



HAL
open science

Impact of ion-implantation-induced band gap engineering on the temperature-dependent photoluminescence properties of InAs/InP quantum dashes

M. Hadj Alouane, B. Ilahi, H. Maaref, B. Salem, V. Aimez, D. Morris, A. Turala, P. Regreny, M. Gendry

► To cite this version:

M. Hadj Alouane, B. Ilahi, H. Maaref, B. Salem, V. Aimez, et al.. Impact of ion-implantation-induced band gap engineering on the temperature-dependent photoluminescence properties of InAs/InP quantum dashes. *Journal of Applied Physics*, 2010, 108 (2), pp.024317. 10.1063/1.3460646 . hal-00623421

HAL Id: hal-00623421

<https://hal.science/hal-00623421>

Submitted on 16 Mar 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Impact of ion-implantation-induced band gap engineering on the temperature-dependent photoluminescence properties of InAs/InP quantum dashes

M. H. Hadj Alouane,¹ B. Ilahi,^{1,a)} H. Maaref,¹ B. Salem,^{2,b)} V. Aimez,² D. Morris,² A. Turala,³ P. Regreny,³ and M. Gendry³

¹Laboratoire de Micro-Optoélectronique et Nanostructures (LMON), Faculté des Sciences, Avenue de l'environnement, 5019 Monastir, Tunisia

²Centre de Recherche en Nanofabrication et Nanocaractérisation (CRN2), Université de Sherbrooke, (Québec) J1K 2R1, Canada

³Institut des Nanotechnologies de Lyon (INL), UMR CNRS 5270, Université de Lyon, Ecole Centrale de Lyon, 36 avenue Guy de Collongue, F-69134 Ecully, France

(Received 19 April 2010; accepted 7 June 2010; published online 30 July 2010)

We report on the effects of the As/P intermixing induced by phosphorus ion implantation in InAs/InP quantum dashes (QDas) on their photoluminescence (PL) properties. For nonintermixed QDas, usual temperature-dependent PL properties characterized by a monotonic redshift in the emission band and a continual broadening of the PL linewidth as the temperature increases, are observed. For intermediate ion implantation doses, the inhomogeneous intermixing enhances the QDas size dispersion and the enlarged distribution of carrier confining potential depths strongly affects the temperature-dependent PL properties below 180 K. An important redshift in the PL emission band occurs between 10 and 180 K which is explained by a redistribution of carriers among the different intermixed QDas of the ensemble. For higher implantation doses, the homogeneous intermixing reduces the broadening of the localized QDas state distribution and the measured linewidth temperature behavior matches that of the nonintermixed QDas. An anomalous temperature-dependent emission energy behavior has been observed for extremely high implantation doses, which is interpreted by a possible QDas dissolution. © 2010 American Institute of Physics. [doi:10.1063/1.3460646]

I. INTRODUCTION

Self assembled quantum dots (QDs) engineering has long been the subject of intense research over recent years, in order to exploit the properties of their discrete atomic-like energy states. Indeed, QDs have several applications in advanced electronic and optoelectronic devices.¹ Furthermore, the fabrication of monolithically integrated QDs based optoelectronic devices is strongly dependent on the selective tuning of their emission wavelength. This can be ensured by highly spatial selective intermixing across the same sample surface.² Among the several existing interdiffusion techniques that have been widely and successively used to study the evolution of the QDs properties, ion implantation and subsequent annealing turn out to be the most appropriate one.^{3–7} Indeed, using suitable ion implantation masks, this approach, allows the feasibility of selective and controlled intermixing in QDs' structures, so one can selectively tune the optical transition energies in the same sample surface. This lead to a better control of the QD emission wavelength which is attractive for the fabrication of multiple-section photonic integrated circuits.⁸ The previous works enrolled in this context have so far been limited to the investigation of the impact of the ion implantation dose on low temperature

optical properties of the QDs structures. Following the evolution of the temperature-dependent optical properties of intermixed quantum islands helps understanding the nature of the optical transitions that might change with the intermixing degree. Such study is also important for better understanding the intermixing process and the accurate control it could offer for designing optoelectronic devices such as broadband light emitting diodes.

In this work, we study the temperature-dependent photoluminescence (PL) properties of InAs/InP quantum dashes (QDas) (also called quantum sticks) selectively intermixed by phosphorus ion implantation and subsequent rapid thermal annealing (RTA). Our study provides major insight into the evolution of the temperature-dependent optical properties of InAs/InP QDas as a function of the intermixing degree.

II. EXPERIMENTS

The samples were grown on sulfur-doped InP substrates using solid-source molecular beam epitaxy. A 200 nm-thick buffer layer was first grown at 480 °C. The InAs QDas were then grown at 520 °C with a 4 monolayers (ML) nominal thickness of InAs. The QDas were covered at 480 °C with a 70 nm-thick InP layer followed by a 50 nm-thick In₅₃Ga₄₇As layer used as a sacrificial layer. Structural studies indicate that the QDas are elongated along the [1-10] direction with typical size of 50–100 nm in length, 22 ± 1.2 nm in width and 2.4 nm in height and with a surface density around 7.5

^{a)}Electronic mail: bouraoui.ilahi@fsm.rnu.tn.

^{b)}Present address: LTM-CNRS/CEA-Grenoble, 17, rue des martyrs, F-38054, Grenoble Cedex 9, France.

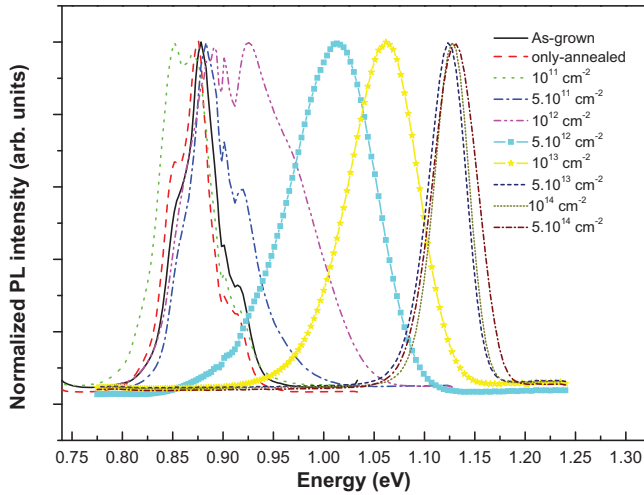


FIG. 1. (Color online) 10 K-PL spectra of InAs/InP QDAs samples as a function of the ion implantation dose.

$\times 10^{10} \text{ cm}^{-2}$.⁹ The samples were then subjected to a phosphorus ion implantation, at 18 keV, at 200 °C with doses ranging from 1×10^{11} to 5×10^{14} ions cm^{-2} .⁵ The energy of phosphorus ions was chosen to confine the damage peak into the InGaAs sacrificial layer that can be selectively removed after the RTA process. After implantation, the samples were annealed at 650 °C for 120 s to set off the atomic intermixing. For comparison, a reference sample (only annealed) was also prepared.

For the PL measurements, the samples were excited with the 514.5 nm line of an Ar⁺ laser and the spectra were collected using a thermoelectrically cooled InGaAs photodetector using a conventional lock-in technique.

III. RESULTS AND DISCUSSION

Figure 1 shows the 10 K PL spectra of the as-grown sample, the reference sample and the samples implanted at

various doses and subsequently annealed. The presence of sharp water-vapor absorption bands between 0.85 and 0.91 eV are artifacts of our detection system and unfortunately tends to deform the PL emission band in that spectral range. The absence of PL shift between the as-grown and the reference sample allows the investigation of the intermixing purely produced by the phosphorus ion implantation. Increasing the ion doses induces a blueshift in the emission energy and fluctuation of the PL linewidth. Indeed, previous study⁵ of these structures revealed that the QDAs emission wavelength can be selectively tuned up to 350 nm. This value corresponds to the band gap tuning limit for this system which is achieved for an implantation dose of 5×10^{13} ions cm^{-2} . Higher implantation doses result in a saturation of the blueshift and a decrease in the integrated PL intensity. The QDAs are also found to be inhomogeneously intermixed for ion implantation doses up to 10^{12} ions cm^{-2} resulting in an increase in the PL linewidth. For higher implantation doses, a decrease in the PL linewidth has been found to occur suggesting that the QDAs size, composition and the strain distributions evolve toward more uniform ones. Such behavior has also been reported for InAs/GaAs QDs system where an onset of active point defects per dot is required for homogeneous intermixing.¹⁰

A complete set of temperature-dependent PL spectra have been obtained for each sample. Figure 2 shows the PL spectra obtained for three significant samples of the investigated series of QDAs structures, at temperatures ranging from 10 K to 300 K. The temperature-dependent QDAs PL line shape and emission energy are found to be strongly dependent on the intermixing degree. For the nonintermixed sample a continuous redshift in the emission band is observed which is characteristic of a Varshni-like temperature dependence of the band gap energy [see Fig. 2(a)]. Atypical sigmoidal emission energy and V-shaped PL linewidth have been observed for intermediate ion implantation doses in the 5×10^{11} – 10^{13} ions cm^{-2} range [see Fig. 2(b)]. For implan-

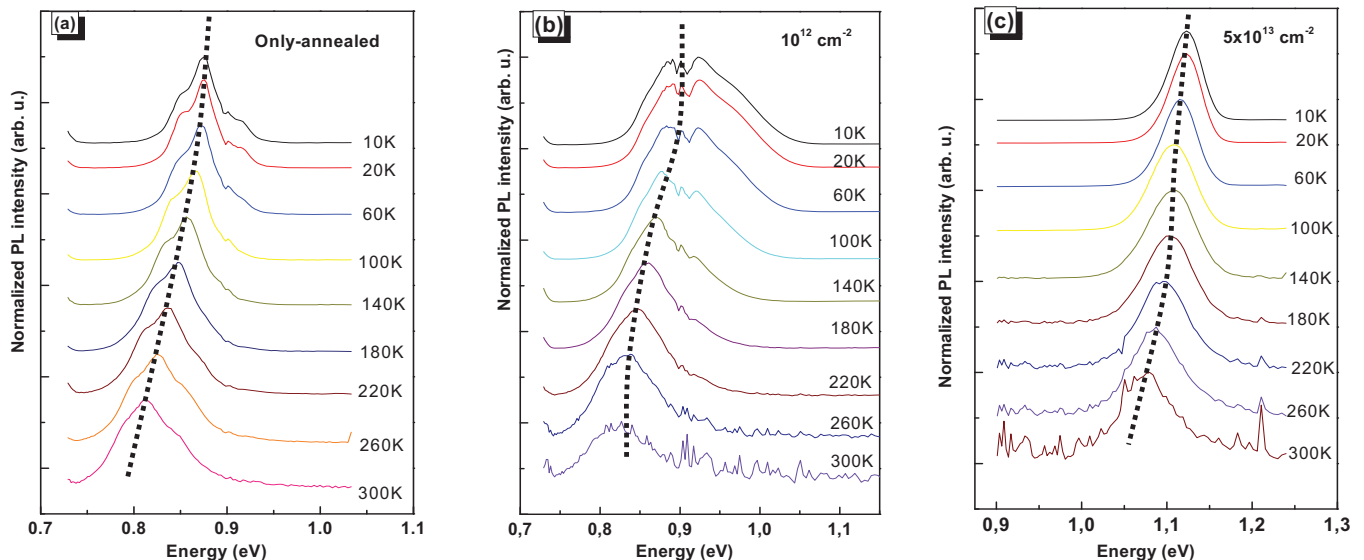


FIG. 2. (Color online) Temperature induced changes in the PL spectrum for three studied QDAs samples: a nonintermixed QDAs sample (a), and two samples implanted with phosphorous ions at a dose of 10^{12} ions cm^{-2} (b) and 5×10^{13} ions cm^{-2} (c), respectively. All spectra are normalized to the PL peak maximum.

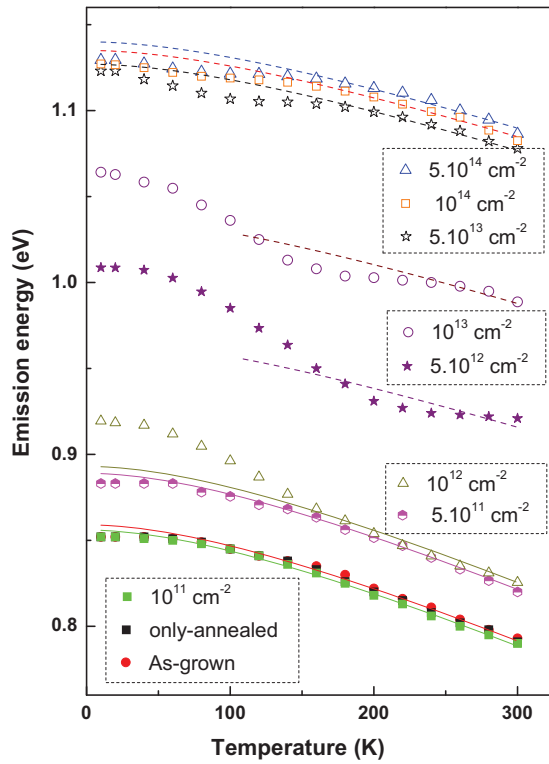


FIG. 3. (Color online) Temperature dependence of the PL peak energy of the investigated samples. The symbols are experimental data and the solid lines are calculated according to the Varshni law.

tation doses beyond the band gap tuning limit ($\geq 5 \times 10^{13}$ ions cm^{-2}), the temperature dependence of the emission energy is similar to the one observed for nonintermixed sample [see Fig. 2(c)] and the PL linewidth exhibits only a slight increase with increasing temperature.

The above-mentioned behaviors are better revealed in Fig. 3 in which we have plotted the energy of the emission band maximum versus the temperature, for each sample. Except for samples showing a very large PL linewidth, these data points are well reproduced using the empirical Varshni relation¹¹

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T},$$

with α and β parameters approaching those found for the InAs material.¹² The as-grown sample data points are best reproduced for parameters $\beta=220$ K and $\alpha=3.9 \times 10^{-4}$ eV K^{-1} , within a 10% confidence on these values. The same fitting parameters have been used for the bottom four curves (solid lines). For these samples, the low temperature data points (<50 K) are systematically below the empirical curves by about 5 meV. Similar behavior has been reported for InAs/GaAs QDs and attributed to the carriers' localization at low temperature.^{13,14} For the topmost three curves corresponding to a high degree of intermixing, the bowing of the curves at high temperatures is reduced compared to the one observed for the four bottom curves. We thus use $\beta=220$ K and a smaller value of $\alpha=2.9 \times 10^{-4}$ eV K^{-1} in order to pass through these high-temperature data points (160–300 K). It is interesting to note

that the 10 K-data points are again below the empirical curves for this set of samples. The corresponding energy difference reaches about 11 meV for the sample ion-implanted at the highest dose. Additionally, the discrepancy between experimental data and empirical curves extend up to 160 K. In this situation, the large energy difference might be related to an extra confinement of the exciton. This behavior is similar to that observed for III-V-N quantum wells.¹⁵ In fact, for that system the low temperature PL emission arises from localized states located a few tens of millielectron volt below the quantum well's ground state. In our case, the high implantation doses (around the band gap tuning limit) are expected to create a high density of point defects that may agglomerate into complex defects and stable clusters becoming hard to restore after annealing. Furthermore, when the QDas structures are highly intermixed, the partial dissolution of the QDas to form a quasi-two-dimensional (2D) layer with potential fluctuation becomes very probable.^{16,17} This is likely to be the origin of the carrier's localization at low temperature since carriers collected by the well preferentially locate in regions where the 2D layer/well width is maximum and/or the local strain is minimum. The difference in PL energy between experiment and theory at lowest temperature usually represents the depth of localization.¹⁸

Finally, for samples implanted at intermediate doses (5×10^{12} and 1×10^{13} ions cm^{-2}) it is impossible to reproduce their data points over all the temperature range using a simple empirical Varshni relation. The position of the PL peak decreases rapidly with increasing temperature, an inflexion point is observed in the 100–180 K temperature range, and the curve tends to recover a normal Varshni-like behavior at higher temperatures. The fast redshift in the PL emission energy is typical of thermally activated carrier redistribution from smaller QDas having small activation energy to larger QDas with deeper confining potential.^{19,20} Then the temperature dependence of the PL peak energy observed in the high temperature range is well explained by that fact that PL signal mainly comes from carrier recombination into the smaller QDas.

Further understanding of the influence of the ion implantation dose on the size/compositional distribution of a large ensemble of QDas can be obtained by investigating how the emission peak linewidth evolves with the temperature. The PL peak linewidth of the investigated samples is plotted as a function of the temperature in the Fig. 4. For nonintermixed QDas, namely the as-grown sample, the reference sample and sample implanted at 10^{11} ions cm^{-2} , the initial QDas size dispersion is preserved. The linewidth exhibits a slight continual increase with increasing temperature meaning that the electron phonon scattering is the dominant broadening factor in the whole temperature range.^{21,22} As also, revealed by the evolution of the emission energy (Fig. 3), the temperature-dependent luminescence properties of nonintermixed QDas are not sensitive to carrier's redistribution within the localized states.²³ However, by further increasing the ion implantation dose in the 5×10^{11} – 10^{12} ions cm^{-2} range, the linewidth first decreases at low temperatures (20–150 K) and then increases slightly at higher temperatures. The position of the minimum seems to depend on the ion

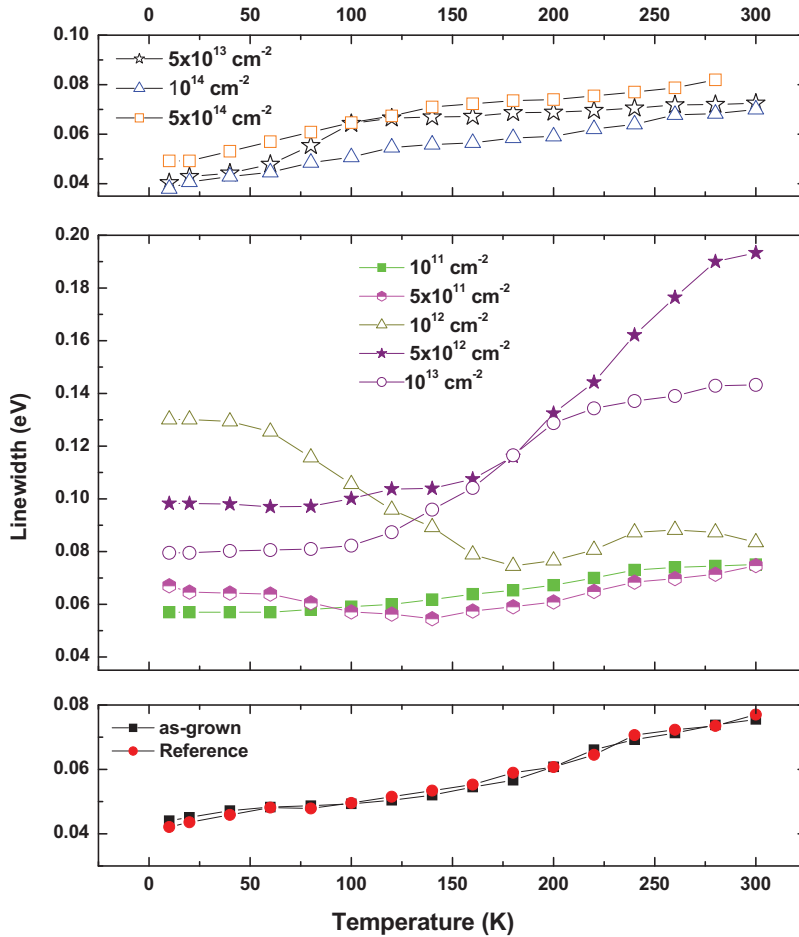


FIG. 4. (Color online) Evolution of the PL peak linewidth as a function of the temperature for the as grown sample, the reference sample and the samples subjected to the ion implantation at different doses and subsequently annealed.

implantation dose. For the samples implanted at 5×10^{12} and 10^{13} ions cm^{-2} the linewidth remains nearly constant at low temperature (up to 180 meV) and increases monotonically at high temperature. For the intermediate implantation dose range (5×10^{11} – 10^{13} ions cm^{-2}), the appearance of such low temperature PL peak linewidth behavior, indicates that the luminescence properties are dominated by carriers redistribution within the broadened localized states induced by the QDas size fluctuation which is strongly affected by the inhomogeneous intermixing. Accordingly, when the temperature increases the carriers predominantly repopulate the QDas of larger sizes having deeper confining potential resulting in the observed PL peak linewidth behavior. This effect is more important for the sample implanted at a dose of 1×10^{12} ions cm^{-2} which appears to be the one with the widest size dispersion. For most of the investigated samples, the PL peak linewidth temperature-dependent behavior still results from the dominant contribution of the electron phonon scattering at high temperatures.²⁴ The PL linewidth is nevertheless smaller at 300 K for the 1×10^{12} ions cm^{-2} sample. The carrier confinement potential is important for this sample and this value increases as carriers get trapped in bigger dashed of the ensemble. Consequently the linewidth broadening mechanism related to carrier-phonon scattering is less important for this sample because only quantum levels of these bigger dashes have to be considered. For higher implantation doses, the QDas initial size distribution is ex-

pected to be recovered and the PL peak linewidth variation with temperature follows that of nonintermixed QDas.

IV. CONCLUSION

The PL emission energy and linewidth temperature behaviors of InAs/InP QDas are found to be strongly dependent on the degree of intermixing showing three different regimes. Usual temperature-dependent PL properties have been observed for both slightly and strongly intermixed QDas structures although the emission energy behavior from highly intermixed QDas suggests the possibility of dissolution to a rough 2D layer. On counterpart, atypical temperature dependences are observed for samples implanted with phosphorous ions at intermediate doses (5×10^{11} – 10^{13} ions cm^{-2}). This result is explained by the broadening of the localized QDas states distribution due to inhomogeneous As/P intermixing and consequent carriers' redistribution within these states. Such analysis reveals the actual limitation of this intermixing process that one has to take into account for the design of optoelectronic devices. It can also be used to guide the development of approaches to further optimize this fabrication process.

¹D. Bimberg, *J. Phys. D* **38**, 2055 (2005).

²S. J. Xu, X. C. Wang, S. J. Chua, C. H. Wang, W. J. Fan, J. Jiang, and X. G. Xie, *Appl. Phys. Lett.* **72**, 3335 (1998).

³P. Lever, H. H. Tan, C. Jagadish, P. Reece, and M. Gal, *Appl. Phys. Lett.* **82**, 2053 (2003).

⁴Y. Ji, W. Lu, G. Chen, X. Chen, and Q. Wang, *J. Appl. Phys.* **93**, 1208

- (2003).
- ⁵B. Salem, V. Aimez, D. Morris, A. Turala, P. Regreny, and M. Gendry, *Appl. Phys. Lett.* **87**, 241115 (2005).
- ⁶H. S. Djie, B. S. Ooi, and V. Aimez, *Appl. Phys. Lett.* **87**, 261102 (2005).
- ⁷B. Ilahi, B. Salem, V. Aimez, L. Sfaxi, H. Maaref, and D. Morris, *Nanotechnology* **17**, 3707 (2006).
- ⁸H. S. Djie, Y. Wang, Y. H. Ding, D. N. Wang, J. C. M. Hwan, X. M. Fang, Y. Wu, J. M. Fastenau, A. W. K. Liu, G. T. Dang, W. H. Chang, and B. S. Ooi, *IEEE J. Sel. Top. Quantum Electron.* **14**, 1239 (2008).
- ⁹M. Gendry, C. Monat, J. Brault, P. Regreny, G. Hollinger, B. Salem, G. Guillot, T. Benyattou, C. Bru-chevallier, G. Bremond, and O. Marty, *J. Appl. Phys.* **95**, 4761 (2004).
- ¹⁰Z. Zaâboub, B. Ilahi, L. Sfaxi, H. Maaref, B. Salem, V. Aimez, and D. Morris, *Nanotechnology* **19**, 285715 (2008).
- ¹¹Y. P. Varshni, *Physica (Amsterdam)* **34**, 149 (1967).
- ¹²S. Paul, J. B. Roy, and P. K. Basu, *J. Appl. Phys.* **69**, 827 (1991).
- ¹³L. Kong, Z. C. Feng, Z. Wu, and W. Lu, *J. Appl. Phys.* **106**, 013512 (2009).
- ¹⁴K. Yamaguchi, E. Waki, and H. Hasegawa, *Jpn. J. Appl. Phys., Part 2* **36**, L871 (1997).
- ¹⁵L. Grenouillet, C. Bru-Chevallier, G. Guillot, P. Gilet, P. Duvaut, C. Van-nuffel, A. Million, and A. Chenevas-Paule, *Appl. Phys. Lett.* **76**, 2241 (2000).
- ¹⁶S. Barik, H. H. Tan, and C. Jagadish, *Nanotechnology* **18**, 175305 (2007).
- ¹⁷C. Dion, P. Desjardins, M. Chicoine, F. Schiettekatte, P. J. Poole, and S. Raymond, *Nanotechnology* **18**, 015404 (2007).
- ¹⁸H. D. Sun, R. Macaluso, M. D. Dawson, F. Robert, A. C. Bryce, J. H. Marsh, and H. Riechert, *J. Appl. Phys.* **94**, 1550 (2003).
- ¹⁹V. G. Dorogan, Y. I. Mazur, J. H. Lee, Z. M. Wang, M. E. Ware, and G. J. Salamo, *J. Appl. Phys.* **104**, 104303 (2008).
- ²⁰T. V. Torchynska, J. L. Casas Espinola, L. V. Borkovska, S. Ostapenko, M. Dybiec, O. Polupan, N. O. Korsunskaya, A. Stintz, P. G. Eliseev, and K. J. Malloy, *J. Appl. Phys.* **101**, 024323 (2007).
- ²¹M. B. Smirnov, V. G. Talalaev, B. V. Novikov, S. V. Sarangov, G. É. Tsyrlin, and N. D. Zakharov, *Phys. Solid State* **49**, 1184 (2007).
- ²²V. G. Talalaev, B. V. Novikov, M. B. Smirnov, V. V. Kachakanov, G. Gobsch, R. Golhahhn, A. Winzer, G. E. Cirilin, V. A. Egorov, and V. M. Ustinov, *Nanotechnology* **13**, 143 (2002).
- ²³Q. Li, S. Barik, H. H. Tan, and C. Jagadish, *J. Phys. D: Appl. Phys.* **41**, 205107 (2008).
- ²⁴Y. I. Mazur, B. L. Liang, Z. M. Wang, G. G. Tarasov, D. Guzun, and G. J. Salamo, *J. Appl. Phys.* **101**, 014301 (2007).