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Electrical and optical characterization of GaN HVPE layers related to extended defects

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Abstract

The study of the effect of extended defects, present in very large numbers in GaN epilayers, on the material properties and device performance is one of the most important aims of the current research in the field of III nitrides.

Thickness strongly influences electrical and optical properties of epitaxially grown GaN. Due to the lattice mismatch between sapphire and GaN, extended defects (mainly threading dislocations) are generated at the sapphire/epilayer interface, and a degenerate layer, characterized by high defect density and high conductivity, has been observed. Moving toward the top surface, the density of the extended defects, which seem to greatly affect the material properties, gradually decreases. This fact mainly causes the commonly observed electrical and optical inhomogeneities.

This work deals with the comparative study by means of optical and electrical characterization between two HVPE-grown layers with different thickness (2.6 and 55 μm) in order to check the effects of the extended defect distribution across the sample.

1. Introduction

The ever-increasing interest for gallium nitride and its wide applications has promoted intensive investigations and strong efforts in the study and modelling of the material and GaN-based devices. The influence of dislocations and other extended defects, present in very high concentration (10^6 cm^{-2} in the best samples), on the electrical and optical properties of these materials, is one of the main topics of the recent literature. As a matter of fact, the constraints of heteroepitaxial growth on sapphire and other substrates are orienting the research towards an exhaustive knowledge of the effects of defects as well as towards their reduction [1]. The evolution of defective states as a function of sample thickness, which strictly determines their distribution, has been already analysed by DLTS [2], and correlated with transmission electron microscopy results. This paper reports results on photoconductivity (PC)

and cathodoluminescence measurements (performed in time-resolution) relevant to samples with different content of dislocations. Photopersistent conductivity (PPC) analysis has also been carried out in order to determine the time decay constants of the extrinsic transitions.

2. Experimental details

Measurements have been carried out on two hydride vapour phase epitaxy (HVPE) GaN layers grown at the Lincoln Laboratory, Massachusetts Institute of Technology [3]. Samples are unintentionally doped GaN layers grown on sapphire substrates. The sample labelled LH 1232 is 2.6 μm thick and has a measured mobility at room temperature of $260 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and a carrier concentration of $4 \times 10^{17} \text{ cm}^{-3}$ as determined by Hall measurements [1]; sample LH 1234 is 55 μm thick and its values of mobility and carrier concentration at room temperature are $810 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and $5 \times 10^{16} \text{ cm}^{-3}$ respectively. Schottky contacts (1.5 mm in diameter) have been obtained by gold metallization, ohmic contacts by In soldering. Current–voltage (I – V) and capacitance–voltage (C – V) characteristics have been carried out at room temperature on GaN Schottky diodes. DLTS (deep level transient spectroscopy) from 80 up to 550 K allowed us to investigate the gap and detect deep levels as far as 1.1 eV from the conduction band.

PC measurements have been performed at room temperature in a coplanar geometry with two In contacts soldered to the GaN surface [4].

A white light source has been used, entering a monochromator: from the output slit the monochromatic photon beam is focused onto the sample, and hits the GaN surface at a chopper frequency of 3–5 Hz. The photon flux ranges between 10^{12} and $10^{14} \text{ photons cm}^{-2} \text{ s}^{-1}$ depending on the wavelength. A dc voltage has been supplied in order to have the same dark current flowing across the two samples. The photo-current signal has been collected by a lock-in amplifier.

While the spectral range of wavelengths from 330 and 650 nm is covered, the variation of current signal due to the release of photo-generated carriers from deep traps evidences deep centre-to-band transitions.

For PPC measurements, constant photo-excitation has been furnished until the current signal has reached a sort of saturation (after some minutes), then light has been turned off. The decay of photocurrent after excitations at wavelengths corresponding to each PC peak has been recorded and analysed to determine the relevant decay times [5, 6]. CL observations were carried out in a Hitachi S-2500 SEM. Measurements were performed at accelerating voltages ranging from 7 to 25 kV and temperatures between 85 and 295 K. Steady-state CL spectra were acquired using a CCD camera with a built-in spectrograph (Hamamatsu PMA-11). For time-resolved CL measurements, a periodic beam was generated using a graphite chopper and beam-blanking electronics including a function generator. To record CL spectra at different delay times, a boxcar integrator triggered by the pulse generator collects the output signal of a photomultiplier. The time resolution of the total CL setup is about 100 ns [7]. Time-resolved CL spectra were measured at delay times ranging from 500 ns to 5 ms with time windows between 50 ns and 500 μs . Spectra were corrected for the optical response of the system. The decay transients of the different CL emissions were monitored with the aid of a digital oscilloscope.

3. Results and discussion

3.1. Electrical characterization

GaN Schottky diodes have been characterized by I – V and C – V measurements. Sample LH 1232 shows values of the reverse current many orders of magnitude higher than the thicker sample. The barrier height ϕ_b , as measured from I – V and C – V is 1.6 and 1.4 eV

for the LH 1234 and LH 1232 respectively. Concerning the net carrier concentration as deduced by $C-V$ measurements at room temperature, in LH 1234 has been calculated as $N_{\text{eff}} = 1.6 \times 10^{16} \text{ cm}^{-3}$ and in LH 1232 as $N_{\text{eff}} = 7.6 \times 10^{16} \text{ cm}^{-3}$. The higher conductivity of the thinner sample (LH 1232) has been already observed by Hall effect measurements, and can be ascribed to the higher density of electrically active defects. For both samples, however, the carrier density deduced from $C-V$ appears to be lower (almost one order of magnitude) than the one deduced from Hall effect technique, due to the different regions investigated by these methods. The capacitance method explores the depletion region originated from the top surface for a depth on some tenths of a micron, while Hall measurements give a measure of the free carrier density averaged over the whole thickness of the sample, taking into account also the strong contribution of the degenerate layer [8].

3.2. Photocurrent and CL

Differences in recombining defect distribution have been qualitatively evaluated by CL panchromatic images (figures 1(a) and (b)), showing a denser granular distribution of radiative recombination centres for the thinner sample.

Once assessed the thickness-related density distributions, we evaluated the electrical activity of defects by means of spectral PC measurements. PC spectra have been collected in co-planar and semi-transparent Schottky diode configuration. At room temperature in co-planar setup four well resolved PC peaks beyond the near band edge (NBE) have been observed in LH 1232 (figure 2). Normalization of the measured photocurrent spectrum by the incident photon density did not significantly alter these observations.

Peaks are located at the same energy values of luminescence emission found by CL and PL [9–11] and, although the physical mechanism responsible for such transitions is quite different [12], we will call them blue band (2.83 eV), green band (2.47 eV), yellow band (2.24 eV) and red band (2.01 eV), in analogy with luminescence terminology. One of the main characteristics of these PC spectra is the good separation between green and yellow bands, as found in the spectrum relevant to sample LH 1232, that are rarely observed with luminescence techniques. Blue and red bands are also well resolved.

The thicker sample LH 1234 shows some differences in the NBE peak position and a less pronounced blue photocurrent peak. Moreover a broad band, a convolution of green and yellow bands, peaked at 2.30 eV is observed.

The lower PC signal relevant to the thick sample can be related to the lower density of states inducing deep-centre to band transitions, although a quantitative interpretation [13] needs a deeper analysis beyond the aim of this research.

Concerning the NBE peaks, whose position varies in the two samples, being at 3.39 eV in LH 1234 and at 3.45 eV in LH 1232, this difference is certainly related to their thickness. One of the possible explanations for such a difference invokes the close correlation between the optical absorption spectrum and the PC spectral response [14]. In the high absorption region, corresponding to photon energies higher than the bandgap, PC is controlled by the surface lifetime; on approaching the bandgap energy, PC is controlled by the bulk lifetime and reaches its maximum when the absorption constant is approximately equal to the reciprocal of the sample thickness. This occurs in the 2.6 μm thick sample where the absorption coefficient approaches the reciprocal of its thickness at 3.45 eV giving rise to a PC peak, which may not correspond to the band-to-band transition.

In the thicker sample, the NBE photo-current peak corresponding to the transition valence-to-conduction band, is located at 3.39 eV, corresponding to the band-edge energy at room temperature [15].

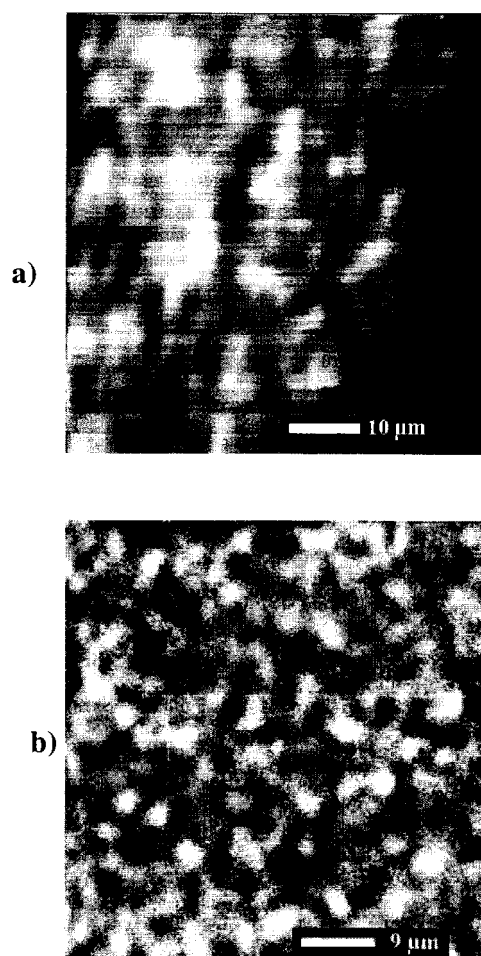


Figure 1. CL panchromatic images of HVPE GaN (a) LH 1234 (55 μm); (b) LH 1232 (2.6 μm). The density of radiative recombination centres is higher in the thinner sample.

However, a similar trend in the NBE energy emission for the two samples is also observed by our CL measurements, as shown in figure 3(b).

Recent papers dealing with the PL and CL blue-shift of the NBE emission [16–18] for decreasing epilayer thickness, attributed this effect to a compressive biaxial strain, which develops after the cool-down process from the growth temperature due to the difference in thermal expansion coefficients of GaN and sapphire. Moreover, also the gradient of the free-carrier concentration due to impurities associated with the early stages of growth, is considered to be involved in the NBE blue-shift [16].

Figure 3 summarizes our findings in PC and CL measurements; the higher energy values observed in CL peaks are due to the lower temperature of measurements.

CL spectra obtained at 87 K from the LH 1234 and LH 1232 GaN samples are shown in figure 4. Besides NBE emission, other peaks related to shallow donor–acceptor transitions, centred between 3.4 and 3.2 eV, can be appreciated in both films. These features were found to depend on beam excitation conditions. In particular, several deep-level-related emissions,

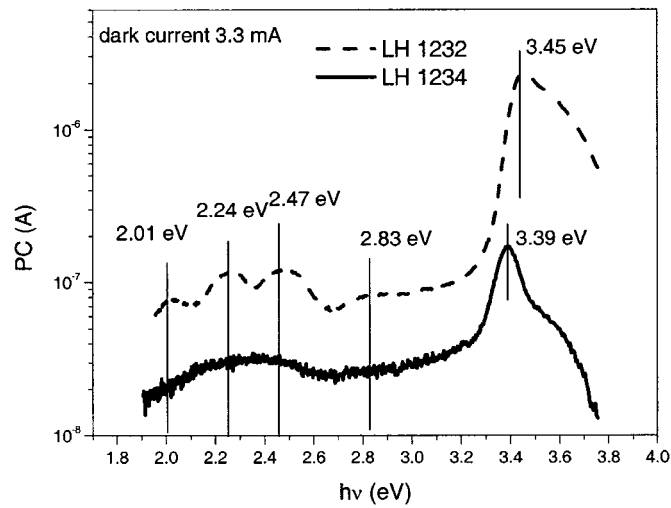


Figure 2. PC spectra of samples LH 1232 (dashed curve) and of LH 1234 (solid curve).

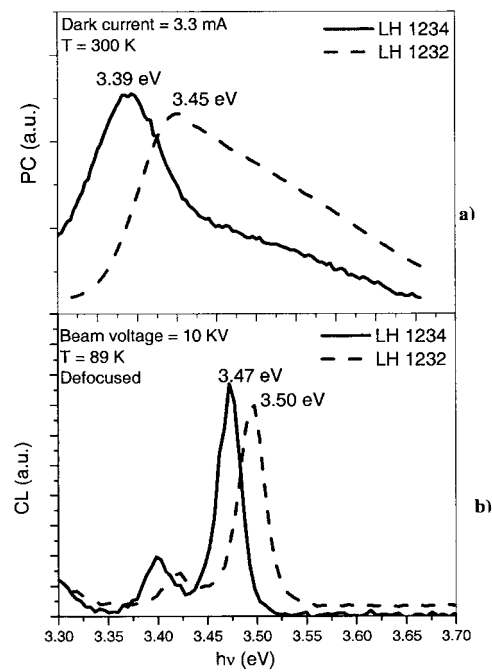


Figure 3. PC (a) and CL (b) spectra in the NBE region. A blue-shift is observed at the lowering of the thickness.

which are weak as compared with near bandgap luminescence, could be clearly resolved using defocused SEM electron beam.

Some of the deep-level-related emissions are common to both the layers investigated. This is the case of a broad CL emission peaked at 2.91 eV. In addition, CL emission is also observed in the yellow and red ranges of the visible spectrum. Gaussian deconvolution of CL spectra

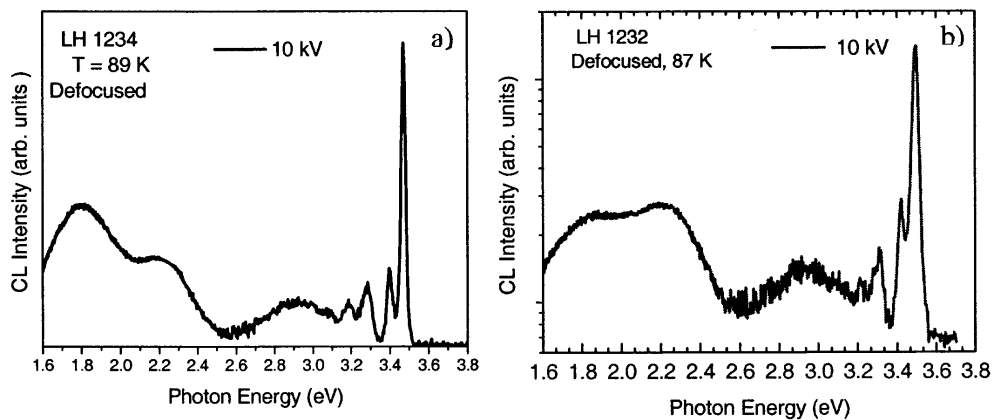


Figure 4. CL spectra of LH 1234 (a) and LH 1232 (b) layers recorded at 87 K.

recorded at different temperatures and beam excitation conditions in the thick layer (LH 1234) show that the two emission bands observed in figure 4 are centred at 1.81 and 2.23 eV.

These bands are also observed in CL spectra from the thin layers, peaked at 1.85 and 2.22 eV, but deconvolution reveals the existence of an additional emission centred at 2.02 eV.

A clear correlation between the peaks appearing in the yellow range of the PC spectra of each sample and those appearing in the corresponding CL spectra can be observed. Simultaneous appearance of these components in PC and CL spectra indicates that such emissions are either related to deep levels to band transitions or transitions involving deep levels and very shallow levels with a maximum depth on the order of the thermal energy (25 meV in our case). Present day views generally agree in the acceptor character of the deep levels involved in the GaN yellow luminescence, gallium vacancies and its complexes with oxygen or carbon often being suggested candidates (e.g. [19, 20]). Observation of the 2.02 eV peak only in the thin layer indicates that this band may be related to structural defects located at the GaN–sapphire interface. The 2.02 eV band has been also found in PC and CL spectra of thin, Si-doped, GaN films grown by MBE [10]. The PC peak located at 2.47 eV was not observed by CL spectroscopy, which indicates that it is probably related to a non-radiative transition.

Comparison between spectra of the two layers show that the intensity of the deep level CL emissions relative to the NBE luminescence is much higher in the thinner sample, suggesting that distribution and density of extended defects could play an important role in the appearance and intensity of the mentioned bands.

In order to evidence a possible thickness dependence of the radiative centre distribution, depth-resolved CL measurements were performed by varying the beam accelerating voltage (V_b) while using a constant electron–hole pair injection rate.

In this way, real inhomogeneities in the in-depth defect centres distribution can be distinguished from effects due to unequal carrier injection conditions. Figure 5 shows CL spectra from the LH 1234 sample recorded at 87 K under increasing accelerating voltages. Spectra were normalized with respect to the band-edge peak, to compare the relative intensity of each deep level band with respect to the near bandgap emission. These spectra show that the ratios of the band edge to the 1.8, 2.23 and 2.91 eV band intensities decreases by increasing the accelerating beam voltage, which suggests that concentration of deep levels responsible for these emissions is higher near the surface of the samples. This trend is also observed in CL spectra obtained from the thin LH 1232 layer under similar experimental conditions.

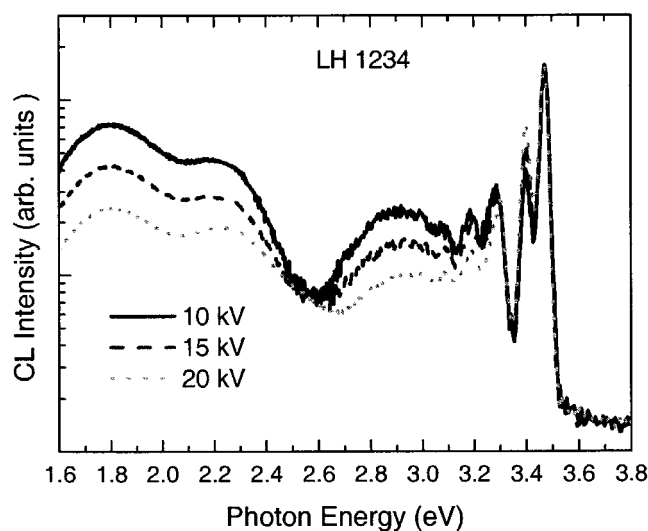


Figure 5. Low temperature (87 K) CL spectra from the GaN LH 1234 layers recorded at different accelerating voltages keeping a constant power of 30 μ W.

A blue band centred at 2.88 eV has been previously observed in cross-sectional CL investigations of HVPE-grown GaN layers [9], where monochromatic CL images revealed that this emission was much more intense near the surface of the sample. According to different authors, oxygen donors are clearly involved in the mechanism responsible for this band [21]. Theoretical calculations indicate [22] that there is a tendency for O to segregate to the surface, which has been experimentally verified by SIMS measurements [21]. Concerning the 2.23 eV band, previous results [23, 24] indicate that a yellow emission is dominant near the surface of GaN layers. The emission was associated to V_{Ga} or V_{Ga} complexes bound to structural surface imperfections. Such results agree with the increased 2.9 and 2.23 eV CL emission intensities observed near the surface of our samples.

3.3. Time-resolved analyses

Interesting results are observed in time-resolved CL spectra, where the emissions show a long persistence especially for the blue and red bands as clearly visible in the spectra shown in figure 6.

The relative intensities of the deep level emissions change by varying the delay time due to the different decay kinetics of each band. An increase of the delay time makes the 1.81 eV emission dominate the spectra, while the relative intensity of the yellow band decreases in comparison. The blue 2.9 eV band can be clearly appreciated even for delay times longer than 3 ms.

Similar trend was observed in TRCL spectra of the LH 1232 layer. CL transients recorded at the peak energies of the bands found either by deconvolution of the steady state spectra or observed in TRCL measurements, can be analysed in order to extract information about the corresponding decay times. Preliminary measurements show that these transients are well described by single-exponential decays. All the measured decay times lay in the $10^2 \mu$ s range. The shorter decay time corresponds to the 2.23 eV emission band, while longer decay times are observed for the 1.81 eV (700 μ s) and 2.91 eV (430 μ s) bands, in good agreement with TRCL spectrum shown in figure 6.

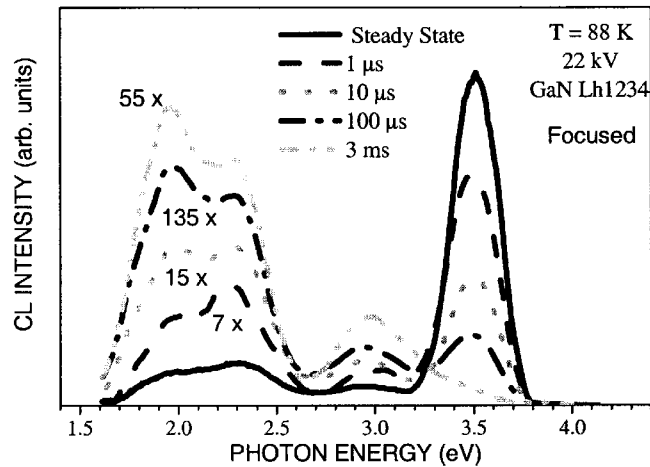


Figure 6. Time-resolved CL spectra relevant to sample LH 1234.

To investigate the band photodecay kinetics we also performed persistence PC (PPC) measurements for each of the PC peaks found.

PPC is a light-induced change in the free carrier concentration, which persists after excitation removal. Possible origins for such an effect in highly dislocated materials are the presence of random local potential fluctuations separating carriers from traps or band-bending [25] originating macroscopic barriers.

The data were analysed according to a stretched exponential model, commonly used in materials characterized by a non-exponential nature of the photocurrent decay [5, 6].

According to this model the photocurrent decay follows the analytical trend

$$\Delta I = \Delta I_{0d} \exp(-t/\tau)^b$$

where $\Delta I = I(t) - I(d)$ and $\Delta I_{0d} = I(t = 0) - I(d)$, $I(d)$ being the dark current measured keeping the sample in the dark for a very long time in order to avoid any persistence effect, $I(t)$ is the current value at t seconds after the light is turned off and $I(t = 0)$ is the value of current after excitation (usually some minutes until the signal saturation).

The PC relaxation graph is shown in figure 7. The stretched exponential turns out to vary in the range (0.2–0.4) as commonly found [5, 6], but the interesting point is that the time decay constant, as calculated for each PC peak energy, turns out to be very high for the blue band (around 500 s), and similar decay times have been obtained for the yellow and green bands (140–150 s), which could explain why these two bands are often unresolved. These PPC measurement results seem to confirm that the persistence effects, usually attributed to the YL, are instead strongly affected also by the green and the blue emission. This could partially support the hypothesis that not only YL, which seem to be also related to surface states, but mostly the blue band plays a key role in the photo-persistence mechanisms.

4. Conclusions

We reported a cross-comparison, by means of electrical and optical characterization, of the properties of two GaN layers of different thickness in order to reveal the extended defect related feature. Photocurrent and CL measurements have found similar results, relevant to the detection of extrinsic transitions corresponding to emissions in the blue, green, yellow and red range.

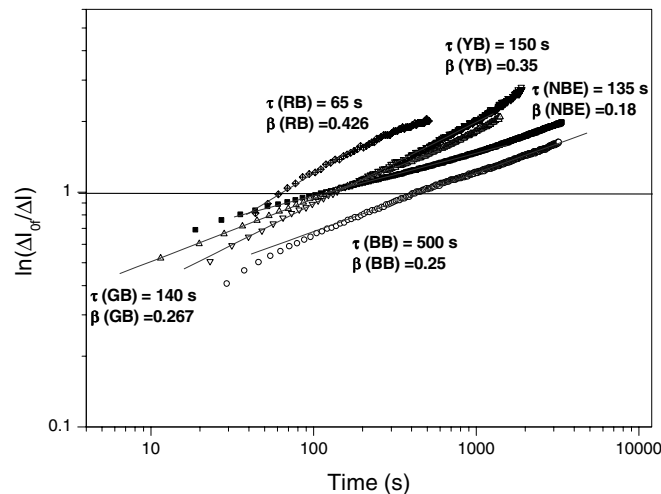


Figure 7. PPC results obtained by illuminating the samples at the PC peak wavelengths in LH 1232.

PPC analyses, moreover, indicate that not only yellow, but mostly green and blue bands are involved in the mechanism responsible for photo-persistence. TRCL measurements attributed the longer decay times to blue and red luminescence. The blue shift of the NBE emission, probably related to the higher substrate-induced strain in GaN epilayer lattice, has been observed in the thinner sample.

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References

- [1] Morkoç H 2001 *Mater. Sci. Eng. R* **33** 135 and references therein
- [2] Fang Z-Q, Look D C, Jasinski J, Banamara M, Liliental-Weber Z and Molnar R J 2001 *Appl. Phys. Lett.* **78** 332
- [3] Molnar R J 1999 *Semicond. Semimet.* **57** 1
- [4] Castaldini A, Cavallini A and Polenta L 2000 *Mater. Res. Soc. Symp. Proc* **588** 51
- [5] Qiu C H and Pankove J I 1997 *Appl. Phys. Lett.* **70** 1983
- [6] Beadie G, Rabinovich W S, Wickenden A E, Koleske D D, Binari S C and Freitas J A Jr 1997 *Appl. Phys. Lett.* **71** 1092
- [7] Urbietta A, Fernández P, Piqueras J, Hardalov Ch and Sekiguchi T 2001 *J. Phys. D: Appl. Phys.* **34** 2945
- [8] Look D C, Reynolds D C, Hemsley J W, Szelove J R, Jones R L and Molnar R J 1997 *Phys. Rev. Lett.* **79** 2273
- [9] Herrera M, Zaldívar P, Fernández P and Piqueras J 1998 *J. Appl. Phys.* **83** 2796
- [10] Castaldini A, Cavallini A, Polenta L, Díaz-Guerra C and Piqueras J 2002 *Mater. Sci. Eng. B* **91/92** 308–12
- [11] Kauffmann U, Kunzer M, Obloh H, Maier M, Manz Ch, Ramakrishnan A and Santic B 1999 *Phys. Rev. B* **59** 5561
- [12] Klein P B, Binari S C, Freitas J A Jr and Wickenden A E 2000 *J. Appl. Phys.* **88** 2843
- [13] Shmidt J A and Rubinelli F A 1998 *J. Appl. Phys.* **83** 339
- [14] Bube R H 1992 *Photoelectronic Properties of Semiconductors* (Cambridge: Cambridge University Press)

-
- [15] Levinshtein M E, Rumyantsev S L and Shur M S (ed) 2001 *Properties of Advanced Semiconductor Materials: GaN, AlN, InN, BN, SiC, and SiGe* (New York: Wiley)
- [16] Bertram F, Srinivasan S, Ponce F, Reinmann T, Christen J and Molnar R J 2001 *Appl. Phys. Lett.* **78** 1222
- [17] Perlin P, Mattos L, Shapiro N A, Kruger J, Wong W S, Sands T, Cheung N W and Weber E R 1999 *J. Appl. Phys.* **85** 2385
- [18] Reynolds D C, Look D C, Jogai B, Hoelscher J E, Sherriff R E and Molnar R J 2000 *J. Appl. Phys.* **88** 1460
- [19] Neugebauer J and Van de Walle C G 1996 *Appl. Phys. Lett.* **69** 503
- [20] Saarinen K *et al* 1997 *Phys. Rev. Lett.* **79** 3030
- [21] Yang H C, Lin T Y and Chen Y F 2000 *Phys. Rev. B* **62** 12593
- [22] Jones R *et al* 1999 *Phys. Status Solidi a* **171** 167
- [23] Reshchikov M A, Morkoç H, Park S S and Lee K Y 2001 *Appl. Phys. Lett.* **78** 3041
- [24] Shalish I, Kronik L, Segal G, Rosenwaks Y, Shapira Y, Tisch U and Salzman J 1999 *Phys. Rev. B* **59** 9748
- [25] Queisser H J and Theodorou D E 1986 *Phys. Rev. B* **33** 4027