Optical anisotropy in self-assembled InAs nanostructures grown on GaAs high index substrate

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We present a study of the optical properties of InAs self-assembled nanostructures grown by molecular beam epitaxy on GaAs(11*N*)A substrates ($N = 3-5$). Photoluminescence (PL) measurements revealed good optical properties of InAs quantum dots (QDs) grown on GaAs(115)A compared to those grown on GaAs(113)A and (114)A orientations substrate. An additional peak localized at 1.39 eV has been shown on PL spectra of both GaAs(114)A and (113)A samples. This peak persists even at lower power density. Supporting on the polarized photoluminescence characterization, we have attributed this additional peak to the quantum strings (QSTs) emission. A theoretical study based on the resolution of the three dimensional Schrödinger equation, using the finite element method, including strain and piezoelectric-field effect was adopted to distinguish the observed photoluminescence emission peaks. The mechanism of QDs and QSTs formation on such a high index GaAs substrates was explained in terms of piezoelectric driven atoms and the equilibrium surfaces at edges. © 2012 American Institute of Physics. [doi:10.1063/1.3677952]

I. INTRODUCTION

InAs self-assembled quantum dots (QDs) have attracted much attention in the past few years due to the ability to tailor their structural and optical properties for optoelectronic devices such as single photon detectors,¹ 1.3 μm QD lasers for optical fiber communications,^{2,3} and photovoltaic cells.⁴ However, QDs with high density and good uniformity are necessary to achieve the desired active volume. Among ways to improve the QD properties is the utilization of high index substrates. High index GaAs substrates have received considerable attention because of their large impact on the formation and optical properties of the confined structures; this is due to the significant piezo-electric field (PZ-field), surface polarity, and the difference chemical potentials in surfaces.⁵⁻⁹ In fact, the PZ-field considerably changes the electronic structures and the optical properties of the QDs.^{8,10} The screening of the *internal* PZ-field by photogenerated *carriers* leads to a non-linear optical behavior and produces a large blueshift of the transition energies.¹¹⁻¹³

Several reports have exhibited successful growth of self-assembled QDs on high-index substrates, with compared to those grown on (001) surfaces. Henini have demonstrated that the GaAs(113)A corrugated surfaces lead to the optical anisotropy and aligned arrow-shaped InAs QDs along to $[3\bar{3}2]$ direction.¹⁴ Just as well, the theoretical study of Mlinar and Peeters show that the QD size determines the degree of the substrate orientation effects on the electronic and optical properties of InAs QDs grown on GaAs (11*N*), whereas the influence of the shape is a secondary importance.^{10,16} Most recently, a remarkable achievement is the ability to tune

both vertical and lateral alignments of InGaAs QDs on GaAs(N11)B^{17,18} and on GaAs(210) substrates.¹⁹ This is an advantage likely to be transformable to low threshold QD laser diodes using high index substrates. Meanwhile, there have been a lot of studies focused on the B termination, and few authors have reported on InAs grown on GaAs(11*N*)A termination,^{14,20,21} although the substrate termination depends mainly by the piezoelectric fields²² and the chemical potential.²³ On the other hand, and contrary to what has been reported in Refs. 16 and 24, the wetting layer (WL) has a non-neglected effect on the optical properties of quantum dots.^{25,26}

In this work, photoluminescence (PL) dependences of power excitation densities, polarized photoluminescence (PPL), and an adequate theoretical model has been used to investigate the optical transition energy of InAs QDs grown on GaAs(11*N*)A substrate orientations, where $N = 3-5$. These characterization suggest the existence of other nanostructures grown on GaAs (113)A and (114)A, so-called quantum strings (QSTs). The presented work will be helpful to understand the growth mechanism of InAs nanostructures grown on high index substrates.

II. EXPERIMENTAL DETAILS

The InAs/GaAs nanostructures under investigation were grown by molecular beam epitaxy on semi-insulating GaAs substrates with three different orientations (115)A (sample S1), (114)A (sample S2), and (113)A (sample S3). After oxide desorption at 600 °C, a GaAs buffer layer of 0.4 μm thickness was grown at a substrate temperature of 570 °C. Afterward, the growth temperature was reduced to 500 °C and a 2.5 ML InAs layer thickness was deposited at a growth rate of 0.081 Å/s. After 60 s growth interruption, a

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30 nm GaAs cap layer was finally deposited at a growth rate of 2.4 Å/s at 500°C. The reflection high energy electron diffraction pattern changed from streaky to spotty after 2 ML InAs amount deposition, this is demonstrating the transition 2D–3D growth mode. The samples were investigated by the PL and the linear PPL. The PL spectra were measured at lower temperature (10 K) closed-cycle helium cryostat under the excitation of a continuous-wave Ar⁺ laser with an operated wavelength of 514.5 nm. The response signal of the PL

FIG. 1. (Color online) Normalized photoluminescence spectra of InAs nanostructures on (a) GaAs(115)A (sample S1), (b) GaAs(114)A (sample S2), (c) GaAs(113)A (sample S3) at different excitation power densities. The dotted lines show Gaussians fit of S3 spectrum measured at 20 W/cm². The solid arrows represent the energy emission.

FIG. 2. (Color online) The excitation power densities dependence of the ground state QD PL peak position (red circles) and FWHM (blue triangles) for InAs/GaAs(114)A. The dotted line is the guide for the eyes.

was dispersed using a monochromator and detected with a cooled InGaAs photodetector.

III. RESULTS AND DISCUSSION

Figure 1 shows the normalized PL spectra of all samples, measured at 10 K, for different excitation power densities. For the S1 sample, the ground state (GS) emission energy of the InAs QDs is at 1.18 eV. The peak localized at 1.26 eV should originate from the first excited state emission. On the other hand, the GS of QDs in the sample S2 is located at 1.21 eV (peak P0). However, with increasing the excitation power density, the spectrum of sample S2 shows a broadening of the full width at half maximum (FWHM) (about 11.7 meV) accompanied by a blueshift (about 20 meV) (Fig. 2). This behavior may be attributed to the contribution of the excited states in the PL spectra⁸ (or/and) to the tunnel electronic coupling between neighboring quantum dots.²⁷

As shown in Fig. 1(c), the S3 spectrum is well fitted by three Gaussian curves with peak position of 1.238, 1.325, and 1.390 eV those denoted by P1, P2, and P3, respectively. The peak P1 was attributed to the GS emission of larger QDs. As increasing the excitation power density, an enhancement of PL intensity of P2 and P3 peaks is observed (Fig. 1(c)). In spite of the persistence of the P3 peak in S2 and S3 PL spectra at lower excitation power densities, P3

FIG. 3. (Color online) Schematic representation of the conduction band structure with the electron states and the related transition energy.

TABLE I. Comparison of simulated results with experiment data for the energy transitions from conduction to valence band.

GaAs substrate orientation	Experimental value (eV)				Calculated value (eV)				Estimated QD size (nm)	
	E_0	E_1	E_2	E_3	E_0	E_1	E_2	E_3	h	D
(115)A	1.181	1.260	...	...	1.183	1.256	1.331	1.380	3	22
(114)A	1.210	...	...	1.390	1.213	1.291	1.367	1.390	3	20
(113)A	1.238	1.325	...	1.390	1.238	1.316	1.386	1.399	3	19.5

peak perhaps originated from another nanostructure. Thus, P2 is from smaller QDs and first excited state of the larger QDs, and P3 is originated from first excited state of the smaller QDs and another nanostructure (Fig. 3).

It is worth noticing that, the energy shift and the FWHM evolution cannot be observed for PL spectra of sample S3, due to the overlap of the three Gaussian peaks. However, for the sample S1, the FWHM is not very large, in that situation,

FIG. 4. (Color online) Calculated envelope wave function of electrons in a lens-shaped InAs QD with a height of 3 nm, a diameter of 20 nm on GaAs(114)A (a–d), GaAs (113)A (e–h) and a quantum number $l=0-3$ (up to down), respectively. The wetting layer thickness is taken to be 0.56 nm.

the spectral resolution between the excited states and the fundamental transition is more efficient than that of two others samples (S2, S3) where the FWHM is larger (>100 meV).

On the other hand, when comparing the GS emission energy of the three samples QDs, we have demonstrated an increasing of the GS emission energy from 1.181 eV for S1 to 1.238 eV for S3. Three possible reasons can be considered to explain this behavior. (i) The increasing of the hydrostatic strain lead to an enhancement of the energy emission when the disorientation between (001) and (11 $\bar{N}$) was enlarged.¹⁰ (ii) Our theoretical calculation revealed that the PZ-field is about 260 kV/cm for InAs QDs grown on GaAs(113)A compared to 170 and 120 kV/cm for InAs QDs grown on GaAs(114)A and (115)A, respectively. Thus, the interaction between carriers and the great internal PZ-field induced a reduction of the quantum confined Stark effect, then an increasing of the GS emission energy.^{22,28} (iii) Solving the Schrödinger equation affords a numerical estimate of the energy level with regard to the QD size and the substrate orientations. Table I reports the comparison of experiment data with simulated results for the energy transitions from conduction to valence band. The estimated diameter of InAs QD grown on GaAs (114)A and GaAs(113)A is taken to be $D=20$ and 19.5 nm, respectively, and their height is to be 3 nm. Whereas, the size of InAs QD grown on GaAs (115)A is $D=22$ nm and $h=3$ nm. Recently, Liang *et al.* demonstrated a clear evolution from QDs to quantum wells (QWs), when the disorientation between (11 $\bar{N}$) and (001) was enlarged. This evolution revealed an increased critical thickness of InAs WL and a delayed formation of InAs QDs as the substrate disorientation angle augmented from 0° to 15.8°.¹⁵ This behavior leads to the formation of smaller InAs QDs in samples S2 and S3 compared to those formed in sample S1. These results confirm that the slight increasing of the GS emission energy from samples S1 to S3 QDs is partially due to the decrease in the lateral size of InAs QDs.

Finally, in order to identify the holding peak P3 in both PL spectra of samples S2 and S3, we have presented in Fig. 4 the wave function of electrons in a lens-shaped InAs QD on GaAs(114)A and GaAs(113)A when the quantum number l is varied from 0 to 3. As shown in Fig. 4, the carriers are well-localized in the ground and first excited states. However, the wave function associated to the energy transition of 1.39 eV ($l=3$) is found to be outside the dots. In fact, this energy transition cannot be attributed to the WLs, as its PL intensity persists even at lower excitation power density. On the other hand, it was found that the anisotropy of GaAs(113)A and GaAs(114)A surfaces is very favorable to the formation of quantum wires (QWRs). This is due to the disorientation of the substrate and the different terraces, which exist on GaAs(113)A and GaAs(114)A.^{7,23} In our case, the InAs amount deposition (2.5 MLs) is not sufficient to the growth of QWRs in samples S2 and S3. Therefore, the peak P3 may be originated from QSTs. So as to study the anisotropy of the nanostructures, we have investigated the linear PPL for all samples. The PPL spectra are performed, at 10 K and at lower excitation power densities, to take out the PL excited states emissions. The degree of linear polarization (DLP) was defined as the ratio of the difference

of PL intensities for the two mutually orthogonal directions $[\bar{1}10]$ and $[NN\bar{2}]$ to the sum of these intensities.

Figures 5(b) and 5(c) show that the peak P3 has a DLP of about 20% for S2 and 35% for S3. In comparison, the typical linear polarization for the InGaAs QWRs is between 16% and 60%.^{29–31} As a result, the DLP of the peak P3 is comparable to the DLP of small QWRs, then, we can confirm our attribution of this PL peak to the QSTs emission energy. Moreover, we note that the higher DLP of P3 for S3 sample compared to S2 is caused by the taller QSTs trained on GaAs(113)A due to the great internal piezoelectric-field on the GaAs(113)A than those on GaAs(114)A surface. However, the weak optical anisotropy (DLP $\sim$ 10%) reported in DLP of sample S1 (Fig. 5(a)), implies that the InAs QDs grown on GaAs(115)A is slightly elongated along to the $[55\bar{2}]$ direction. Similar behavior has been observed previously by using the scanning tunneling microscopy and the atomic force microscopy in the InGaAs/GaAs(311)A QDs^{14,32} and the InAs/GaAs(211)B QDs⁸ and this elongated QDs is generally accompanied by a lateral ordering.^{8,14,17,32–34}

The extending of the QDs and QSTs along to the $[55\bar{2}]$, $[22\bar{1}]$, and $[33\bar{2}]$ direction for samples S1, S2, and S3,

FIG. 5. (Color online) Solid lines: Linear polarized PL spectra of the InAs nanostructures on (a) GaAs(115)A, (b) GaAs(114)A, and (c) GaAs(113)A substrates. Blue circles are PL spectrum taken in $[55\bar{2}]$, $[22\bar{1}]$, and $[33\bar{2}]$ directions for (115)A, (114)A, and (113)A samples, respectively, and red triangles are PL spectrum in $[\bar{1}10]$ directions for all samples.

FIG. 6. (Color online) Schematic of the growth mechanism of the QDs and QSTs on the GaAs(113)A and GaAs(114)A surfaces.

respectively, is attributed to the localization of the strain at the step edges and to the bipolar moment generated by the internal PZ-field. In fact, $[NN\bar{2}]$ directions have a minima energy strain. As well, polar semiconductors are characterized by an anisotropic diffusion of atoms^{22,35} and the bipolar moment is larger in the direction of smaller confinement.³⁶ In that situation, $[NN\bar{2}]$ is more polar than $[\bar{1}10]$ direction. On the other hand, no polarized PL spectrum on the lower energy side has been shown in Figs. 5(b) and 5(c). This behavior suggests the existence of smaller QDs or multi-shapes QDs.³⁷ Formation mechanism of these QDs and QSTs is schematically summarized in Fig. 6. Indeed, indium diffusion can be inhibited progressively due to the existence of terraces. As QDs nucleate preferentially along to the step edges, they expand their sizes and coalesce along the $[NN\bar{2}]$ direction. This is followed to form QSTs structures. Other atoms which have not enough surface mobility will be nucleated randomly on the surface terraces. This phenomenon leads to the growth of irregularly QDs shape and size, which was explained by the broad spectrum of S2 and S3 samples.

IV. CONCLUSION

In summary, optical properties of InAs nanostructures grown on GaAs (11*N*)A, where $N=3-5$, are investigated using PL and PPL measurements. A numerical approach to calculate optical transition energies of lens shape QDs with their WLs, including strain and piezoelectric fields are used to explain the obtained PL spectra. PL measurements reveal good optical properties of InAs QDs grown on GaAs(115)A compared to those grown on GaAs(113)A and (114)A oriented substrates. According to the PPL measurements and the theoretical calculation (envelope wave function), we have assigned QSTs formation on GaAs(114)A and (113)A emitted at 1.39 eV and elongated to $[NN\bar{2}]$ direction. The results are explained in terms of PZ-fields driven surface mechanism with considering the strain accumulation on the step edges surfaces.

APPENDIX: THEORETICAL CONSIDERATION

Electron and heavy-hole energy levels in a single lens shape QD with its wetting layer can be obtained by solving the Schrödinger equation using the single band effective mass approximation.³⁸ The Schrödinger equation will be written in cylindrical coordinates, as follows:

$$\left(\frac{-\hbar^2}{2m^*} \left(\frac{\partial^2}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \varphi^2} + \frac{\partial^2}{\partial z^2} \right) + V \right) \psi(r, \varphi, z) = E \psi(r, \varphi, z), \quad (\text{A1})$$

where V represents the 3D confining potential energy and it will be more described later. $\hbar$, m^* , E , and ψ are, respectively, the reduced Planck's constant, the electron or heavy-hole effective mass, the energy, and the envelope function. φ is the azimuthal angle in the range of $[0, 2\pi]$ and r and z are, respectively, the radial and axial coordinate. It is assumed, that the solution of Eq. (A1) can be written as

$$\psi(r, \varphi, z) = R(r, z) \Phi(\varphi). \quad (\text{A2})$$

By dividing Eq. (A1) by Eq. (A2) and then multiplying the result with r^2 we obtain the following equation:

$$-\frac{\hbar^2}{2m^*} \left(\frac{r^2}{R(r, z)} \frac{\partial^2 R(r, z)}{\partial r^2} + \frac{r}{R(r, z)} \frac{\partial R(r, z)}{\partial r} + \frac{r^2}{R(r, z)} \frac{\partial^2 R(r, z)}{\partial z^2} \right) + r^2(V - E) = \frac{\hbar^2}{2m^*} \frac{1}{\Phi(\varphi)} \frac{\partial^2 \Phi(\varphi)}{\partial \varphi^2}. \quad (\text{A3})$$

As the left- and right-hand sides of Eq. (3) are independent, we can write

$$\frac{\hbar^2}{2m^*} \frac{1}{\Phi(\varphi)} \frac{\partial^2 \Phi(\varphi)}{\partial \varphi^2} = -\frac{\hbar^2}{2m^*} l^2. \quad (\text{A4})$$

Thus, Eq. (A4) can be solved and give

$$\Phi(\varphi) = \exp(jl\varphi) \quad \varphi \in [0, 2\pi], \quad (\text{A5})$$

where the quantum number l must be an integer to hold the boundary condition $\Phi(0) = \Phi(2\pi)$. Now, we can rewrite Eq. (A3) as follows:

$$-\frac{\hbar^2}{2m^*} \left(\frac{r^2}{R(r, z)} \frac{\partial^2 R(r, z)}{\partial r^2} + \frac{r}{R(r, z)} \frac{\partial R(r, z)}{\partial r} + \frac{r^2}{R(r, z)} \frac{\partial^2 R(r, z)}{\partial z^2} \right) + r^2(V - E) + \frac{\hbar^2}{2m^*} l^2 = 0. \quad (\text{A6})$$

When multiplying this equation by $R(r, z)/r^2$, we find the following equation:

$$-\frac{\hbar^2}{2m^*} \left(\frac{\partial^2 R(r, z)}{\partial r^2} + \frac{1}{r} \frac{\partial R(r, z)}{\partial r} + \frac{\partial^2 R(r, z)}{\partial z^2} \right) + \left(V + \frac{\hbar^2}{2m^* r^2} l^2 \right) R(r, z) = E R(r, z). \quad (\text{A7})$$

Finally, the three-dimensional problem was reduced to only two-dimensional problem. This model was meshed by the finite element method with quadratic Lagrangian elements on a tetrahedral grid (Fig. 7).

FIG. 7. (Color online) Mesh grid of the lens-shaped InAs QDs imbedded in a GaAs matrix.

For the symmetrical axis ($r = 0$), Dirichlet conditions must be imposed at this symmetry line when $l \geq 1$. However, when the quantum number l equal to zero ($l = 0$), the Neumann boundary conditions must be employed to ensure that $\nabla\Psi$ exists at $r = 0$.

In the model described in Fig. 7, we define V to be

$$V = \begin{cases} V_{pz} & \text{inside the InAs QDs and WL regions} \\ V = V_A + V_{ctr} & \text{outside the InAs material (in the barrier)} \end{cases}, \quad (\text{A8})$$

where V_A is the offset of the unstrained conduction or valence band:³⁹

$$V_A = E_{v,av}^0 + \frac{\Delta_0}{3} + E_g \quad \text{for conduction band} \quad (\text{A9})$$

and

$$V_A = E_{v,av}^0 + \frac{\Delta_0}{3} \quad \text{for valence band}, \quad (\text{A10})$$

where Δ_0 is the spin-orbit splitting, E_g is the unstrained bandgap, and $E_{v,av}^0$ is the average valence band-edge.

V_{ctr} is the strain-induced shift of the conduction band or valence band which is expressed as

$$V_{ctr} = a_c(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) \quad \text{in conduction band}, \quad (\text{A11})$$

$$V_{ctr} = a_v(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) - \frac{1}{2}b\left(\varepsilon_{zz} - \frac{1}{2}(\varepsilon_{xx} + \varepsilon_{yy})\right) \quad \text{in valence band}, \quad (\text{A12})$$

where a_c is the deformation potential for the conduction band, a_v is the equibiaxial deformation potential for the valence band, and b is the uniaxial deformation potential.

V_{pz} is the piezoelectric potential energy that can be obtained from

$$\vec{E}_{pz}(r, \varphi, z) = -\frac{1}{e}\vec{\nabla}V_{pz}(r, \varphi, z), \quad (\text{A13})$$

where e is the elementary charge, and E_{pz} is the magnitude of the piezoelectric field for a $(11N)A$ ($N=3-5$) orientated substrate, which can be written as

$$\vec{E}_{pz(11N)A} = \begin{cases} E_{pzr} = \frac{-4e_{14}\delta(C_{11} + 2C_{12})(N^2 - 1)(2 + N^2)}{\varepsilon_0\varepsilon_r D\sqrt{2N^2 + 4}} \\ E_{pz\varphi} = 0 \\ E_{pzz} = \frac{6e_{14}\delta N(C_{11} + 2C_{12})(2 + N^2)}{\varepsilon_0\varepsilon_r D\sqrt{2 + N^2}} \end{cases}, \quad (\text{A14})$$

where

$$D = (2 + N^4)C_{11} + 2(1 + 2N^2)C_{12} + 4(1 + 2N^2)C_{44}. \quad (\text{A15})$$

C_{11} , C_{12} , and C_{44} are the elastic stiffness tensor coefficients, e_{14} is the material piezoelectric constant, and δ is the lattice-constant mismatch:

$$\delta = \frac{a_{GaAs} - a_{InAs}}{a_{InAs}}. \quad (\text{A16})$$

To take into account the substrate orientation, the strain tensor elements must be described with the coordinate system of the epitaxial growth.^{10,16,40} The general $[11N]$ coordinate system is related to the conventional $[001]$ system through a transformation matrix $U = U(\varphi, \theta)$ as follows:

$$U = \begin{pmatrix} \cos \varphi \cos \theta & -\sin \varphi & \cos \varphi \sin \theta \\ \sin \varphi \cos \theta & \cos \varphi & \sin \varphi \sin \theta \\ -\sin \theta & 0 & \cos \theta \end{pmatrix}, \quad (\text{A17})$$

where θ is the polar angle of the $[11N]$ direction relative to the $[001]$ coordinate system: $\varphi = 45^\circ$ and $\sin(\theta) = \sqrt{2}/\sqrt{2 + N}$.

Finally, the material parameters used in our calculations are taken from Ref. 38.

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¹A. J. Shields, M. P. O'Sullivan, I. Farrer, D. A. Ritchie, M. L. Leadbeater, N. K. Patel, R. A. Hogg, C. E. Norman, N. J. Curson, and M. Pepper, *Appl. Phys. Lett.* **76**, 3673 (2000).

²Y. Arakawa and H. Sakaki, *Appl. Phys. Lett.* **40**, 939 (1982).

³N. N. Ledentsov, *Semicond. Sci. Technol.* **26**, 014001 (2011).

⁴S. P. Bremner, M. Y. Levy, and C. B. Honsberg, *Appl. Phys. Lett.* **92**, 171110 (2008).

⁵V. R. Yazdanpanah, Z. M. Wang, and G. J. Salamo, *Appl. Phys. Lett.* **82**, 1766 (2003).

⁶S. Sanguinetti, M. Gurioli, and M. Henini, *Microelectron. J.* **33**, 583 (2002).

⁷H. Wen, Z. M. Wang, and G. J. Salamo, *Appl. Phys. Lett.* **84**, 1756 (2004).

- ⁸G. E. Dialynas, S. Kalliakos, C. Xenogianni, M. Androulidaki, T. Kehagias, P. Komninou, P. G. Savvidis, Z. Hatzopoulos, and N. T. Pelekanos, *J. Appl. Phys.* **108**, 103525 (2010).
- ⁹Z. Li, J. Wu, Z. M. Wang, D. Fan, A. Guo, S. Li, S. Q. Yu, O. Manasreh, and G. J. Salamo, *Nanoscale Res. Lett.* **5**, 1079 (2010).
- ¹⁰V. Mlinar and F. M. Peeters, *J. Mater. Chem.* **17**, 3687 (2007).
- ¹¹E. A. Caridi, T. Y. Chang, K. W. Goossen, and L. F. Eastman, *Appl. Phys. Lett.* **56**, 659 (1990).
- ¹²K. Nishi and T. Anan, *J. Appl. Phys.* **70**, 5004 (1991).
- ¹³I. Sela, D. E. Watkins, B. K. Laurich, D. L. Smith, S. Subbanna, and H. Kroemer, *Appl. Phys. Lett.* **58**, 684 (1991).
- ¹⁴M. Hanini, *Phys. Rev. B* **57**, 6815 (1998).
- ¹⁵B. L. Liang, Zh. M. Wang, K. A. Sablon, Yu. I. Mazur, and G. J. Salamo, *Nanoscale Res. Lett.* **2**, 609 (2007).
- ¹⁶V. Mlinar and F. M. Peeters, *Appl. Phys. Lett.* **89**, 261910 (2006).
- ¹⁷B. L. Liang, Zh. M. Wang, Yu. I. Mazur, V. V. Strelchuck, K. Homes, J. H. Lee, and G. J. Salamo, *Nanotechnology* **17**, 2736 (2006).
- ¹⁸M. Schmidbauer, S. Seydmohamadi, D. Grigoriev, Zh. H. M. Wang, Yu. I. Mazur, P. Schafer, M. Hanke, R. Kohler, and G. J. Salamo, *Phys. Rev. Lett.* **96**, 066108 (2006).
- ¹⁹Z. M. Wang, Y. Z. Xie, V. P. Kunets, V. G. Dorogan, Y. I. Mazur, and G. J. Salamo, *Nanoscale Res. Lett.* **5**, 1320 (2010).
- ²⁰L. Bouzaïene, F. Saidi, L. Sfaxi, and H. Maaref, *Physica B* **405**, 744 (2010).
- ²¹M. Bennour, L. Bouzaïene, F. Saidi, L. Sfaxi, and H. Maaref, *J. Nanopart. Res.* **13**, 6527 (2011).
- ²²S. Sanguinetti, M. Gurioli, E. Grilli, and M. Guzzi, *Appl. Phys. Lett.* **77**, 1982 (2000).
- ²³Sh. Seydmohamadi, H. Wen, Zh. M. Wang, and G. J. Salamo, *Mater. Res. Soc. Symp. Proc.* **849**, 854E (2005).
- ²⁴M. Baira, L. Bouzaïene, L. Sfaxi, H. Maaref, O. Marty, and C. Bru-Chevallier, *J. Appl. Phys.* **105**, 094322 (2009).
- ²⁵L. Seravalli, G. Trevisi, P. Frigeri, S. Franchi, M. Geddo, and G. Guizzetti, *Nanotechnology* **20**, 275703 (2009).
- ²⁶R. V. N. Melnik and M. Willatzen, *Nanotechnology* **15**, 1 (2004).
- ²⁷T. V. Lippen, A. Yu. Silov, and R. Nötzel, *Phys. Rev. B* **75**, 115414 (2007).
- ²⁸W. Ma, X. Wang, Z. Wang, M. L. Hussein, J. Shultz, M. Xiao, and G. J. Salamo, *Phys. Rev. B* **67**, 035315 (2003).
- ²⁹W. Ma, R. Nötzel, A. Trampert, M. Ramsteiner, H. Zhu, H.-P. Schönherr, and K. H. Ploog, *Appl. Phys. Lett.* **78**, 1297 (2001).
- ³⁰V. G. Dorogan, Zh. M. Wang, V. P. Kunets, M. Schmidbauer, Y. Z. Xie, M. D. Teodoro, P. M. Lytvyn, Yu. I. Mazur, and G. J. Salamo, *Mater. Lett.* **65**, 1427 (2011).
- ³¹P. Ils, Ch. Gréus, and A. Forchel, *Phys. Rev. B* **51**, 4272 (1995).
- ³²W. Jiang, H. Xu, B. Xu, W. Zhou, Q. Gong, D. Ding, J. Liang, and Z. Wang, *J. Vac. Sci. Technol. B* **19**, 197 (2001).
- ³³Zh. M. Wang, Y. I. Mazur, Sh. Seydmohamadi, and G. J. Salamo, *Appl. Phys. Lett.* **87**, 213105 (2005).
- ³⁴Zh. M. Wang, Y. Z. Xie, V. P. Kunets, V. G. Dorogan, Y. I. Mazur, and G. J. Salamo, *Nanoscale Res. Lett.* **5**, 1320 (2011).
- ³⁵S. A. Blokhin, A. M. Nadtochiy, A. A. Krasivichev, L. Ya. Karachinsky, A. P. Vasil'ev, M. V. Maximov, A. E. Zhukov, N. N. Ledentsov, and V. M. Ustinov, *Tech. Phys. Lett.* **36**, 1079 (2010).
- ³⁶S. Noda, T. Abe, and M. Tamura, *Phys. Rev. B* **58**, 7181 (1998).
- ³⁷P. Yu, W. Langbein, K. Leosson, J. M. Hvam, N. N. Ledentsov, D. Bimberg, V. M. Ustinov, A. Yu. Egorov, A. E. Zhukov, A. F. Tsatsul'nikov, and Yu. G. Musikhin, *Phys. Rev. B* **60**, 16680 (1999).
- ³⁸M. Grundmann, O. Stier, and D. Bimberg, *Phys. Rev. B* **52**, 11969 (1995).
- ³⁹V.-G. Stoleru, D. Pal, and E. Towe, *Physica E* **15**, 131 (2002).
- ⁴⁰E. A. Caridi and J. B. Stark, *Appl. Phys. Lett.* **60**, 1441 (1992).