Electronic structure of the 0.88-eV luminescence center in electron-irradiated gallium nitride

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(Received 30 November 1998; revised manuscript received 25 February 1999)

Photoluminescence (PL) spectroscopy is employed to determine the nature of a near-infrared PL emission with a no-phonon line at ~ 0.88 eV, commonly present in electron-irradiated GaN. This PL emission is suggested to originate from an internal transition between a moderately shallow excited state (with an ionization energy ~ 21 meV) and the deep ground state (with an ionization energy ~ 900 meV) of a deep defect. The existence of a higher-lying second excited state related to the 0.88-eV PL center is also shown from temperature-dependent studies. A different electronic character of the wave functions related to the first and second excited states has been revealed by PL polarization measurements. Since the PL emission has been observed with comparable intensity in all electron-irradiated GaN samples independent of doping on the starting material, it is proposed that either native defects, or common residual contaminants or their complexes are involved. The substitutional O_N donor (or related complex) is considered as the most probable candidate, based on the observed striking similarity in the local vibrational properties between the 0.88-eV PL centers and the substitutional O_P donor in GaP. [S0163-1829(99)13027-3]

I. INTRODUCTION

Group-III nitrides are currently among the most intensively studied semiconductor materials, in view of the recent realization of light-emitting devices, and are also a promising potential for a variety of other device applications. Unlike most other semiconductors, where the achievement of superior material quality with well-controlled defect properties has been the first necessary step towards subsequent device applications, the successful operation of nitride-based light-emitting diodes (LED) has been demonstrated with a material containing a very high defect density. This demonstrates the high potential of III nitrides for applications in light-emitting devices. A full exploitation and optimization of such devices, however, essentially rely on a better understanding and control of material properties. Optical and electrical properties of nitrides are strongly influenced by impurities and native defects. The nature of these defects has been a subject of intense experimental¹⁻³ and theoretical⁴⁻⁶ investigations. However, little information about the defect identity has been obtained so far in the majority of cases, due to a lack of direct experimental evidence from microscopically informative studies, such as electron paramagnetic resonance or local vibrational spectroscopy. One of the exceptions is a photoluminescence (PL) center responsible for the broad PL band with a maximum position of PL intensity at around 0.93 eV, detected in electron-irradiated GaN. The observation of the resolved hyperfine-interaction structure from the optically detected magnetic resonance (ODMR) signal re-

lated to this PL indicates the participation in the recombination process of a complex defect involving an interstitial Ga_i^{2+} atom.⁷

The other promising case in the sense of a possible defect identification seems to be a near-infrared (NIR) PL band with a no-phonon line at ~ 0.88 eV accompanied by a rich phonon-assisted subband, also mainly observed in GaN after electron irradiation.⁸ Based on the unique and striking similarity between the local phonon modes of the 0.88-eV PL in GaN with the major local phonon modes of the substitutional oxygen donor O_P in GaP, we have suggested⁹ that the substitutional oxygen donor O_N can be involved in the 0.88-eV PL in GaN. In the present paper we continue these studies in substantially more detail and also add experimental findings, with the emphasis on the electronic structure of the corresponding PL center. We shall show that the 0.88-eV PL emission is caused by an internal transition between a relatively shallow excited state (with an ionization energy ~ 21 meV) and the deep ground state (with an ionization energy ~ 900 meV) of the deep center. This follows from temperature-dependent PL measurements and the observed dependence of the PL transition on the residual strain in GaN epilayers. A complicated structure of excited states for the defect is revealed from temperature-dependent PL and polarization studies.

II. EXPERIMENTAL DETAILS

The most common types of wurtzite GaN material, i.e., strained heteroepitaxial thin layers grown on 6H SiC or Al_2O_3 substrates and thick or bulklike layers, were studied in

this work. They were grown either by the metal-organic chemical vapor deposition (MOCVD) technique (1–2- μm -thick heteroepitaxial layers), or by hydride-phase vapor epitaxy (HVPE) ($\approx 200\text{-}\mu\text{m}$ -thick samples) on (0001) 6H SiC or sapphire substrates at a temperature of about 1050 °C. The conductivity of the layers varies over a wide range from highly n type with $n > 10^{18} \text{ cm}^{-3}$ (unintentionally doped layers), to compensated and p -type with $p \sim 10^{15} - 10^{17} \text{ cm}^{-3}$ (Zn- or Mg-doped GaN). Electron irradiation was performed at room temperature by 2.5-MeV electrons from a Van de Graaff accelerator to a dose of up to $4 \times 10^{18} \text{ cm}^{-2}$. Since the expected penetration range for the 2.5-MeV electrons in GaN is about a few millimeters, electron-induced damage can be regarded to be uniformly produced through the GaN films. During irradiation the samples were mounted on a water-cooled holder to avoid any possible heating.

The PL measurements were done using an Oxford Instruments SM4000 cryomagnetic system allowing measurements in the range from 1.8 K up to 300 K. PL was excited by the 351-nm line of an Ar^+ ion. The PL emissions were dispersed using a 0.8-m SPEX double-grating monochromator and detected using a conventional lock-in technique by a liquid-nitrogen-cooled North Coast Ge detector. The spectra were not corrected for the spectral response of the detection system. The reflectance measurements were performed with a single-beam low-temperature reflectometer consisting of a Xe arc lamp and a Cary 14 monochromator. During PL polarization measurements the orthogonal scheme of the PL detection was used with the direction of the excitation light coinciding with the c axis of GaN (perpendicular to the growth plane). The PL polarization was measured with respect to the c axis using a Glan-Thompson prism.

III. EXPERIMENTAL RESULTS

Typical PL spectra of the 0.88-eV PL emission, which are observed in all investigated GaN samples, are shown in Fig. 1(a). The spectra contain a relatively narrow no-phonon (NP) line at $\sim 0.88 \text{ eV}$ at low temperatures followed by a number of much broader lines corresponding to phonon-assisted transitions. A comparison of the observed phonon modes with the known lattice phonons in the GaN material¹⁰ indicates that they are mainly related to the local vibrations of the 0.88-eV PL center. Thus these phonon modes can be regarded as a fingerprint of the corresponding defect, providing a possibility for its identification, as we have discussed previously in Ref. 9.

The position of the NP line varies from 0.867 eV up to 0.882 eV among various samples. This variation is found to correlate with the change of the GaN band gap induced by the residual strain in GaN epilayers created due to the lattice mismatch and the difference in thermal expansion coefficients between the GaN epilayers and the foreign substrates. The dependence of the spectral position of the NP line on the GaN band gap E_g is shown in Fig. 2. The value E_g represents the excitonic band gap determined by reflectance measurements, as previously described.¹¹

Information about the nature of the radiative recombination can be obtained by analyzing the temperature dependence of the PL spectra. A temperature increase causes the appearance of a new hot PL emission with the position of the new no-phonon line (denoted as NP*) at 2–4 meV above the

FIG. 1. (a) PL spectra of the 0.88-eV PL recorded at 2 and 30 K, showing the appearance of a hot emission with the no-phonon line NP* due to the thermal occupation of a higher-lying excited state of the same defect. The marks show the phonon-assisted transitions related to the NP and NP* lines. The presented spectra were recorded from GaN epilayers grown on both SiC and sapphire substrates, respectively, to demonstrate the dependence of the splitting between the NP and NP* lines on the residual strain in GaN. (b) Arrhenius plots of the intensity ratio between the NP* and NP lines measured from the same samples as shown in (a). Note the agreement between the directly measured energy separation of the NP* and NP lines in (a) and the value deduced from the Arrhenius plots.

0.88-eV NP line, as also shown in Fig. 1(a). As an example, PL spectra from two GaN epilayers grown on SiC and Al₂O₃ substrates, respectively, are displayed in Fig. 1(a). This new hot PL emission NP* exhibits exactly the same phonon structure as the NP PL, indicating that both of them are related to the same defect. Moreover, the activation energy of the hot emission deduced from the Arrhenius plot of the NP*/NP intensity ratio [Fig. 1(b)] agrees well with the energy separation between the NP and NP* lines observed in the PL spectra—compare Figs. 1(a) and 1(b). This clearly shows that the hot emission appears to be due to the thermal occupation of a higher-lying excited state of the 0.88-eV defect, and is caused by radiative recombination from this state to the ground state of the defect. As also demonstrated in Fig. 1, the splitting between the excited states depends on the residual strain in the GaN epilayers, and changes from $\sim 2 \text{ meV}$ for the GaN/SiC samples up to $\sim 4 \text{ meV}$ for some

FIG. 2. Energy position of the NP line of the 0.88-eV PL emission as a function of the excitonic band gap from various GaN samples with a built-in strain field of different strength, due to the difference in thermal expansion coefficients and the lattice mismatch between GaN epilayers and foreign substrates.

of the GaN epilayers grown on Al_2O_3 substrates.

A further temperature increase causes a decrease in intensity of the entire 0.88-eV PL spectrum. The activation energy of this process can be estimated from an Arrhenius plot of the integrated PL intensity (Fig. 3) measured either by the above band-gap excitation or by using resonant excitation in the NIR spectral region to avoid strong overlap with the structureless background emission. Both measurements pro-

FIG. 3. Arrhenius plots of the integrated intensity of the 0.88-eV PL emission measured either by above band-gap excitation (a), or using resonant excitation in the NIR spectral region (b). Both measurements provide a similar value of the activation energy for thermal quenching of the PL intensity. The accuracy of this value is poor for the above band gap excitation (a) due to strong overlapping with background emissions. Therefore the value of 21 meV determined by the resonant excitation is regarded as a more reliable value for the ionization energy of the excited state. The solid lines denote the fitting curves with the indicated activation energies.

FIG. 4. PL spectra measured within the NP spectral region with the polarization parallel (solid lines) and perpendicular (dotted lines) to the c axis. Spectra were measured at 1.7 and 20 K to determine the polarization properties of both the NP and NP* lines.

vide the same value of the activation energy of ~ 21 meV. This locates the energy level of the excited state involved in the PL transitions at ~ 21 meV from the band edge.

To gain further insights into the electronic structure of the 0.88-eV defect, polarization studies have been performed. The PL spectra of the 0.88-eV emission measured within the NP region with a linear polarization parallel or perpendicular to the c axis (denoted as $E \parallel c$ or $E \perp c$, respectively) are shown in Fig. 4. As it is clear from the figure, the NP transition is mainly polarized along the c axis ($E \parallel c$). On the contrary, the NP* transition is allowed in both $E \parallel c$ and $E \perp c$ polarizations with the oscillator strength being higher for the $E \perp c$ polarization.

IV. DISCUSSION

Based on the results obtained we suggest that the 0.88-eV emission originates from an internal transition between a relatively shallow excited state (E^1) and the deep ground state (E^0) of a deep defect. The estimated energy-level positions of these states are ~ 21 meV and ~ 900 meV from one of the band edges, respectively. Below we will justify the proposed model.

The participation of a relatively shallow state in the PL transitions follows from (i) the observed strong dependence of the spectral position of the NP line on the band-gap energy of the GaN epilayers; (ii) the rapid thermal quenching of the 0.88-eV PL with a low activation energy. Indeed, the observed dependence of the spectral position of the NP line on the band gap of GaN reflects its dependence on the residual strain, and thus can be used to determine the pressure behavior of the defect levels. The residual strain in the GaN epilayer can be decomposed into hydrostatic and biaxial components. The hydrostatic component mainly causes the strain-induced variation of the band gap, whereas the biaxial strain leads to a modification of the valence-band (VB) splitting¹² and may also cause splitting of the defect-related states of different symmetry. The dependence of the fundamental band gap $\Gamma_c - \Gamma_v$ on the hydrostatic pressure (P) has

FIG. 5. (a) Pressure-induced shift of the GaN excitonic band gap, determined by reflectance measurements, and of the energy position of the NP line of the 0.88-eV PL emission. The values of the hydrostatic pressure were calculated from the measured shift of the excitonic band gap using Eq. (1). Points represent experimental data. Lines represent fits using pressure coefficients of 39 meV/GPa and 16 meV/GPa for the excitonic band gap (the solid line) and the NP line position (the dotted line), respectively. (b) Schematic pressure dependence of the GaN band gap and the E^0 and E^1 levels of the 0.88-eV defect. The position of the shallow E^1 level is chosen close to the CB edge as an example.

previously been calculated by Christensen and Gorczyca using the local-density approach.¹³ The predicted shift of the band gap is

$$\Delta E_g (\text{meV}) = 39 (\text{MeV/GPa}) * P - 0.32 (\text{meV/GPa}^2) * P^2 \quad (1)$$

and is in a good agreement with the experimental values.¹⁴ Using these pressure coefficients we can recalculate the change of the band gap E_g , shown in Fig. 2, in terms of the change of the hydrostatic pressure component in the GaN epilayers, and determine the pressure coefficient of the 0.88-eV PL emission [Fig. 5(a)]. The pressure dependence of the NP line energy obtained in this way can be fitted by a linear dependence with a pressure coefficient $+(16 \pm 2)$ meV/GPa [Fig. 5(a)]. We need to point out that the obtained coefficients represent the relative pressure-induced variation of the two states E^1 and E^0 involved in the recombination process. It is obvious that these two states exhibit different pressure behavior pointing towards their different origin.

Let us consider the possible nature of these states and discuss the behavior of the defect levels corresponding to shallow impurities (donors and acceptors) and deep defects under hydrostatic pressure. The delocalized effective-mass states of shallow donors are primarily derived from the wave functions near the bottom of the conduction band (CB), i.e., the Γ minimum for GaN. These states will follow the CB upon a pressure-induced shift, as has been experimentally observed for the donor bound-exciton emission.¹⁵ In the case of shallow acceptors theoretical calculations based on the linear muffin-tin orbital Green-function method⁶ show that the pressure coefficients of the corresponding defect states are almost the same as that of the VB, also in accordance with experimental findings.¹⁶ For deep centers, which are strongly localized in real space, on the other hand, the wave functions of the corresponding states are built up from the whole Brillouin zone. Thus their pressure dependence is obtained as an average of many bands,¹⁷ which results in a much weaker pressure dependence of the deep-level position relative to the VB as compared with that of the shallow donors.¹⁸ Theory predicts⁶ that pressure coefficients of the deep levels do not depend on their nature (donor- or acceptor-type) but slightly change depending on the level position in the band gap. The calculated pressure coefficients⁶ vary from +14 meV/GPa for the states resonant with the CB to the +9 meV for deep levels in the lower part of the band gap. Thus pressure coefficient of an internal transition between two deep states is expected to be within 0–5 meV/GPa as indeed observed for the transition-metal impurities, where only a minor change of the PL spectral positions (less than 3 meV) is observed for GaN epilayers grown on different foreign substrates.¹⁹ The observed sizable pressure coefficient in this work has made us conclude that the excited state E^1 of the 0.88-eV defect is rather shallow in nature. The pressure dependences of the GaN band gap and the E^0 and E^1 levels of the 0.88-eV defect are illustrated in Fig. 5(b). (The reference level for the E^0 and E^1 levels is either the CB edge or the VB edge. In Fig. 5(b) the position of the shallow E^1 level is chosen close to the CB edge, as an example). The energy position of this state deduced from the temperature-dependent PL measurements is about 21 meV from the band edge (Fig. 3). This locates the deep ground state E^0 at ~ 900 meV relative to the band edge.

The temperature-dependent studies reveal that the 0.88 eV defect also has a higher-lying excited state E^2 responsible for the hot emission NP* (Fig. 1). Since the splitting between the E^1 and E^2 excited states changes with the residual strain in GaN, the pressure coefficients of these states are also different. This is likely caused by their different electronic character of the corresponding wave functions, evident from their different polarizations—Fig. 4. It is expected that the effect of the anisotropic (biaxial) strain field in the GaN epilayers is different on electronic states of different symmetry. We are not able to provide an in-depth discussion here, unfortunately, due to the lack of knowledge on the exact geometric symmetry of the defect and also on the electronic symmetry of both excited and ground states.

The results obtained do not provide any direct evidence whether the excited states of the 0.88-eV defect are related to the conduction or to the valence band. The first option, however, seems to be more consistent with the following experi-

FIG. 6. Dependence of the 0.88-eV PL intensity on the irradiation dose measured for GaN epilayers with different electrical conductivity before the electron irradiation.

mental findings. Firstly, the energy positions of the E^1 and E^2 levels are similar to the effective-mass donor states in GaN, whereas the shallow acceptor-related states are usually much deeper (typically more than 200 meV from the VB for the ground state and thus ~ 50 meV for the first excited states). Secondly, our magneto-optical measurements²⁰ indicate that all states participating in the PL process (i.e., E^0 , E^1 , and E^2) are singlet states, which is easier to explain by assuming that the particles involved in the recombination have spinlike character such as a shallow donor electron. Thirdly, the splitting between the excited states E^1 and E^2 (from 2 to 4 meV) does not follow the splitting of the valence band (from 0 up to 12 meV in our samples judging from the energy separation between the *A* and *B* free excitons), which is otherwise expected if the shallow E^1 and E^2 states are constructed from the corresponding VB states. Finally, the 0.88-eV PL can be detected after electron irradiation in all investigated GaN samples. The dose, required to activate the emission is, however, different between the compensated or *p*-type GaN ($\sim 1 \times 10^{17} \text{ cm}^{-2}$) and highly *n*-type material ($\sim 4 \times 10^{18} \text{ cm}^{-2}$), as shown in Fig. 6. There are at least two possible explanations of the observed dose dependence: (i) it can reflect the existence of an offset dose for the formation of the 0.88-eV defect due to some competing defect formation processes which is efficient in *n*-type GaN only; (ii) the intensity of the 0.88-eV PL depends on the Fermi-level position in the sample, which is modified by the electron irradiation consistent with our electrical measurements. If the second explanation is correct, it implies that the energy levels of the 0.88-eV defect are located in the upper part of the band gap, since the 0.88-eV emission is insensitive to the change in the Fermi-level position in the compensated or *p*-type samples.

It should be pointed out that even though the excited states (E^1 and E^2) are relatively shallow, they cannot be treated as the strict effective-mass states of a shallow donor based on their singlet nature. This is because the effective-mass states of a shallow donor are expected to be at least spin degenerate according to the Kramer's theorem.

Let us briefly discuss the possible models for the 0.88-eV defect. The corresponding PL emission can be observed with a comparable intensity in all electron-irradiated GaN epilay-

ers independent of the doping of the starting material (Fig. 6). This provides evidence that the defect involved is either a radiation-induced native defect, a radiation-activated residual impurity commonly present in GaN material, or a related complex. The very characteristic feature of the 0.88-eV PL is the presence of the richly structured phonon-assisted sideband. Most of the observed phonon energies are different from the known lattice phonons in GaN and are inherent to the 0.88-eV defect only, providing a probe for identification. Most surprisingly, the phonon modes involved in the 0.88-eV PL are almost identical (excluding the lattice phonons) to the local phonons observed for the 0.841-eV PL emission in GaP.⁹ The latter emission has been unambiguously proved to be caused by the internal transition between the shallow excited state and the deep ground state of the substitutional oxygen donor O_P in GaP.²¹ Since in GaP these local vibrational modes are characteristic only for the substitutional O_P donor, their observation in GaN can be considered as a strong indication towards the involvement of the substitutional oxygen donor in the 0.88-eV PL in GaN.⁹

V. SUMMARY

In summary, we have used photoluminescence spectroscopy to determine the mechanism of the radiative recombination responsible for the near-infrared PL emission with the no-phonon line at ~ 0.88 eV, commonly present in electron-irradiated GaN independent of doping and growth method. We suggest that the PL emission is caused by the internal transition between the relatively shallow excited state and the deep ground state of a deep defect. The participation of the shallow excited state was concluded based on (i) the observed correlation of the NP-line spectral position with the change of the GaN band gap, caused by the residual strain in the epilayers; (ii) the determined activation energy (~ 21 meV) from the thermal quenching of the PL intensity. The ionization energies of the excited and ground states were then estimated as ~ 21 and ~ 900 meV. Although no definite conclusion has been made whether the defect levels are located closer to the conduction or to the valence band, the first option seems to be more consistent with all data.

The existence of the higher-lying second excited state also related to the 0.88-eV PL center was shown from the temperature-dependent studies. The different electronic character of the wave functions related to the first and second excited states has been revealed by the polarization measurements. It is proposed that this difference in electronic character is responsible for the observed variation in splitting between them with the residual strain in GaN epilayers.

As to the nature of the defects participating in the 0.88-eV PL, it was concluded that either a native defect, a common residual contaminant, or their complex is involved, since the PL emission has been observed with a comparable intensity in all electron-irradiated GaN independent of doping of the starting material. The substitutional O_N donor (or related complex) has been proposed as the most probable candidate, based on the observed striking similarity in the local vibrational properties of the 0.88-eV PL centers with the substitutional O_P donor in GaP.

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- ¹P. Perlin, T. Suski, H. Teisseyre, M. Leszczynski, I. Grzegory, J. Jun, S. Porowski, P. Boguslawski, J. Bernholc, J. C. Chervin, A. Polian, and T. D. Moustakas, *Phys. Rev. Lett.* **75**, 296 (1995).
- ²C. Wetzel, T. Suski, J. W. Ager III, E. R. Weber, E. E. Haller, S. Fischer, B. K. Meyer, R. J. Molnar, and P. Perlin, *Phys. Rev. Lett.* **78**, 39 923 (1997).
- ³D. C. Look, D. C. Reynolds, J. W. Hemsky, J. R. Sizelove, R. L. Jones, and R. J. Molnar, *Phys. Rev. Lett.* **79**, 2273 (1997).
- ⁴J. Neugebauer and C. G. Van de Walle, *Phys. Rev. B* **50**, 8067 (1994).
- ⁵J. Neugebauer and C. G. Van de Walle, *Appl. Phys. Lett.* **69**, 503 (1996).
- ⁶I. Gorczyca, A. Svane, and N. E. Christensen, *MRS Internet J. Nitride Semicond. Res.* **2**, 18 (1997).
- ⁷M. Linde, S. F. Uftring, G. D. Watkins, V. Härle, and F. Scholz, *Phys. Rev. B* **55**, R10 177 (1997).
- ⁸I. A. Buyanova, Mt. Wagner, W. M. Chen, B. Monemar, J. L. Lindström, H. Amano, and I. Akasaki, *Appl. Phys. Lett.* **73**, 2968 (1998).
- ⁹W. M. Chen, I. A. Buyanova, Mt. Wagner, B. Monemar, J. L. Lindström, H. Amano, and I. Akasaki, *Phys. Rev. B* **58**, R13 351 (1998).
- ¹⁰P. Perlin, C. Janberthie-Carillon, J. P. Itie, A. S. Miguel, I. Grzegory, and A. Polian, *Phys. Rev. B* **45**, 83 (1992); K. Miwa and A. Fukumoto, *ibid.* **48**, 7897 (1993).
- ¹¹N. V. Edwards, S. D. Yoo, M. D. Bremser, T. W. Weeks, Jr., O. H. Ham, R. F. Davis, H. Liu, R. A. Stall, M. N. Norton, N. R. Perkins, T. F. Kuech, and D. E. Aspnes, *Appl. Phys. Lett.* **70**, 2001 (1997).
- ¹²B. Gil, O. Briot, and R.-L. Aulombard, *Phys. Rev. B* **52**, R17 028 (1995).
- ¹³N. E. Christensen and I. Gorczyca, *Phys. Rev. B* **50**, 4397 (1994).
- ¹⁴P. Perlin, I. Gorczyca, N. E. Christensen, I. Grzegory, H. Teisseyre, and T. Suski, *Phys. Rev. B* **45**, 13 307 (1992).
- ¹⁵S. Kim, P. Herman, J. A. Tuchman, K. Doverspike, L. B. Rowland, and D. K. Gaskill, *Appl. Phys. Lett.* **67**, 380 (1995).
- ¹⁶H. Teisseyre, P. Perlin, T. Suski, I. Grzegory, J. Jun, and S. Porowski, *J. Phys. Chem. Solids* **56**, 353 (1995).
- ¹⁷D. J. Chadi and K. J. Chang, *Phys. Rev. B* **39**, 10 063 (1989).
- ¹⁸C. Wetzel, W. Walukiewicz, E. E. Haller, J. Auger III, I. Grzegory, S. Porowski, and T. Suski, *Phys. Rev. B* **53**, 1322 (1996).
- ¹⁹J. Baur, U. Kaufmann, M. Kunzer, J. Schneider, H. Amano, I. Akasaki, T. Detchprohm, and K. Hiramatsu, *Appl. Phys. Lett.* **67**, 1140 (1995); R. Heitz, P. Thurian, I. Loa, A. Hoffmann, I. Broser, K. Pressel, B. K. Meyer, and E. N. Mokhov, *Mater. Sci. Forum* **196-201**, 719 (1995).
- ²⁰Mt. Wagner, I. A. Buyanova, W. M. Chen, B. Monemar, J. L. Lindström, H. Amano, and I. Akasaki (unpublished).
- ²¹For review, see, e.g., P. J. Dean, in *Deep Centers in Semiconductors*, edited by S. T. Pantelides (Gordon and Breach, New York, 1986), p. 185.