Absorption recovery time reduction in InGaN/GaN quantum well saturable absorbers

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In this work, a simple method to reduce the absorption recovery time of the InGaN/GaN quantum well saturable absorber was demonstrated. The recovery time of the saturable absorber grown by metal organic chemical vapor deposition was effectively controlled by controlling the crystal quality. Transmission electron microscopy results showed that, for saturable absorbers with reduced GaN buffer thicknesses, increased dislocations were introduced into the quantum well regions. The degraded crystal quality would therefore cause an increased density of nonradiative recombination centers, which were responsible for the fast recovery of the absorption. In addition, with the as-grown thin GaN buffers, the severe interference-induced reflectivity fluctuations were successfully suppressed. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2924412]

I. INTRODUCTION

Passive mode locking by semiconductor saturable absorber mirrors (SESAMs) has been successfully demonstrated in solid state lasers,[1–3] fiber lasers,[4–6] and semiconductor lasers[3,7,8] to generate ultrashort optical pulses in a wide wavelength region. However, for the blue/UV region, the important wavelength region for high density data storage applications, the ultrashort pulses directly generated from passive mode locking are still not available. So far, the blue/UV ultrashort pulses have been mainly obtained by frequency conversion methods from infrared solid state lasers, such as Ti:sapphire lasers[9] and Cr:LiSAF lasers.[10] Recently, we have fabricated the first SESAM operating in the blue region, which consisted of InGaN/GaN multiple quantum wells (MQWs).[11] A nonmonolithic SiO_2/Si_3N_4 distributed Bragg reflector (DBR) was used in order to achieve a broadband operation. It was found that the thick high-temperature (HT) GaN buffer caused severe interference-induced reflectivity fluctuations on the stopband of the SESAM. A postgrowth optimization process, which included laser lift-off and plasma etching, was subsequently conducted to reduce the thickness of the HT GaN buffer so as to suppress the interferences.[12]

For passive mode locking by SESAMs, to achieve efficient pulse shaping, the saturable absorption of a saturable absorber should recover to its initial state in a short time (a few picoseconds to a few tens of picoseconds). The absorption recovery times of those epitaxially grown compound semiconductors normally fall in the nanosecond range. Therefore, many methods have been developed to purposely reduce the recovery times of the saturable absorbers. The most common methods are low-temperature (LT) growth,[13] ion implantation,[14] and proton bombardment.[15] More recently, recovery time reduction by controlling the InP buffer thickness has been demonstrated in the metamorphically grown GaAs-based SESAMs.[16]

To reduce the recovery time of the GaN-based saturable absorber, the methods of LT growth, ion implantation, and proton bombardment may also be applied. However, to further fabricate a GaN-based SESAM, an optimization process to reduce the thickness of the thick HT GaN buffer (normally with the thickness of 1.5–4 μm to provide good crystal quality) is still unavoidable,[12] which would add much complexity to the fabrication process. If the as-grown HT GaN buffer in the saturable absorber could be made thin enough not only to prevent the severe interference but also to effectively reduce the recovery time, the fabrication process of the SESAM would be greatly simplified.

In this paper, we present a novel and easy method to simultaneously reduce the absorption recovery time and the interference effect of the GaN-based saturable absorber. The influences of the GaN buffers on the crystal quality and absorption recovery time of the InGaN/GaN quantum well saturable absorber are investigated.

II. EXPERIMENTS

Three InGaN/GaN MQW samples, marked as A, B, and C, were grown on double-side polished *c*-plane sapphire substrates by metal organic chemical vapor deposition (MOCVD). Trimethylgallium and trimethylindium were used as group-III sources and NH_3 as the group-V source. Before the growth of MQWs, the LT GaN buffer was first deposited at 520 °C, followed by a HT GaN buffer grown at 1020 °C. The InGaN/GaN MQWs consisted of five periods of 3 nm $In_{0.18}Ga_{0.82}N$ (nominal composition) wells and 15 nm GaN barriers. Finally, a 30 nm GaN cap was deposited.

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TABLE I. LT GaN buffer and HT GaN buffer thicknesses of samples A–C.

Sample	LT GaN buffer (nm)	HT GaN buffer (nm)
A	28	1800
B	22	500
C	15	500

The LT and HT GaN buffer thicknesses of each sample are listed in Table I. These InGaN/GaN MQW samples act as saturable absorbers.

The cross-sectional transmission electron microscopy (XTEM) characterizations were carried out using a Philips CM300FEG system at an operating voltage of 300 kV. The high-resolution x-ray diffraction (HRXRD) scans were conducted using a double-crystal high-resolution x-ray (Cu $K\alpha_1$) diffractometer (X'Pert-MRD, Philips). The absorption recovery time of the saturable absorber was studied in a pump-probe setup. The light sources for this experiment were frequency doubled pulses from a tunable Ti:sapphire mode locked laser tuned at a wavelength of 410 nm, with a repetition rate of 80 MHz. The pump beam was polarized perpendicular to the probe beam, and the probe beam energy was approximately 4% of the pump beam energy. Both beams were collimated to a beam size with the diameter of ~ 50 μm. The energy fluence of the pump pulse was about 51 $\mu J/cm^2$. The optical reflectance spectra were recorded at room temperature using a Shimadzu UV-1700 UV-visible spectrophotometer.

III. RESULTS AND DISCUSSION

Conventionally, to grow the GaN-based epitaxial structures on sapphire substrates by MOCVD, the optimal thicknesses are 25–30 nm for the LT GaN buffer and 1.5–4 μm for the HT GaN buffer. As shown in Table I, the GaN buffers in sample A were grown with optimal thicknesses, and there was no postgrowth treatment. According to our previous study on InGaN/GaN saturable absorbers,[11] sample A is expected to have good crystal quality and work as a slow absorber. The XTEM characterization was conducted at the quantum well region of sample A [Fig. 1(a)], using both [0002] and $[11\bar{2}0]$ dark field imagings. As shown in the figure, it was almost dislocation-free at the quantum well region of sample A, indicating very good crystal quality for the growth on a lattice-mismatched substrate. The good crystal quality was also verified by the narrow full width at half maximum (FWHM) of the GaN (0002) diffraction peak and the well-defined satellite peaks from the quantum wells, shown in the HRXRD spectra in ω-2θ geometry (see Fig. 2). Figure 3(a) shows the time-resolved transmission response of sample A, recorded by the pump-probe technique. As can be observed, the recovery time of sample A was in the nanosecond range, indicating that it is indeed a slow absorber.

In order to achieve short recovery times, both the LT and the HT GaN buffer thicknesses were reduced in samples B and C, as described in Table I. As the main function of these two GaN buffers is to accommodate the lattice mismatch between the sapphire substrate and the GaN, it is expected that the reduced thicknesses will lead to the introduction of more defects into the MQW regions so as to enhance the nonradiative recombination.

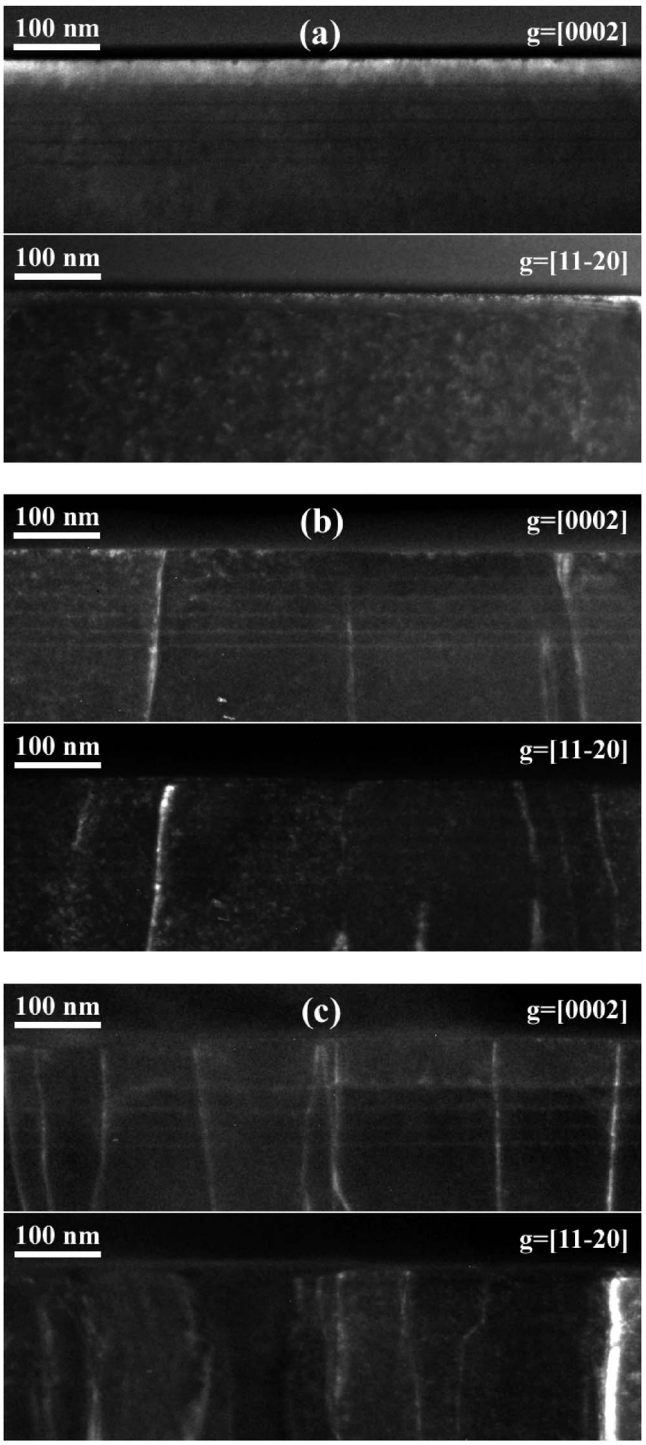

FIG. 1. XTEM micrographs from the quantum well regions of (a) sample A, (b) sample B, and (c) sample C, using both [0002] and $[11\bar{2}0]$ dark field imagings.

To study the crystallographic lattice perfection of the saturable absorbers with reduced GaN buffer thicknesses, XTEM was also conducted on samples B and C, similarly using both [0002] and $[11\bar{2}0]$ dark field imagings. As shown in Figs. 1(b) and 1(c), sample B exhibited a few dislocations distributed over the quantum well region, while in sample C,

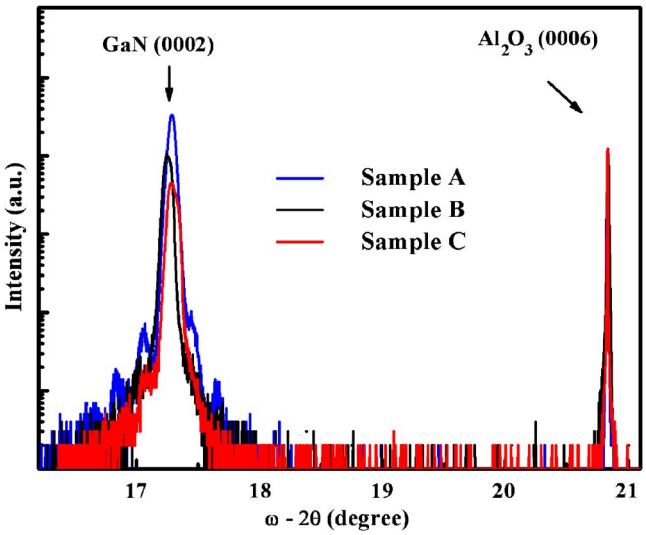

FIG. 2. (Color online) HRXRD spectra in ω-2θ geometry from samples A to C, taken near the GaN (0002) diffraction peak. The Al_2O_3 (0006) diffraction peaks are also shown as a reference.

a significantly larger number of dislocations were observed, owing to its thinner LT GaN buffer. The HRXRD measurements were performed on these two samples to further explore their crystal quality. The spectra in ω-2θ geometry are also shown in Fig. 2. As expected, sample B with thicker LT GaN buffer exhibited better crystal quality than sample C, indicated by the narrower FWHM of the GaN (0002) diffraction peak. In addition, if compared to sample A (grown under optimal conditions), both samples B and C showed degraded crystal quality, in terms of the rougher interfaces and the larger number of dislocations, owing to their smaller GaN buffer thicknesses.

Subsequently, the absorption recovery times of samples B and C were investigated by the pump-probe technique. The time-resolved transmission responses of samples B and C are shown in Figs. 3(b) and 3(c). As observed, sample B showed a single-exponential decay with an absorption recovery time constant of 90 ps. Whereas for sample C, a double-exponential decay was observed, consisting of a fast recovery time constant of 34 ps followed by a slow recovery time constant in hundreds of picoseconds. This longer lasting residual component may be caused by the residual temperature changes or absorption due to those longer-lived trapped carriers.[15] It could also be due to the increased number of energy barriers surrounding the increased defects, which will be discussed later in detail. The fast recovery component of sample C can be used for mode locking, and it is much shorter than the recovery time of sample B, due to the increased number of dislocations in sample C. Hence, with reduced GaN buffer thicknesses, both samples significantly exhibit shorter recovery times than sample A and other InGaN/GaN MQWs grown under optimal conditions reported by other groups.[17–20] The increased numbers of the lattice-mismatch induced dislocations or misfits in the quantum well regions of samples B and C have effectively enhanced the nonradiative recombinations, and shortened the absorption recovery times. This method to achieve ultrashort recovery time requires no postgrowth treatment, and therefore is much simpler compared to the traditional methods, such as ion implantation[14] and proton bombardment.[15]

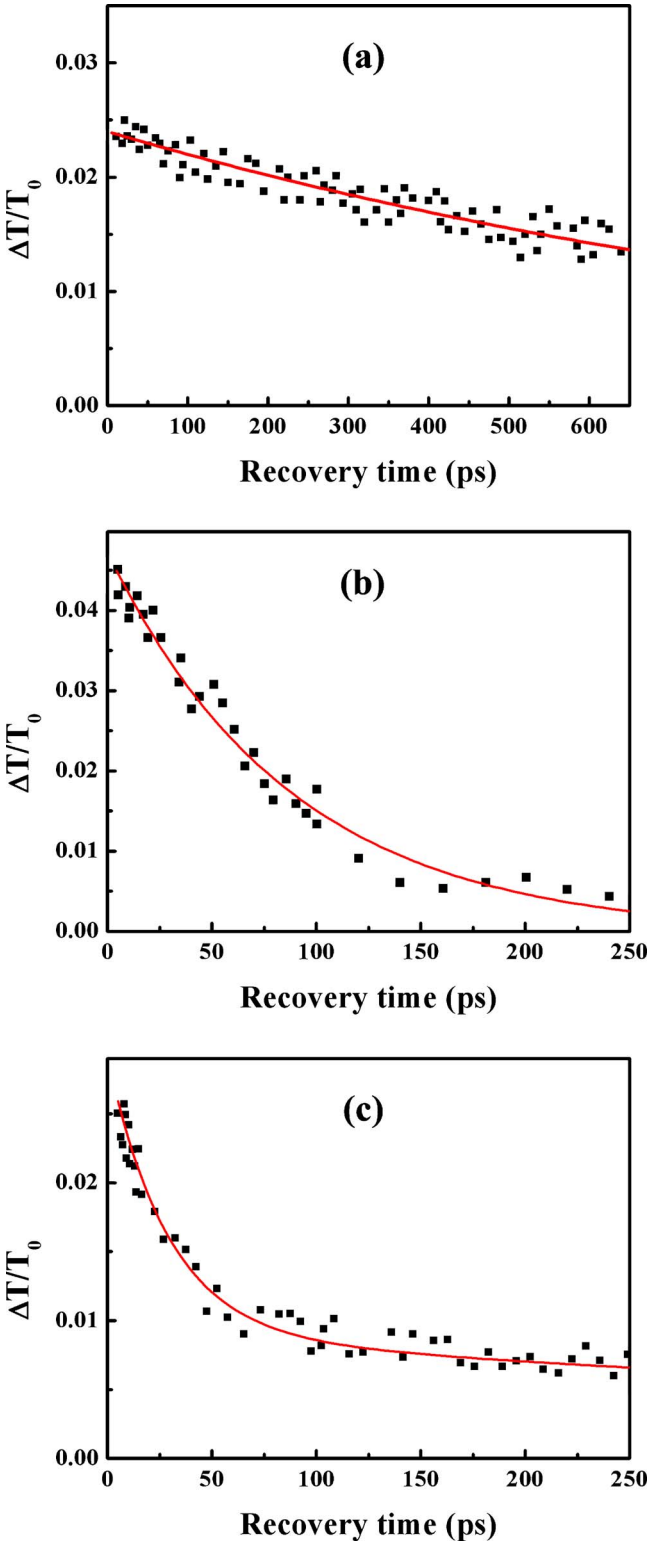

FIG. 3. (Color online) Time-resolved transmission responses of (a) sample A, (b) sample B, and (c) sample C, at the pump energy fluence of 51 $\mu J/cm^2$. The solid curves show the exponential curve-fitting results according to the experimental data points. $\Delta T/T_0$ is the change in transmission, and $\Delta T/T_0=(T-T_0)/T_0$ (T, T_0: transmission with and without pump, respectively).

In addition, it is noted that the as-grown HT GaN buffer was only ~500 nm thick in samples B and C, while in our

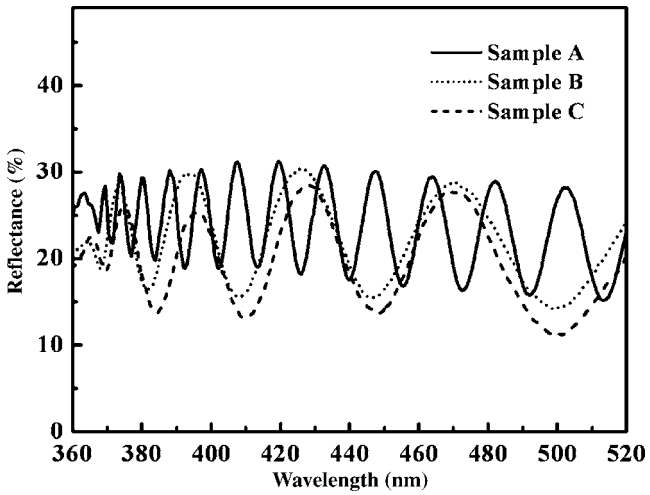

FIG. 4. Reflectance spectra of samples A–C.

optimized GaN-based SESAM structure reported in Ref. 12, to suppress the interference-induced reflectivity fluctuations, the final thickness of the HT GaN buffer after etching was also ~500 nm. Thus, it is expected that the interference effect should be much less severe in samples B and C, as compared to sample A. To verify this, the reflectance spectra of samples A–C were studied, as shown in Fig. 4. The oscillation periods of the fringes here should represent the extent of reflectivity fluctuations on the stopbands of the corresponding SESAM structures. It is clear that sample A with thick GaN buffers suffered from severe interference-induced oscillations. Whereas for samples B and C, the oscillation periods of the interference fringes were largely increased. Consequently, reflectivity fluctuations within a small wavelength span would be much smaller in samples B and C, and the reflectivity fluctuations can be further reduced by adding an antireflective coating, as demonstrated in Ref. 12. Hence, to fabricate a GaN-based SESAM with thin GaN buffers, no further optimization process to suppress the interference is needed. The damage during the substrate transfer and plasma etching[12] can then be avoided and the device reliability would therefore be greatly improved.

It should also be pointed out that although the LT GaN buffer in sample C with further reduced thickness could give shorter recovery time, this layer cannot be made too thin. The trade-off between the absorption recovery time and the crystal quality should be considered. We have grown a saturable absorber only with a 5 nm LT GaN buffer. It is found that the crystal quality of the sample was severely compromised. The quantum wells were not flat or continuous, and the surface roughness was also largely increased. Saturable absorbers with such poor quality may suffer from large nonsaturable loss and degraded nonlinear property. In addition, it is known that InGaN MQWs exhibit highly unusual optical properties, i.e., they have strong luminescence in spite of the relatively large number of dislocations, and it was proposed that the energy barriers surrounding the defects might keep carriers from reaching the defects and from recombining nonradiatively.[21] Hence, if the LT GaN buffer thickness is further reduced to introduce more dislocations or misfits, the increased number of energy barriers might prevent the further shortening in the recovery time. This may also explain the observed longer lasting recovery time component for sample C with an increased number of dislocations.

IV. CONCLUSION

We have demonstrated an effective reduction in the absorption recovery time of the InGaN/GaN quantum well saturable absorber, by controlling the crystal quality at the active region. An absorption recovery time as short as 34 ps was achieved by an InGaN/GaN quantum well saturable absorber with a 15 nm LT GaN buffer and a 500 nm HT GaN buffer. This method requires no postgrowth treatment for recovery time reduction and is therefore convenient. The thin GaN buffer will also largely reduce the interference-induced reflectivity fluctuations in the corresponding nonmonolithic GaN-based SESAM, and hence greatly simplify the SESAM fabrication process.

[1] S. Tsuda, W. H. Knox, S. T. Cundiff, W. Y. Jan, and J. E. Cunningham, IEEE J. Sel. Top. Quantum Electron. **2**, 454 (1996).
[2] A. A. Lagatsky, E. U. Rafailov, C. G. Leburn, C. T. A. Brown, N. Xiang, O. G. Okhotnikov, and W. Sibbett, Electron. Lett. **39**, 1108 (2003).
[3] U. Keller, Nature (London) **424**, 831 (2003).
[4] R. Herda, O. G. Okhotnikov, E. U. Rafailov, W. Sibbett, P. Crittenden, and A. Starodumov, IEEE Photonics Technol. Lett. **18**, 157 (2006).
[5] N. Xiang, M. Guina, A. Vainionpää, J. Lyytikäinen, S. Suomalainen, M. Saarinen, O. Okhotnikov, T. Sajavaara, and J. Keinonen, IEEE J. Quantum Electron. **38**, 369 (2002).
[6] B. C. Collings, K. Bergman, S. T. Cundiff, S. Tsuda, J. N. Kutz, J. E. Cunningham, W. Y. Jan, M. Koch, and W. H. Knox, IEEE J. Sel. Top. Quantum Electron. . **3**, 1065 (1997).
[7] R. Häring, R. Paschotta, A. Aschwanden, E. Gini, F. Morier-Genoud, and U. Keller, IEEE J. Quantum Electron. **38**, 1268 (2002).
[8] S. Hoogland, A. Garnache, I. Sagnes, B. Paldus, K. J. Weingarten, R. Grange, M. Haiml, R. Paschotta, U. Keller, and A. C. Tropper, Electron. Lett. **39**, 846 (2003).
[9] T. Wilhelm, J. Piel, and E. Ridle, Opt. Lett. **22**, 1494 (1997).
[10] B. Agate, E. U. Rafailov, W. Sibbett, S. M. Saltiel, K. Koynov, M. Tiihonen, S. Wang, F. Laurell, P. Battle, T. Fry, T. Roberts, and E. Noonan IEEE J. Sel. Top. Quantum Electron. **10**, 1268 (2004).
[11] N. Xiang, F. Lin, H. P. Li, H. F. Liu, W. Liu, W. Ji, and S. J. Chua, Thin Solid Films **515**, 4484 (2007).
[12] F. Lin, N. Xiang, X. C. Wang, J. Arokiaraj, W. Liu, and S. J. Chua, J. Electrochem. Soc. **155**, H307 (2008).
[13] S. Gupta, J. F. Whitaker, and G. A. Mourou, IEEE J. Quantum Electron. **28**, 2464 (1992).
[14] E. Lugagne Delpon, J. L. Oudar, N. Bouché, R. Raj, A. Shen, N. Stelmakh, and J. M. Lourtioz, Appl. Phys. Lett. **72**, 759 (1998).
[15] J. T. Gopinath, E. R. Thoen, E. M. Koontz, M. E. Grein, L. A. Kolodziejski, E. P. Ippen, and J. P. Donnelly, Appl. Phys. Lett. **78**, 3409 (2001).
[16] S. Suomalainen, A. Vainionpää, O. Tengvall, T. Hakulinen, S. Karirinne, M. Guina, and O. G. Okhotnikov, Appl. Phys. Lett. **87**, 121106 (2005).
[17] S. W. Feng, Y. C. Cheng, Y. Y. Chung, C. C. Yang, M. H. Mao, Y. S. Lin, K. J. Ma, and J. I. Chyi, Appl. Phys. Lett. **80**, 4375 (2002).
[18] E. S. Jeon, V. Kozlov, Y.-K. Song, A. Vertikov, M. Kuball, A. V. Nurmikko, H. Liu, C. Chen, R. S. Kern, C. P. Kuo, and M. G. Craford, Appl. Phys. Lett. **69**, 4194 (1996).
[19] P. Lefebvre, J. Allègre, and H. Mathieu, Mater. Sci. Eng., B **59**, 307 (1999).
[20] S. F. Chichibu, T. Azuhata, H. Okumura, A. Tackeuchi, T. Sota, and T. Mukai, Appl. Surf. Sci. **190**, 330 (2002).
[21] A. Hangleiter, F. Hitzel, C. Netzel, D. Fuhrmann, U. Rossow, G. Ade, and P. Hinze, Phys. Rev. Lett. **95**, 127402 (2005).