

p-Type Doping of Cubic GaN by Carbon

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(Received June 21, 2001; accepted July 12, 2001)

Subject classification: 68.55.Ln; 71.55.Eq; 78.55.Cr; 73.61.Ey; 81.15.Hi; S7.14

Successful p-type doping of cubic GaN epilayers by carbon using an e-beam evaporation source is reported. At room temperature Hall-effect measurements of the C-doped cubic GaN epilayer gave hole concentrations and hole mobilities as high as $6 \times 10^{17} \text{ cm}^{-3}$ and $200 \text{ cm}^2/\text{Vs}$, respectively. The thermal activation energy of the C-acceptor is $(215 \pm 10) \text{ meV}$. Low temperature photoluminescence spectra show a new line appearing at 3.08 eV. The emission energy increases with increasing e-beam evaporation power. This 3.08 eV line is attributed to a C related donor acceptor (D^0A^0) transition.

Introduction For the development of electronic and optoelectronic devices based on group III-nitrides controlled p-type doping is crucial. Up to now Mg has been the commonly used p-type dopant in the molecular beam epitaxial (MBE) growth of both hexagonal and cubic phase GaN and is the only acceptor in GaN that reproducibly generates useful p conduction. However, magnesium has several disadvantages which still limit the usually reported doping efficiency of Mg in GaN to maximum hole concentrations in the upper 10^{17} cm^{-3} . This is mainly ascribed to large acceptor ionization energy and compensation effects [1]. MBE growth further showed that Mg is very volatile [2], requires low substrate temperatures and N-rich growth conditions. Both conditions are disadvantageous for high quality epilayers, especially for the cubic phase, where N-rich conditions deteriorate the phase purity [3].

Among possible alternative acceptor dopants especially carbon has received a considerable interest due to its similarity to nitrogen in atomic radius and electronegativity. Abernathy et al. [4] reported on p-type doping of cubic GaN by carbon grown by metal organic molecular beam epitaxy (MOMBE) on GaAs substrates. However, due to the use of CCl_4 a pronounced reduction in growth rate prohibited the incorporation of higher C concentrations and the maximum hole concentration reached was $3 \times 10^{17} \text{ cm}^{-3}$.

In hexagonal GaN no successful p-type doping by C has been reported up to now. However, high-quality semi-insulating C-doped GaN layers with resistivities greater than $10^6 \Omega\text{cm}$ have been grown using methane gas as a carbon source in ammonia MBE [5] and rf-plasma-assisted MBE [6]. Carbon doping by using a resistively heated graphite filament in rf-plasma-assisted MBE lead to a reduction of the background electron concentration by one order of magnitude but the material remained n-type [7]. In this study the applicability of C as an alternative acceptor for p-type doping in cubic phase GaN is demonstrated. Hall-effect measurements and photoluminescence spectroscopy have been used to characterize the electrical and optical properties.

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Experimental Cubic GaN (c-GaN) was grown by rf-plasma-assisted molecular beam epitaxy (MBE) on semi-insulating GaAs (001) substrates [3]. C-doping of c-GaN was achieved by e-beam evaporation of a graphite rod through adjusting the e-beam power between 0 and 400 W. The C-flux was externally calibrated through the growth of C-doped GaAs epilayers assuming the same sticking coefficient for both GaAs and c-GaN and measuring the hole concentration and hole mobility by Hall-effect measurements at room temperature. The knowledge of both mobility and concentration allowed to estimate the compensation and acceptor concentration [8, 9]. From results of GaAs:C, it followed that a maximum C-concentration of about 10^{20} cm^{-3} should be achievable in c-GaN. Secondary ion mass spectroscopy (SIMS) measurements of a C-doped cubic GaN sample, where C was evaporated with the maximum e-beam evaporation power of 400 W indeed showed a C incorporation of $2 \times 10^{20} \text{ cm}^{-3}$.

Hall-effect measurements were performed using square shaped samples between 77 and 420 K at a magnetic field of 0.8 T and with the samples in the dark. Low temperature photoluminescence (PL) measurements were performed in a He bath cryostat at 2 K. The luminescence was excited by a cw HeCd UV laser with a power of 3 mW and measured in a standard PL system [10].

Result and Discussion Figure 1 shows the room temperature hole concentration as a function of the e-beam evaporation power of C-doped cubic GaN epilayers. The hole concentration increases up to a maximum value of $6 \times 10^{17} \text{ cm}^{-3}$ at about 150 W. This value is one order of magnitude higher than the value measured by Mg-doping of cubic GaN [11] and demonstrates the ability of C for p-type doping of cubic GaN. In addition, the room temperature hole mobility at the maximum hole concentration is $200 \text{ cm}^2/\text{Vs}$. Above 200 W, however, a clear reduction of the free hole concentration is seen again. This indicates that at higher C concentrations additional compensating centres are introduced into the samples.

The temperature dependence of the hole concentration of a C-doped cubic GaN epilayer between room temperature and 410 K is depicted in Fig. 2. From a fit of the data to Eq. (7.30) of Ref. [12] a thermal activation energy of $E_C = (215 \pm 10) \text{ meV}$ for the C acceptor and an acceptor concentration of $N_A = 9 \times 10^{17} \text{ cm}^{-3}$ are determined. The acceptor concentration is in good agreement with the value of the C concentration estimated via the C-flux calibration of the GaAs reference samples

($1 \times 10^{18} \text{ cm}^{-3}$).

Figure 3 shows PL spectra of different C-doped cubic GaN epilayers

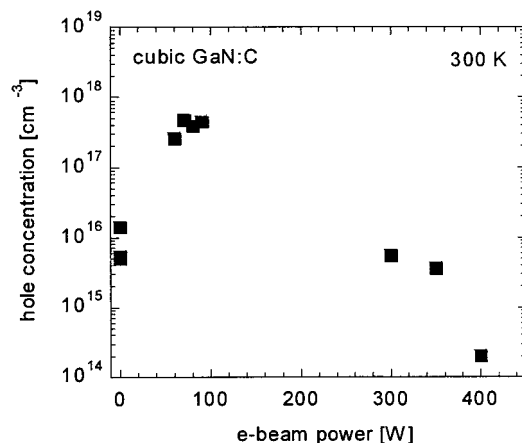


Fig. 1. Hole concentration versus power of the e-beam in cubic GaN measured at room temperature by Hall effect. Carbon was evaporate by an e-beam from a graphite rod

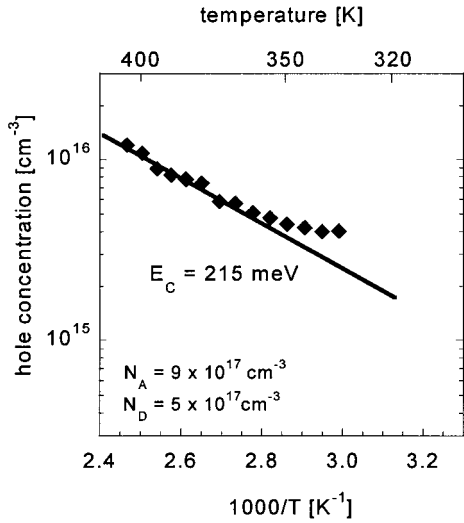
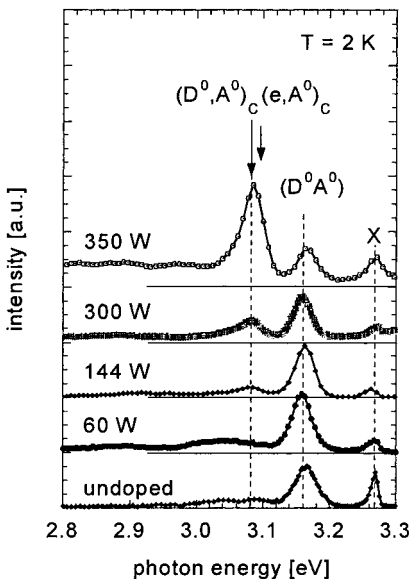


Fig. 2. Hole concentration of a C-doped cubic GaN/GaAs (001) epilayer as a function of $1/T$. The C concentration estimated from GaAs reference samples is about $1 \times 10^{18} \text{ cm}^{-3}$

measured at 2 K. A new C-related PL band at 3.08 eV ($(D^0, A^0)_C$) appears with increasing e-beam evaporation power beside the well-known lines of the nominally undoped c-GaN (X and (D^0, A^0) at 3.27 and 3.16 eV, respectively [10]). Detailed line shape analysis applying a fit procedure using two Gaussian curves and temperature dependent measurements of the 3.08 eV band demonstrate that this band is due to a donor-acceptor ($(D^0, A^0)_C$) recombination, which transforms into a band-acceptor ($(e, A^0)_C$) above 100 K [13]. The involved donor has the same ionisation energy (25 meV) as the one observed in undoped samples [10]. From the spectral energy and the knowledge of the energy gap of c-GaN the optical binding energy of the C acceptor is estimated to be $E_C = 0.215 \text{ eV}$.

Based on effective-mass-theory (EMT) the acceptor binding energy can be determined by

$$E_A = \frac{13.58 \text{ eV}}{\varepsilon(0)^2} m_{hh} \gamma, \tag{1}$$



where $\varepsilon(0)$ is the static dielectric constant, m_{hh} is the heavy hole mass and γ is a correction factor which depends on the ratio of the light hole to heavy hole mass [14, 15]. Using light hole and heavy hole masses of $0.18m_0$ and $0.75m_0$ for cubic GaN, the correction factor γ is 0.6 [14]. In EMT typically $\varepsilon(0)$ is used. However, as pointed out by Orton [16] this should not hold for GaN, where the acceptor binding

Fig. 3. The low-temperature (2 K) near band-edge photoluminescence of different carbon-doped cubic GaN epilayers. The C related transitions are indicated by arrows

energies are comparable or even larger than the optical phonon frequencies. In cubic GaN LO and TO phonon frequencies are 92 and 67 meV, respectively [17]. In this case it should be more appropriate to use the high frequency dielectric constant $\epsilon(\infty)$. Applying $\epsilon(\infty) = 5.35$ we obtain an acceptor binding energy $E_A = 0.213$ eV which is in excellent agreement with our experimental results and demonstrates that C indeed introduces a shallow acceptor in c-GaN.

In other cubic III–V compounds like GaAs, InP and GaP, carbon is the acceptor with the smallest central cell correction and the binding energy is usually close to Mg and increases in the sequence C, Mg, Zn and Cd. The same sequence is verified now also in cubic GaN since the binding energy of C is about 15 meV lower than that observed for the Mg acceptor in c-GaN [18]. In addition, as expected due to the higher crystal symmetry, the binding energy of the C acceptor in the cubic phase is lower than the activation energy of C measured in hexagonal GaN (230 meV) [15].

Conclusions P-type doping of cubic GaN epilayers by carbon has successfully been performed by rf-plasma-assisted MBE using an e-beam evaporation source. At room temperature a maximum hole concentration of $6 \times 10^{17} \text{ cm}^{-3}$ with a mobility of $200 \text{ cm}^2/\text{Vs}$ is measured by Hall-effect measurements. A new photoluminescence line at 3.08 eV appeared at 2 K with increasing e-beam power. This line is attributed to a donor acceptor transition, which involves the shallow C_N acceptor. The thermal and optical binding energies of the C acceptor are estimated to be both 0.215 eV, respectively. Our experiments unambiguously demonstrate that C introduces a shallow acceptor in cubic GaN and that the binding energy of C is 15 meV lower than that observed for the Mg acceptor in cubic GaN.

Acknowledgements The authors gratefully acknowledge SIMS measurements by W. Kriegseis, W. Burkhart and B. K. Meyer and financial support by Deutsche Forschungsgemeinschaft (DFG) under project number As 107/1-3.

References

- [1] U. KAUFMANN, P. SCHLOTTER, H. OBLOH, K. KÖHLER, and M. MAIER, *Phys. Rev. B* **62**, 10867 (2000).
- [2] S. GUHA, N. A. BOJARCZUK, and F. CARDONE, *Appl. Phys. Lett.* **71**, 1685 (1997).
- [3] D. SCHIKORA, M. HANKELN, D. J. AS, K. LISCHKA, T. LITZ, A. WAAG, T. BUHROW, and F. HENNERBERGER, *Phys. Rev. B* **54**, R8381 (1996).
- [4] C. R. ABERNATHY, J. D. MACKENZIE, S. J. PEARTON, and W. S. HOBSON, *Appl. Phys. Lett.* **66**, 1969 (1995).
- [5] J. B. WEBB, H. TANG, S. ROLFE, and J. A. BARDWELL, *Appl. Phys. Lett.* **75**, 953 (1999).
- [6] S. SHIMIZU and S. SONODA, *Proc. Internat. Workshop Nitride Semiconductors, IPAP Conf. Ser.* **1**, 740 (2001).
- [7] U. BIRKLE, M. FEHRER, V. KIRCHNER, S. EINFELDT, D. HOMMEL, S. STRAUF, P. MICHLER, and J. GUTOWSKI, *MRS Internet J. Nitride Semicond. Res.* **4S1**, G5.6 (1999).
- [8] D. C. LOOK, in: *Electrical Characterization of GaAs Materials and Devices*, Wiley, Chichester 1989 (p. 60).
- [9] W. SONGPRAKOB, R. ZALLEN, W. K. LIU, and K. L. BACHER, *Phys. Rev. B* **62**, 4501 (2000).
- [10] D. J. AS, F. SCHMILGUS, C. WANG, B. SCHÖTTKER, D. SCHIKORA, and K. LISCHKA, *Appl. Phys. Lett.* **70**, 1311 (1997).
- [11] D. J. AS and K. LISCHKA, *phys. stat. sol. (a)* **176**, 475 (1999).
- [12] H. MORKOÇ, in: *Nitride Semiconductors and Devices*, Springer-Verlag, Berlin 1999 (p. 224).

- [13] D. J. AS and K. KÖHLER, *J. Phys.: Condens. Matter* **13**, 8923 (2001).
- [14] B. L. GELMONT and M. I. DYAKONOV, *Sov. Phys. Semicond.* **5**, 1905 (1972).
- [15] S. FISCHER, C. WETZEL, E. E. HALLER, and B. K. MEYER, *Appl. Phys. Lett.* **67**, 1298 (1995).
- [16] J. W. ORTON, *Semicond. Sci. Technol.* **10**, 101 (1995).
- [17] H. SIEGLE, L. ECKEY, A. HOFFMANN, C. THOMSEN, B. K. MEYER, D. SCHIKORA, and K. LISCHKA, *Solid State Commun.* **96**, 943 (1995).
- [18] D. J. AS, T. SIMONSMIEIER, B. SCHÖTTKER, T. FREY, D. SCHIKORA, W. KRIEGSEIS, W. BURKHART, and B. K. MEYER, *Appl. Phys. Lett.* **73**, 1835 (1998).

