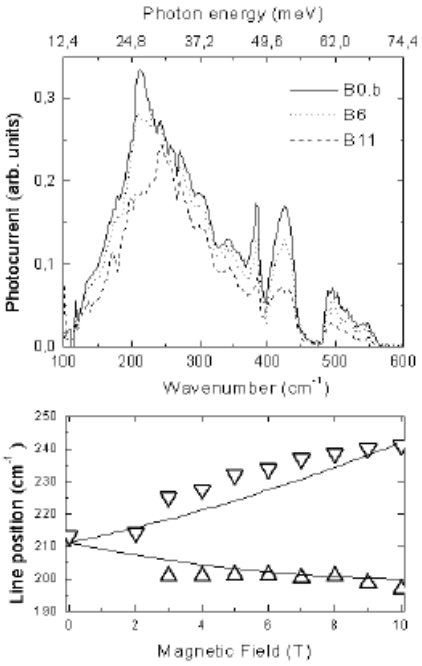

Figure 2. (top) Photocurrent for SAP 119 at different magnetic fields. (bottom) Position of PC lines vs. magnetic field. Lines represent theoretical calculations.

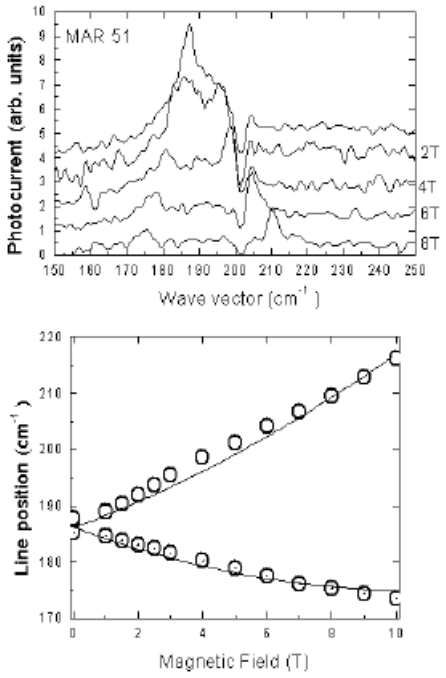

Figure 3. (top) Photocurrent for MAR 51 at different magnetic fields. (bottom) Position of PC lines vs. magnetic field. Lines represent theoretical calculations.

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