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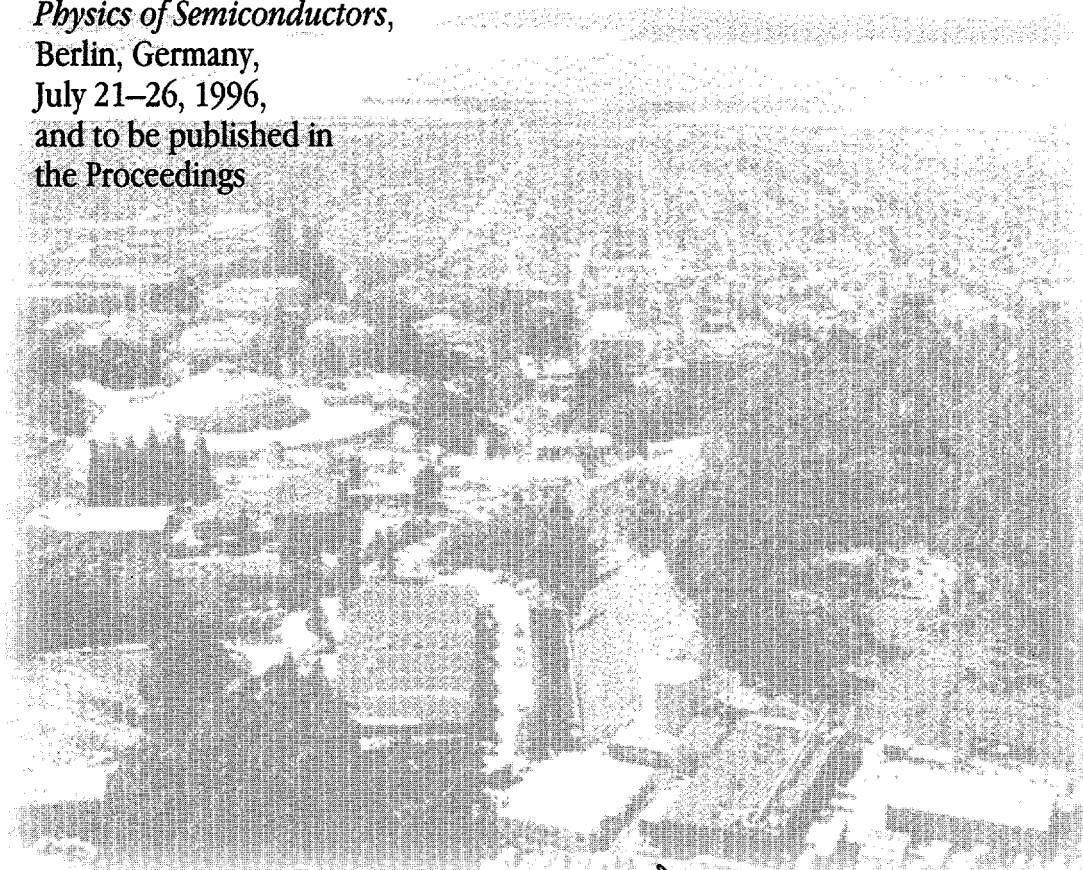
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Oxygen Doped Gallium Nitride**

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# STRONGLY LOCALIZED DONOR LEVEL IN OXYGEN DOPED GALLIUM NITRIDE

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A classification in terms of the localization of donor defects in GaN is performed by Raman spectroscopy under large hydrostatic pressure. We observe a significant decrease of the free carrier concentration in highly O doped GaN epitaxial films at a hydrostatic pressure of 22 GPa. This indicates the presence of a strongly localized donor defect at large pressure. Monitoring the phonon plasmon coupled mode we find similarities with results on highly n-type bulk crystals. We refine the model of localized defects in GaN and transfer it to the AlGaN system.

## 1 Introduction

The problem of p and n-type doping in the alloys of AlGaN and InGaN are closely related to an identification of the origin of high background n-type conductivity in GaN as observed by many different growth processes. Both, native defects and unintentional incorporation of donor species<sup>1</sup> are typically considered. Namely the N vacancy and the Ga interstitial should act as strongly localized donor defects<sup>3</sup>. Oxygen on the other hand is known to be a highly efficient donor in GaN<sup>1</sup> and its proximity to N suggests it to be an effective mass type defect. Here we present a study of the nature of the dominant donors in highly O doped epitaxial films and small GaN bulk single crystals.

## 2 Experimental

Epitaxial GaN films at a thickness of 5  $\mu\text{m}$  were grown on (0001) sapphire by hydride vapor phase epitaxy. Through small amounts of water vapor a doping with O was achieved. Free electron densities in the low  $10^{19} \text{ cm}^{-3}$  were found. Incorporation of O at this concentration was confirmed by Secondary Ion Mass Spectroscopy. Bulk GaN crystals were grown by high pressure synthesis. Small pieces of 200  $\mu\text{m}$  in diameter have been selected for this study. The crystals are typically characterized by a free electron concentration in the mid  $10^{19} \text{ cm}^{-3}$

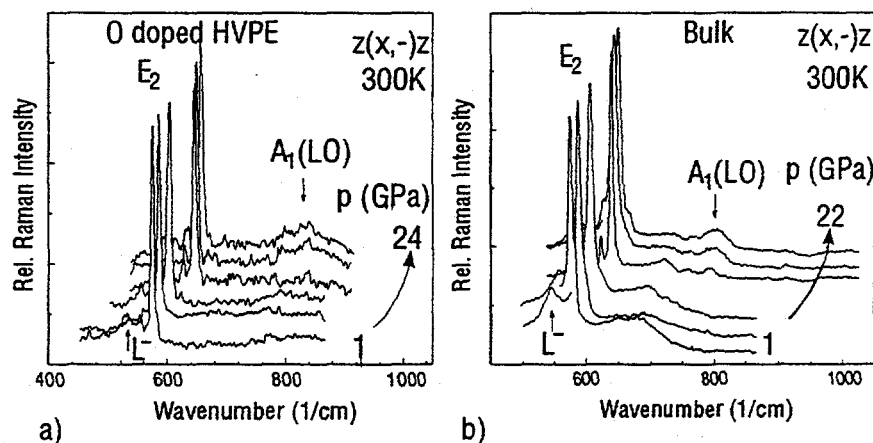


Figure 1: Raman spectra at various hydrostatic pressures for. a) O doped HVPE GaN film: The  $A_1(\text{LO})$  mode appears at 22 GPa for the first time. b) The same mode appears first at 19 GPa and its intensity increases at 20 and 22 GPa. Spectra are normalized to the height of  $E_2$  and offset for clarity.

and mobilities of  $400 \text{ cm}^2/\text{Vs}$ . Hydrostatic pressure was applied by means of a Mao-Bell-type diamond anvil cell using a methanol-ethanol mixture as a pressure medium. The pressure was determined by ruby fluorescence and the pressure dependence of the GaN  $E_2$  phonon mode: Nonresonant Raman spectroscopy in  $z(x,-)z$  forward scattering geometry was performed using 100 mW of the 476.5 nm line of an Ar ion laser. All data were taken at room temperature.

### 2.1 Oxygen doped samples

Raman spectra of the highly O doped films as a function of hydrostatic pressure is presented in Fig. 1 a). At all pressure values the spectra are dominated by the  $E_2(\text{high})$  mode ( $567 \text{ cm}^{-1}$  at ambient pressure). This mode does not couple to the free electrons and is used as an internal intensity reference for the spectra. With increasing pressure this mode shifts towards higher energy at a rate of  $3.75 \text{ cm}^{-1}/\text{GPa}$  up to 24 GPa. For the lowest pressure of 1.4 GPa no contribution in the expected range of the  $A_1(\text{LO})$  mode is observed. Due to the high carrier concentration and the limited mobility of the electrons this mode is overdamped and vanishes in the background signal. This can be

seen from a simulation of the lineshape in an oscillator model for the dielectric function. On the low energy side the phonon plasmon coupled mode  $L^-$  is observed close to the value expected for the  $A_1(\text{TO})$ <sup>2</sup>. There is no change on the high energy  $A_1(\text{LO})$  side until a pressure of 22 GPa. At this pressure, however, a strong contribution occurs centered at  $835\text{ cm}^{-1}$ . There is very little further change at the highest measured pressure of 24 GPa.

## 2.2 Bulk crystals with unknown donor

Raman data for a series of pressure values for the bulk crystals are given in Fig. 1 b). The occurrence of the  $A_1(\text{LO})$  mode in this material has been reported before<sup>4</sup>. Here however, more details are obtained on the very onset at lower pressure. Both,  $E_2$  and  $L^-$  behave similar to the ones in the oxygen doped material. The earliest observation of the  $A_1(\text{LO})$  mode is at 19 GPa. At 20 GPa the mode has increased in area by 3.5 and by another 1.4 at 22 GPa.

## 3 Discussion

The occurrence of the  $A_1(\text{LO})$  mode is interpreted as the result of a decreased concentration of the free carriers<sup>5,4</sup>. In bulk GaN crystals such an effect has been explained by a strongly localized donor defect emerging from the conduction band at large hydrostatic pressure. From Fig. 1 b) we find that there actually is a gradual onset of this mode with pressure which indicates a continuously increasing binding energy for larger pressure. A localization energy of 126 meV at 27 GPa was found<sup>4</sup>. This is consistent with the assumption of a strongly localized donor defect exhibiting a much smaller pressure coefficient than the bandgap. Such a level can be caused by several defects: a typically strongly localized native defect or an otherwise delocalized hydrogenic defect undergoing a pressure induced transformation into a localized one.

Large discrepancies in reported electron concentrations and detectable impurity concentrations support the first model. N vacancies or Ga interstitials should act as a donor and in a model for the pressure behavior of such a donor we find its resonant level  $\sim 400\text{ meV}$  above the conduction band minimum ( $p \sim 0$ ). Carriers would autoionize from the defect to the edge of the conduction band. They would bind in the coulomb potential of the fixed positive charge they left behind and again form a hydrogenic defect. However, the center of this potential corresponds to the high lying resonant state and acts as a repulsive potential barrier. In the consequence we find a positive central cell correction to the binding energies of perfect effective mass type donors in a dilute system.

In the other model commonly assumed quasi hydrogenic donor impurities such as Si or O would induce a localized gap state under hydrostatic pressure. We recently showed that Si doped GaN films do not exhibit a carrier freeze out up to the largest applied pressure of 30 GPa<sup>6</sup>.

Altogether we find that the dominant donor in O doped HVPE GaN films and small bulk GaN crystals from pressure synthesis show a similar pressure behavior inducing a localized gap state in the range of 17 - 22 GPa.

From the established similarities of application of hydrostatic pressure and the alloying with Al in the AlGaAs system a similar effect is expected for the nitrides. Assuming a linear dependence of the bandgap energy in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  with  $x$  and the theoretical pressure dependence of the bandgap,<sup>7</sup> a transition pressure of 19 GPa would correspond to  $x = 0.2$ . This indicates that this localized defect can be the reason for doping problems in  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  for  $x \geq 0.2$ . Si on the other hand should be a good donor up to at least  $x = 0.3$ .

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