C5.3 Gain coefficient and lasing threshold in GaN-based lasers

A. Hangleiter

March 1998

A INTRODUCTION

GaN-based laser diodes have now been shown to be reliable, potentially extremely useful devices [1]. These laser diodes have been developed within a very short time span of about two years. Starting with pulsed operation at room temperature [2] and later CW operation [3], we have experienced an exponentially increasing device lifetime.

Nevertheless, the threshold current density of GaN-based laser diodes is still almost one order of magnitude higher than in other III-V material systems. Being one of the most basic laser properties, this highlights the present lack of understanding of the lasing mechanism in nitride-based semiconductors.

B BASIC RULES FOR SEMICONDUCTOR LASERS

As in any other laser, the lasing threshold in a semiconductor laser diode is reached when the gain of the active material overcomes the losses of the laser cavity. These losses have two basic origins, namely the finite reflectivity of the mirrors and distributed losses due to scattering and parasitic absorption in the active medium. In contrast to other lasers, the mirrors in typical semiconductor lasers are simply formed by cleaved or etched crystal facets. Therefore, the reflectivity (Fresnel reflectivity) is rather low, about 20% in the case of the nitrides.

Unlike atomic or solid-state lasers, the lasing transitions in a semiconductor laser are transitions between continua of extended states rather than between localised states. The inversion criterion [4] then is that the electron and hole quasi-Fermi levels must be separated by more than the bandgap energies. The spectrum of the optical gain g is given by [5,6]

$$g(h\nu)=\frac{e^2h}{2\varepsilon_0 m_0^2 cnEL_z}\frac{2}{(2\pi)^2}\int\left|\vec{\varepsilon}\vec{M}_{if}\right|^2(f_c(k)-f_v(k))\delta(E_i-E_f-E)d^2k \qquad (1)$$

with n being the refractive index, E the transition energy, L_z the width of the quantum well, $\vec{\varepsilon}$ the polarisation vector, M_{if} the transition matrix element, f_c and f_v the Fermi distribution functions in the conduction and valence bands, and E_i and E_f the energies of the various possible initial and final states of the transition.

Essentially, it is determined by the combined density-of-states of the conduction and valence bands and by the difference of the electron and hole distribution functions. In fact, the effect of the band structure is two-fold. On one hand a large combined density-of-states is beneficial for a large optical gain, and on the other hand large densities-of-state correspond to large carrier densities in order to achieve inversion.

In modern heterostructure lasers, the actual active layer is usually very thin, much thinner than the optical mode to be supported by its optical gain. Therefore, it is convenient to introduce the so-called 'optical confinement factor' Γ, which relates the material optical gain g_{mat} to the net optical gain g_{eff} 'seen' by the lasing mode [6]:

$$g_{eff} = \Gamma . g_{mat} \tag{2}$$

Of course, the details of the gain spectra depend on the dimensionality of the active material (bulk, quantum well, etc.) and on the details of the band structure. For such detailed calculations we refer to Chapter A6 of this volume. However, it is important to note that due to the specific band structure of the nitrides, the carrier densities needed to achieve inversion and optical gain are very large compared to other III-V semiconductors. In particular, both the electron effective mass (m_e = 0.22 [7]) as well as the hole effective mass ($m_h \approx 2.0$ [8-10]) are three- to four-fold larger than in GaAs. For the same reason, however, the maximum gain obtainable from nitride structures is also larger.

Moreover, since the wurtzite structure already has a C_2v symmetry, there is not much scope for improvement of the hole density-of-states by utilising strained quantum wells [11]. Only by using structures grown on special surfaces (r-face), can an improvement of the lasing properties by using strained quantum wells be expected [12].

C EXPERIMENTAL DATA ON OPTICAL GAIN IN GaN-BASED LASER STRUCTURES

Most fundamental studies of the optical gain in semiconductor laser materials and structures are based on the stripe excitation method used to measure the optical gain [13]. This relies on optical pumping and a variation of the length of the excited zone. Great care must be taken in order to avoid saturation effects.

One of the most basic properties of the optical gain in nitride-based structures is its polarisation dependence. In contrast to other bulk III-V materials, where the optical gain is isotropic, nitride structures exhibit almost exclusively TE-mode gain [14]. This is due to the symmetry-induced splitting of the valence bands in the wurtzite structure.

Depending on the details of the structure, particularly on the confinement factor, the pump power density needed to achieve an effective optical gain of, say, 50 cm^{-1} is of the order of a few hundred kilowatts per square centimetre at room temperature [14-16].

Typical optical gain spectra (TE polarisation) obtained at various different pump power densities are shown in FIGURE 1 [14]. In this case, a GaInN/GaN double heterostructure was studied, with an active layer thickness of about 16 nm. The pump power density was varied between 0.3 and 3 MW/cm^2. An analysis using a model based on band-to-band transitions and isotropic bands allows for a determination of the carrier density associated with each of the spectra. In this particular case, the transparency carrier density is of the order 1.5×10^{19} cm^{-3} and the differential gain is about 1×10^{-16} cm^2. The spectra are strongly broadened with a broadening parameter of the order 50 meV.

D LASING THRESHOLD FOR OPTICAL AND ELECTRICAL PUMPING

Optical pumping experiments were first used to achieve lasing in GaN-based structures. Stimulated emission from GaN was observed as early as 1971 [17]. More recently, there have been a large number of reports on stimulated emission [18,19], without an intentionally formed cavity. This may partly be due to the well known difficulty of cleaving mirrors in the wurtzite nitrides grown on sapphire, due to the 30° tilt of the GaN unit cell with respect to the sapphire.

However, real optically pumped lasing was observed both for GaInN/GaN and for GaN/AlGaN structures. The mirrors were formed either by cleaving or by dry etching. The threshold power densities were of the order of a few hundred kW/cm^2 [20-22]. In fact, even optically pumped secondorder distributed feedback (DFB) lasers have been fabricated [23,24], with threshold power densities also in the hundreds of kW/cm^2 range.

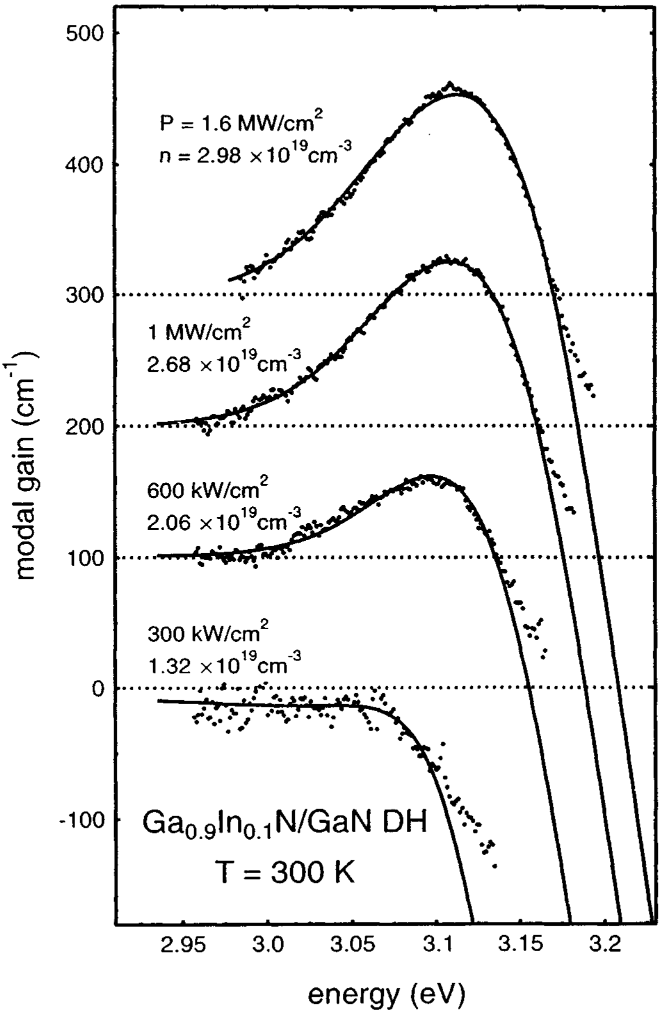

FIGURE 1 Optical gain spectra for a GaInN/GaN double heterostructure at room temperature for various pump power densities [14].

Injection-type laser diodes based on GaInN active layers have now been demonstrated by a number of different groups [2,25-30]. The threshold current densities range from 1.5 kA/cm^2 [31] to about 50 kA/cm^2 [26]. From measurements of the turn-on delay time Nakamura et al [32] have also estimated the threshold carrier density to be about 1 - 2 × 10^{19} cm^{-3}.

These values for the threshold current density are roughly consistent with calculated values. Depending on the cavity losses, theory predicts a practical lower limit of the threshold current density around 1 kA/cm^2 [33,34], in line with the experimental experience. According to the band structure of the nitrides, a large threshold current density is inherent to this material system.

E CONCLUSION

Both injection-type and optically pumped nitride-based semiconductor laser structures exhibit fairly high threshold pump levels compared to other III-V or II-VI semiconductors. This is fundamentally due to the specific band structure of the nitrides, i.e. the extremely large effective masses of both electrons and holes. The carrier densities needed to achieve transparency are of the order 2 × 10^{19} cm^{-3}.

REFERENCES

[1] S. Nakamura et al [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.211]

[2] S. Nakamura et al [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.L74]

[3] S. Nakamura et al [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.4056]

[4] M.G.A. Bernard, G. Duraffourg [*Phys. Status Solidi (Germany)* vol.1 (1961) p.699]

[5] G. Lasher, F. Stern [*Phys. Rev. (USA)* vol.133 (1964) p.554]

[6] H.C. Casey, M.B. Panish [*Heterostructure Lasers* (Academic Press, New York, 1978)]

[7] P. Perlin et al [*Appl. Phys. Lett. (USA)* vol.68 (1996) p.1114]

[8] J.S. Im, A. Moritz, F. Steuber, V. Härle, F. Scholz, A. Hangleiter [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.631]

[9] J.A. Majewski, M. Städele, P. Vogl [*Mater. Res. Soc. Symp. Proc. (USA)* vol.449 (1997) p.887]

[10] K. Kim, W.R.L. Lambrecht, B. Segall, M. van Schilfgaarde [*Phys. Rev. B (USA)* vol.56 (1997) p.7363]

[11] J.B. Jeon, B.C. Lee, Y.M. Sirenko, K.W. Kim, M.A. Littlejohn [*J. Appl. Phys. (USA)* vol.82 (1997) p.386]

[12] K. Domen, K. Horino, A. Kuramata, T. Tanahashi [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.987]

[13] K.L. Shaklee, R.F. Leheny [*Appl. Phys. Lett. (USA)* vol.18 (1971) p.475]

[14] G. Frankowsky, V. Härle, F. Scholz, A. Hangleiter [*Appl. Phys. Lett. (USA)* vol.68 (1996) p.3746]

[15] D. Wiesmann, I. Brener, L. Pfeiffer, M.A. Khan, C.J. Sun [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.3384]

[16] S.T. Kim, H. Amano, I. Akasaki [*Appl. Phys. Lett. (USA)* vol.64 (1994) p.1535]

[17] R. Dingle, K.L. Shaklee, R.F. Leheny, R.B. Zetterstrom [*Appl. Phys. Lett. (USA)* vol.19 (1971) p.5]

[18] H. Amano, T. Tanaka, Y. Kunii, K. Kato, S.T. Kim, I. Akasaki [*Appl. Phys. Lett. (USA)* vol.64 (1994) p.1377]

[19] C.J. Sun et al [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.2978]

[20] M.A. Khan et al [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.2418]

[21] D. Hofstetter, D.P. Bour, R.L. Thornton, N.M. Johnson [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.1650]

[22] F. Binet et al [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.960]

[23] R. Hofmann et al [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.2068]

[24] R. Hofmann et al [*IEEE J. Sel. Top. Quantum Electron. (USA)* vol.3 (1997) p.456]

[25] I. Akasaki, S. Sota, H. Sakai, T. Tanaka, M. Koike, H. Amano [*Electron. Lett. (UK)* vol.32 (1996) p.1105]

[26] K. Itaya et al [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.11315]

[27] G.E. Bulman et al [*Electron. Lett. (UK)* vol.33 (1997) p.1556]

[28] A. Kuramata, K. Domen, R. Soejima, K. Horino, S.-I. Kubota, T. Tanahashi [*Jpn. J. Appl. Phys. (Japan)* vol.36 (1997) p.L1130]

[29] M.P. Mack et al [*MRS Internet J. Nitride Semicond. Res. (USA)* vol.2 (1997) p.41]

[30] F. Nakamura et al [in *Proc. 2nd Int. Conf. on Nitride Semiconductors* Tokushima, Japan, 1997, p.460]

[31] S. Nakamura [*IEEE J. Sel. Top. Quantum Electron. (USA)* vol.3 (1997) p.435]

[32] S. Nakamura et al [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.1568]

[33] P. Rees, C. Cooper, P.M. Smowton, P. Blood, J. Hegarty [*IEEE Photonics Technol. Lett. (USA)* vol.8 (1996) p.197]

[34] T. Uenoyama, M. Suzuki [in *Int. Symp. on Blue Laser and Light Emitting Diodes* Chiba, Japan, 1996, p.271]

Previous Page

C5.4 Theoretical and experimental results on GaN-based lasers

K. Domen and A. Kuramata

April 1998

A INTRODUCTION

In spite of the remarkable progress of nitride lasers [1], the major problems hindering the development of laser oscillation by current injection have not been fully identified. In FIGURE 1, the theoretical prediction of the gain curve is compared with experimental results. The optical gain (solid lines) for the number of wells, n, from one to three, is calculated for a GaInN/GaN 4-nm quantum well structure using band structures by the k.p method [2]. The triangles show experimental results based on laser diodes having a multi-quantum well (MQW) structure with three pairs of 4 nm wells and 5 nm barriers [3]. There is a very large lack of correspondence: the experimental values are less than 10% of those expected from theory. Generally, the experimentally observed optical gain of nitride lasers was smaller than for other materials [4,5]. Park et al reported the theoretical fitting of gain spectra to experimental data: while the spectra matched each other very well, the observed carrier density needed for gain was larger than the theoretical prediction [6]. Thus, nitride lasers show smaller gain than expected and the cause of the difference shown in FIGURE 1 must be found in order to improve the laser.

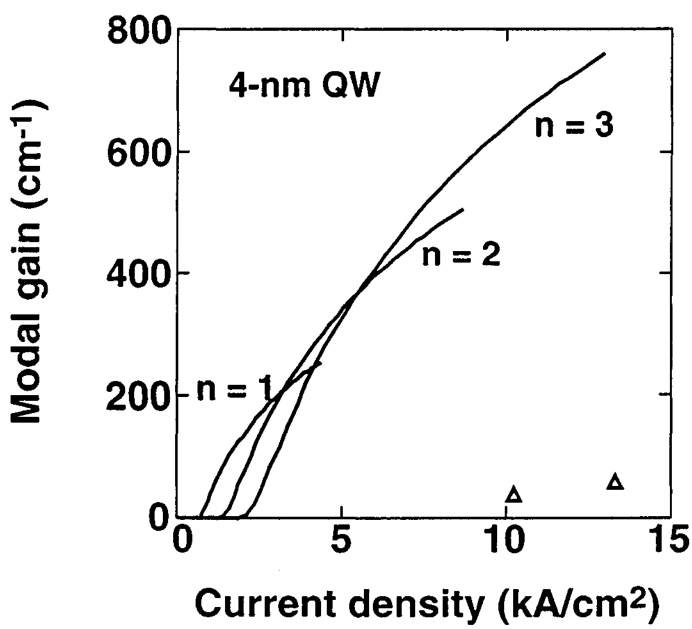

FIGURE 1 Theoretical prediction (solid lines) and experimental results (triangles) for the gain curve of the nitride laser.

The factors which have been postulated as responsible for the relatively poor performance of GaN based lasers are: (1) an inter-well inhomogeneity of carrier injection in MQWs, (2) electron overflow, (3) a bandgap inhomogeneity of InGaN, and (4) an inhomogeneity in the radiative efficiency of InGaN. In this Datareview, the influence of these factors on the gain curve is discussed. First, features of the gain curve of the nitride material are described in Section B. In Sections C to F, it is shown how the various inhomogeneities degrade the gain curve. While a strong piezoelectric effect exists in wurtzite nitride [7], this effect is not treated here, as it has been reported that this effect is completely screened under high excitation at room temperature [8,9]. It is therefore considered not to be involved in the lasing phenomena.

B THEORETICAL CALCULATION OF OPTICAL GAIN

The gain curves shown in FIGURE 1 were calculated by the method of Suzuki et al [10,11] as presented in Chapter A6 of this book, but using different parameters [2]. Experimental data were used for some of the parameters, and others were adjusted so as to reproduce the experimentally observed absorption. The calculated absorption coefficient was 10^5 cm^{-1} in agreement with the experimental data reported by Amano et al [12]. Therefore, this calculation, which produces a larger gain value compared to others [9,13-21], is valid for estimating the magnitude of the optical gain. Since the manybody effects were not considered, the calculation is not valid for discussing the shape of gain spectra or lasing wavelengths. FIGURE 2 shows the calculated TE-mode gain of bulk GaN. Bulk GaN has a significant advantage, large gain, which is the consequence of three factors: the conduction band mass is very large [22]; polarisation is fixed at the TE mode [23]; and both heavy holes (HH) and light holes (LH) contribute to the TE mode gain [11]. However, GaN has a serious drawback too: a very high transparent carrier density. This characteristic is caused by the following factors: both conduction band and valence bands have large masses, there are three valence bands, and HH and LH are particularly close to each other (see Chapter A7). When a quantum well structure is formed, the features are further enhanced: both gain and transparent carrier density become larger. FIGURE 3 shows the modal gain as a function of current density for unstrained 5 nm quantum wells. Gain curves of GaN (solid lines) are compared with those of the same structure in a conventional zincblende material, GaInP (dashed lines). Optical confinement and bandgap difference between well and barrier were set to be almost equal for the two materials. Since GaN has a large gain, a GaN single quantum well (SQW) provides a differential gain similar to that of a three-well MQW in GaInP. On the other hand, increasing the number of wells in GaN leads to a much larger increase of the current density than in GaInP, as the transparent current density of GaN is very large.

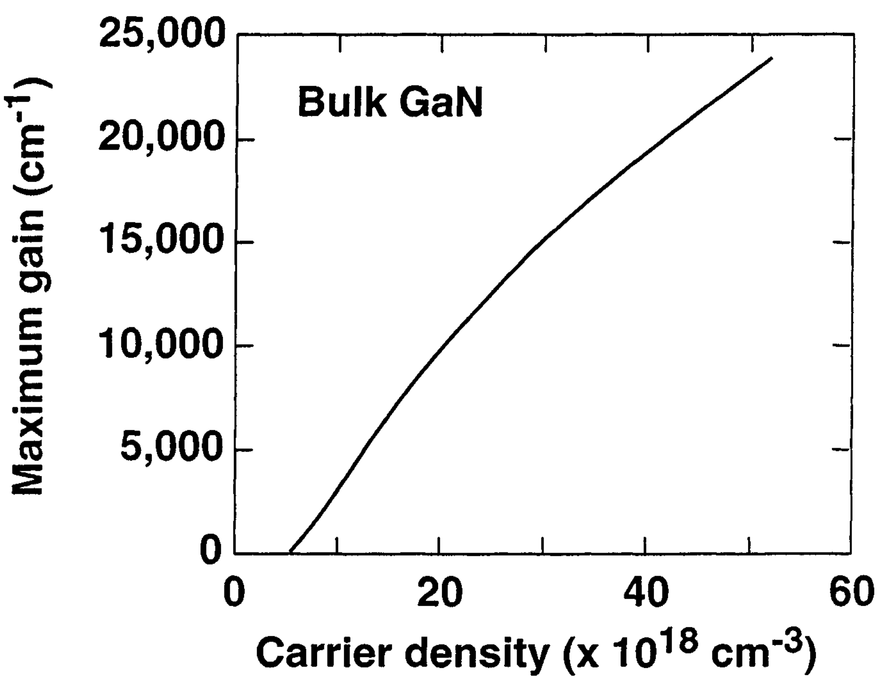

FIGURE 2 Maximum gain of bulk GaN versus carrier density. Bulk GaN has a large gain and a large transparent carrier density.

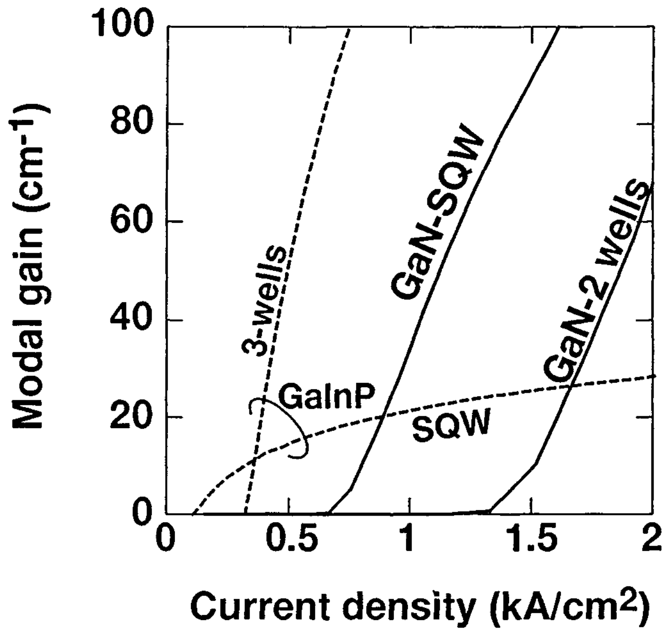

FIGURE 3 Modal gain curves for wurtzite GaN and zincblende GaInP QWs.

C INTER-WELL INHOMOGENEITY OF CARRIER INJECTION

In nitride lasers, hole injection is poor because of the low mobility [24] and thermal velocity. This poor hole injection causes inhomogeneous carrier injection and generation of optical gain between wells [25]. The reportedly large valence-band offset in InGaN/GaN [26] causes inhomogeneous carrier injection as well, even though the exact band offset is still controversial [26-28]. FIGURE 4 shows simulations of the hole and electron distribution across the laser structure when laser oscillation occurs [29]. The poor hole injection causes a higher hole density on the p-side; then electrons are attracted to the p-side and the electron distribution becomes inhomogeneous in the same way as for the holes. Generation of optical gain was simulated for five wells in such an inhomogeneous situation (FIGURE 5). The simulation shows that optical gain is only generated in the three p-side wells. The two n-side wells act as absorption layers, which implies that a laser with a 5-well MQW has a larger internal loss than a laser with a 3-well MQW. Moreover, while the carrier densities of these two n-side wells are below the transparent carrier density, they are still quite high and comparable with the densities in the p-side wells. These carriers are wasted, which leads to a poorer internal quantum efficiency. Consequently, a 5-well laser has a much smaller external quantum efficiency because of the larger internal loss and poorer internal quantum efficiency. In FIGURE 6, the laser power-current characteristics show that a 3-well laser diode has a much higher external quantum efficiency than that of a 5-well laser [3], indicating that inhomogeneous carrier injection occurs.

Although the 3-well laser had better characteristics, gain generation is still inhomogeneous so the 3-well laser is essentially a 2-well laser. This is a disadvantage, because the 3-well laser requires a transparent current density of 3 wells but only generates a 2-well gain. Consequently, the gain curve for the 3-well laser in FIGURE 1 is reduced to two thirds of what was expected.

D ELECTRON OVERFLOW

The other problem of current injection is electron overflow [29]. The carrier densities shown in FIGURE 4 were simulated for an Al composition of 0.1 when the bandgap difference between the InGaN well and

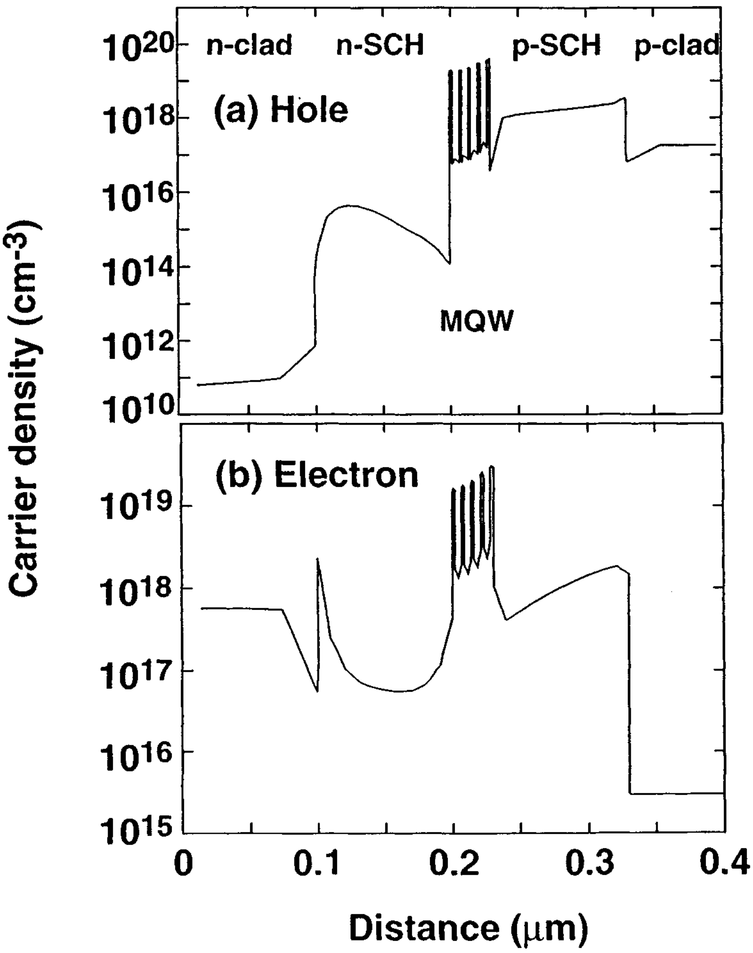

FIGURE 4 (a) Hole and (b) electron density distribution through the laser structure. Both distributions are inhomogeneous, increasing toward the p-side.

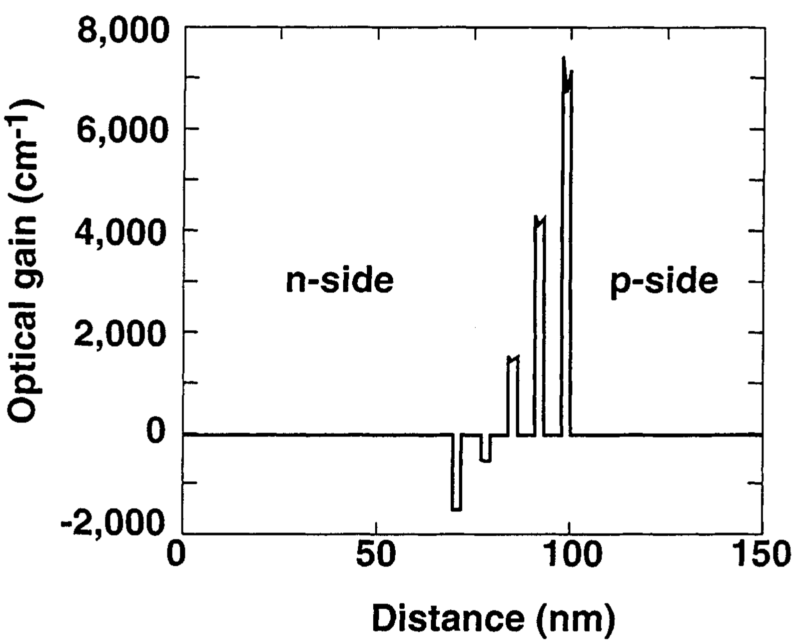

FIGURE 5 Inhomogeneous generation of the optical gain due to the inhomogeneous carrier injection. The two n-side wells will act as absorptive layers.

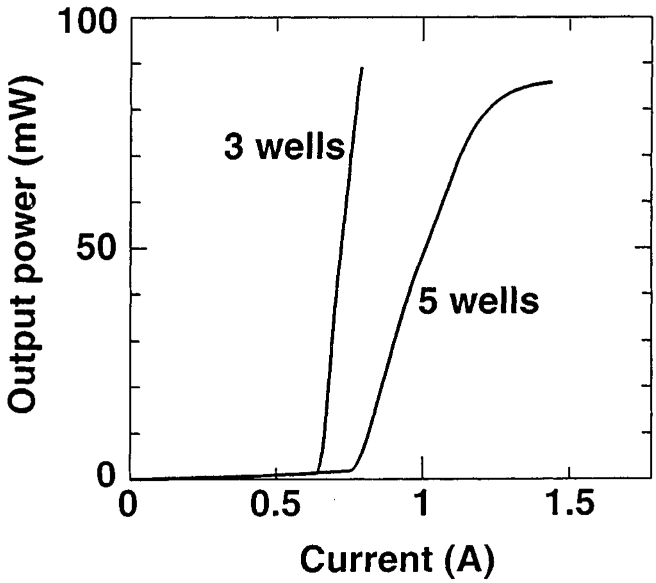

FIGURE 6 I-L characteristics for the 3-well and 5-well lasers.

the AlGaN p-cladding layer, ΔE_g, was 640 meV. From FIGURE 4, we see that poor hole injection into the MQW causes a large hole density in the p-SCH layer, which attracts electrons to the p-side layer. This may be one of the reasons that lasers with a large number of wells can produce lasing [30,31]: electrons migrate to the p-side very easily. This is caused by three factors: poor hole injection, the small band-offset of the conduction band between InGaN and GaN [26], and the high threshold carrier density of over 1×10^{19} cm^{-3} [13]. Thus, even for a ΔE_g of 640 meV, an overflow to the p-cladding layer of over 10^{15} cm^{-3} occurs, and is enhanced by the high electric field in the p-cladding layer. FIGURE 7 shows the simulated leakage current, which is due to electron overflow to the p-cladding layer, as a function of the total current [29]. The Al composition in the p-cladding layers was varied as 0.05, 0.1, 0.15 and 0.2 with corresponding ΔE_g of 500, 640, 780 and 920 meV, respectively. The leakage current is significantly reduced by the increase of Al. A ΔE_g value of about 800 meV was needed to sufficiently

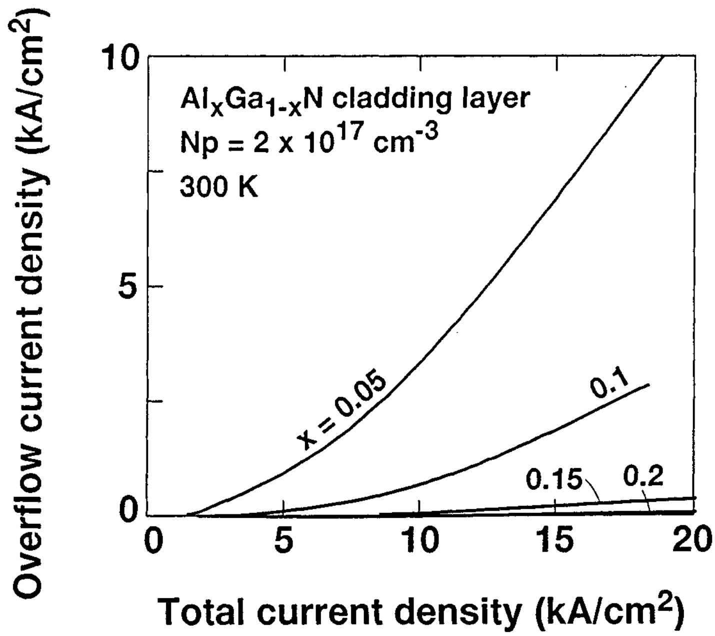

FIGURE 7 Overflow current as a function of total current at several Al compositions. A ΔE_g of about 800 meV is needed to sufficiently suppress the leakage current.

suppress the leakage current. This result indicates that electron overflow easily takes place in a nitride laser, as a ΔE_g value of 500 meV is considered sufficient for conventional III-V lasers. An LED does not suffer from leakage current, since it is operated with a current density below 1 kA/cm^2. This is one of the reasons why bright LEDs do not always produce lasing.

This overflow current seriously deteriorates the gain curve in FIGURE 1 by widening the current axis. It increases the transparent current and decreases the differential gain. Since the three factors causing overflow are intrinsic in nitride materials, it is highly important to improve the other factors that are not intrinsic, i.e. low Al composition, high resistivity and short carrier lifetime in the p-cladding layer.

E BANDGAP INHOMOGENEITY OF InGaN MQW

It has been widely reported that InGaN has large compositional fluctuation [32-39] and, as a result, broad luminescence [40-42]. Moreover, a large broadening of gain spectra was reported for this material [43,5]. The influence of bandgap inhomogeneity seems to be so far an inevitable problem in InGaN material. On the other hand, some groups have reported that InGaN lasers show various lasing lines [44-46]. Photoluminescence (PL) mapping on a laser diode revealed that these various lines were caused by the bandgap inhomogeneity of the InGaN MQW [47]. The PL mapping showed that the variation of the PL peak wavelength in the laser cavity was almost 100 meV. FIGURE 8 is a histogram of the PL peak wavelength obtained by the PL mapping (shaded bars). The spectrum of stimulated emission by optical pumping was superposed on the histogram (solid line). The two matched almost completely. Since the histogram represents spatial volume as a function of the PL peak wavelength, a good match means that these various lasing lines correspond to the in-cavity spatial bandgap inhomogeneity of the InGaN MQW.

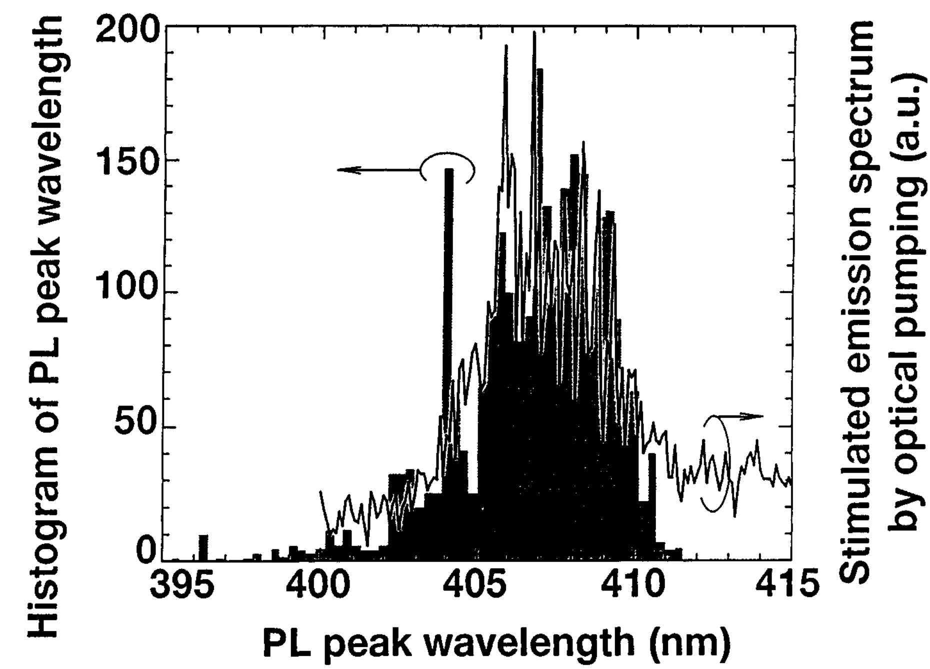

FIGURE 8 Histogram of the peak wavelength (shaded bars) and the stimulated emission spectrum by optical pumping (solid line). The histogram has a periodic modulation with a period of 1 nm. The stimulated emission line is a good match with the modulation.

It has been reported experimentally [48] and theoretically [49] that this inhomogeneity decreases the maximum gain by widening the spectral width of the optical gain. If we neglect carrier diffusion, which is a good approximation in InGaN because the carrier diffusion length is considered to be several tens of nm [50] and the scale of the inhomogeneity is of 1-μm order [47], this bandgap inhomogeneity simply divides the cavity into several regions having different bandgaps. Therefore, the net volume contributing to one lasing line is reduced, and then the maximum gain is reduced by the bandgap inhomogeneity. When the scale of the inhomogeneity is sufficiently small to make quantisation under 10 nm, which has been reported as 'quantum dots' [34], the gain curve will not be degraded but enhanced, provided that the quantum dots have almost the same size and the same In composition. This is because, in an inhomogeneity below this scale, carriers can diffuse into potential minima which have 'homogeneous' three-dimensionally quantised energy levels.

F REDUCTION OF RADIATIVE VOLUME IN InGaN MQW

Several groups have reported non-uniform PL and cathodoluminescence (CL) intensity in nitride material [50-52]. One of the factors responsible for this non-uniformity has been reported to be dislocations which act as non-radiative centres [53-55]. FIGURE 9 shows a mapping of PL peak intensity within a 10-μm square area on the MQW of a laser diode. The inhomogeneity in the PL peak intensity varies roughly over 1-μm^2 areas. Each 1-μm^2 area has a different radiative efficiency, because carriers do not diffuse from one area to another due to the short carrier diffusion length in InGaN [50]. Thus, the InGaN MQW has another kind of inhomogeneity: inhomogeneous radiative efficiency. This is an inhomogeneity of the crystal quality. The total PL intensity can be expressed as $\Sigma G\eta_i$, where G is the carrier generation rate and η_i is the internal quantum efficiency of the ith area. An area having a small η will not contribute to the generation of radiation. Therefore, the radiative volume contributing to the gain generation is reduced in the InGaN MQW. This reduction of radiative volume does not change the transparent current density very much, because it is determined by the η-values of bright areas, which are sufficiently good [47]. However, the reduction seriously degrades the differential gain of the gain curve because the net gain medium is small. The differential gain may be reduced to less than one half of the theoretically expected value by this inhomogeneity.

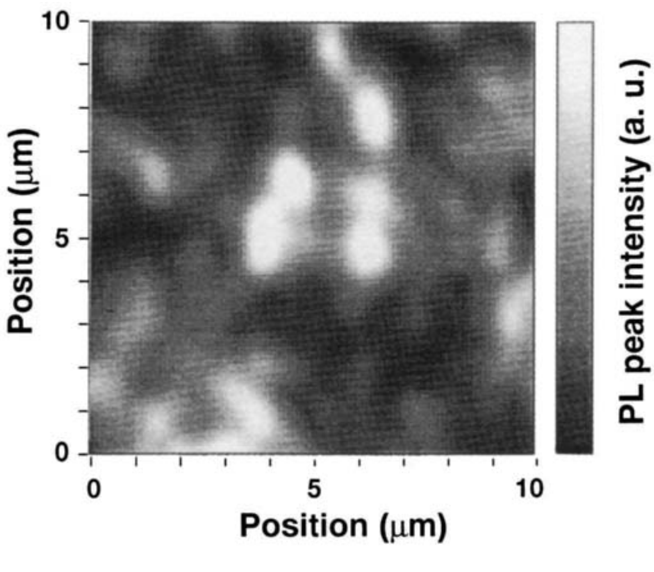

FIGURE 9 PL peak intensity mapping in a 10-μm sided square. The intensity has 1-μm order inhomogeneity.

When the inhomogeneity in crystal quality is sufficiently small compared to carrier diffusion length, carriers diffuse into poor-quality areas due to the slope of the carrier density. (In fact, the actual mechanism may be more complicated, because the bandgap inhomogeneity exists as well.) In this case, radiative efficiency is determined by the poor-quality areas, and consequently the sample exhibits relatively more homogeneous but poor radiative efficiency in total. This results in both higher transparent current density and lower differential gain.

G CONCLUSION

To improve laser performance, four important problems must be solved: the inter-well inhomogeneity of carrier injection in the MQW, electron overflow, InGaN-MQW bandgap inhomogeneity, and a reduction of the radiative volume in the InGaN MQW. These problems result in a small optical gain of nitride lasers. In addition, it is very difficult to establish a theoretical approach for this laser because of the variety of inhomogeneities. In order to study the more essential parameters of the laser, such as the magnitude of the gain, we must first reduce these inhomogeneities.

Once these problems are resolved, we will be able to benefit from the large gain of nitride materials. The SQW structure will probably be the best structure for the nitride laser, as shown in FIGURE 3. The results discussed in Section C independently indicate that the SQW would be the best structure, as inter-well inhomogeneity is to some extent an intrinsic problem. The best way to avoid it is to create entirely homogeneous and high quality SQWs.

REFERENCES

[1] S. Nakamura et al [*Jpn. J. Appl. Phys. (Japan)* vol.37 (1998) p.L309-12]

[2] K. Domen, K. Horino, A. Kuramata, T. Tanahashi [*IEEE J. Sel. Top. Quantum Electron. (USA)* vol.3 (1997) p.450-5]

[3] A. Kuramata, K. Domen, R. Soejima, K. Horino, S. Kubota, T. Tanahashi [*Mater. Res. Soc. Symp. Proc. (USA)* vol.482 (1998) p.1185-96]

[4] S. Nakamura [*MRS Internet J. Nitride Semicond. Res. (USA)* vol.2 (1997) article 5]

[5] M. Kuball et al [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.2580-2]

[6] S.-H. Park, S.-L. Chuang [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.287-9]

[7] T. Takeuchi, I. Akasaki [Datareview in this book: *C2.5 GaInN QWs: piezoelectricity*]

[8] T. Takeuchi et al [*Jpn. J. Appl. Phys. (Japan)* vol.36 (1997) p.L382-5]

[9] I. Akasaki, H. Amano [*Jpn. J. Appl. Phys. (Japan)* vol.36 (1997) p.5393-408]

[10] M. Suzuki, T. Uenoyama, A. Yanase [*Phys. Rev. B (USA)* vol.52 (1995) p.8132-9]

[11] M. Suzuki, T. Uenoyama [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.1420-3]

[12] H. Amano, N. Watanabe, N. Koide, I. Akasaki [*Jpn. J. Appl. Phys. (Japan)* vol.32 (1993) p.L1000-2]

[13] S. Kamiyama, K. Ohnaka, M. Suzuki, T. Uenoyama [*Jpn. J. Appl. Phys. (Japan)* vol.34 (1995) p.L821-3]

[14] W. Fang, S.L. Chuang [*Appl. Phys. Lett. (USA)* vol.67 (1995) p.751-3]

[15] W.W. Chow, A. Knorr, S.W. Koch [*Appl. Phys. Lett. (USA)* vol.67 (1995) p.754-6]

[16] T. Uenoyama, M. Suzuki [*Appl. Phys. Lett. (USA)* vol.67 (1995) p.2527-9]

[17] A.T. Meney, E.P. O'Reilly [*Appl. Phys. Lett. (USA)* vol.67 (1995) p.3013-5]

[18] F. Jain, W. Huang [*IEEE J. Quantum Electron. (USA)* vol.32 (1996) p.859-64]

[19] D. Ahn [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.2498-2500]

[20] S.L. Chuang [*IEEE J. Quantum Electron. (USA)* vol.32 (1996) p.1791-800]

[21] M. Suzuki, T. Uenoyama [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.3378-80]

[22] A.S. Barker, M. Ilegems [*Phys. Rev. B (USA)* vol.7 (1973) p.743-50]

[23] K. Domen, K. Horino, A. Kuramata, T. Tanahashi [*Appl. Phys. Lett. (USA)* vol.71 (1997) p.1996-8]

[24] S. Nakamura, M. Senoh, T. Mukai [*Jpn. J. Appl. Phys. (Japan)* vol.30 (1991) p.L1708-11]

[25] K. Domen, R. Soejima, A. Kuramata, K. Horino, S. Kubota, T. Tanahashi [to be published in *Appl. Phys. Lett. (USA)* (1998)]

[26] G. Martin, A. Botchkarev, A. Rockett, H. Morkoç [*Appl. Phys. Lett. (USA)* vol.68 (1996) p.2541-3]

[27] E.A. Albanesi, W.R.L. Lambrecht, B. Segall [*J. Vac. Sci. Technol. B (USA)* vol.12 (1994) p.2470-4]

[28] S.H. Wei, A. Zunger [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.2719-21]

[29] K. Domen, R. Soejima, A. Kuramata, T. Tanahashi [*MRS Internet J. Nitride Semicond. Res. (USA)* vol.3 (1998) article 2]

[30] S. Nakamura et al [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.L74-6]

[31] K. Itaya et al [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.L1315-7]

[32] K. Osamura, S. Naka, Y. Murakami [*J. Appl. Phys. (USA)* vol.46 (1975) p.3432-7]

[33] S. Chichibu, T. Azuhata, T. Sota, S. Nakamura [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.4188-90]

[34] Y. Narukawa, Y. Kawakami, M. Funato, S. Fujita, S. Fujita, S. Nakamura [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.981-3]

[35] R. Singh, D. Doppalapudi, T.D. Moustakas, L.T. Romano [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.1089-91]

[36] F. Scholz et al [*Mater. Sci. Eng. B (Switzerland)* vol.50 (1997) p.238-44]

[37] A. Wakahara, T. Tokuda, X.-Z. Dang, S. Noda, A. Sasaki [*Appl. Phys. Lett. (USA)* vol.71 (1997) p.906-8]

[38] N.A. El-Masry, E.L. Piner, S.X. Liu, S.M. Bedair [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.40-2]

[39] M.D. McCluskey, L.T. Romano, B.S. Krusor, D.P. Bour, N.M. Johnson, S. Brennan [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.1730-2]

[40] N. Yoshimoto, T. Matsuoka, T. Sasaki, A. Katsui [*Appl. Phys. Lett. (USA)* vol.59 (1991) p.2251-3]

[41] S. Nakamura, M. Senoh, N. Iwasa, S. Nagahama [*Jpn. J. Appl. Phys. (Japan)* vol.34 (1995) p.L797-9]

[42] K.P. O'Donnell et al [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.1843-5]

[43] G. Frankowsky, F. Steuber, V. Härle, F. Scholz, A. Hangleiter [*Appl. Phys. Lett. (USA)* vol.68 (1996) p.3746-8]

[44] S. Nakamura et al [*Jpn. J. Appl. Phys. (Japan)* vol.35 (1996) p.L217-20]

[45] A. Kuramata, K. Domen, R. Soejima, K. Horino, S. Kubota, T. Tanahashi [*Jpn. J. Appl. Phys. (Japan)* vol.36 (1997) p.L1130-2]

[46] M.P. Mack et al [*MRS Internet J. Nitride Semicond. Res. (USA)* vol.2 (1997) article 41]

[47] K. Domen, A. Kuramata, T. Tanahashi [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.1359-61]

[48] Y.-K. Song et al [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.1418-20]

[49] W.W. Chow, A.F. Wright, A. Girndt, F. Jahnke, S.W. Koch [*Appl. Phys. Lett. (USA)* vol.71 (1997) p.2608-10]

[50] S. Chichibu, K. Wada, S. Nakamura [*Appl. Phys. Lett. (USA)* vol.71 (1997) p.2346-8]

[51] J. Liu, N.R. Perkins, M.N. Horton, J.M. Redwing, M.A. Tischler, T.F. Kuech [*Appl. Phys. Lett. (USA)* vol.69 (1996) p.3519-21]

[52] P.A. Crowell, D.K. Young, S. Keller, E.L. Hu, D.D. Awschalom [*Appl. Phys. Lett. (USA)* vol.72 (1998) p.927-9]

[53] S.J. Rosner, E.C. Carr, M.J. Ludowise, G. Girolami, H.I. Erikson [*Appl. Phys. Lett. (USA)* vol.70 (1997) p.420-2]

[54] T. Sugahara et al [*Jpn. J. Appl. Phys. (Japan)* vol.37 (1998) p.L398-400]

[55] F.A. Ponce, S.A. Galloway, W. Goetz, R.S. Kern [*Mater. Res. Soc. Symp. Proc. (USA)* vol.482 (1998) p.625-30]