# TEMPERATURE INFLUENCE ON $In_{0,3}Ga_{0,7}As$ / $GaAs$ NANOSTRUCTURES OF VCSEL LASERS WITH QUANTUM WELLS

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**Abstract.** *Transitions hh,lh1-e1(1s), hh1,lh1-e2(1s), hh2,lh2 -e2(1s), hh3,lh3,-e3(1s) and the particularities conditioned by quantum dots (QD) produced on the boundaries of nanolayers and buffer layer had been revealed in reflection and transparency spectra of quantum wells (QW) of $In_{0,3}Ga_{0,7}As/GaAs$. The reflection and transparency contour lines had been calculated, as for the single oscillatory as for double oscillatory model. The oscillator's force and the dumping factor for QW and QD transitions had been calculated. The radiative lifetime of exciton in QW and QD is the same for the studied structure $t_o = (2\Gamma_0)^{-1} \approx 2\text{-}10^{-12}$ , $c = 5ps$.*

**Keywords:** *quantum wells, quantum dots, VCSEL, heterostructures.*

## I. Introduction

Injection lasers had been manufactured basing on QW and QD nanostructures, which prove a high temperature stability of the threshold current density $J_{th}$, a low value of $J_{th}$ and the emission in a continuous regime at room temperature with an output power up to 3W [1 – 3]. VCSEL lasers based on $In_{0,3}Ga_{0,7}As/GaAs$ nanostructures are used in different optoelectronic communication systems.

## II. Experimental method

The measurement of reflection and transparency spectra were made using МДР-2 and JASCO-670 spectrometers at 10K and 300K temperatures, for S- and P- polarizations and different angles of incident light on the surface of $In_{0,3}Ga_{0,7}As/GaAs$ heterostructures with QW.

## III. Experimental results and discussions

The reflection and transparency coefficients of heterostructures with quantum wells are easily defined as [2, 3]:

$$\omega_0^* = \omega_o + r_{10}\,\Gamma_o \sin 2\varphi, \qquad \Gamma_o = \Gamma_o\,(1 + r_{10}\cos 2\varphi). \tag{1}$$

Here $\omega_o^*$ , $\Gamma_o=(2\tau_o)^{-1}$, $\Gamma=(2\tau)^{-1}$ are the resonance frequency the radiative, and non-radiative exciton damping parameters, respectively, renormalized taking into account the interaction of the exciton with the light wave induced by this exciton and reflected from the external surface. After a number of transformations of the reflection and absorption coefficients, the following expression is obtained for the reflection coefficient [2, 3]:

$$R(\omega) = |r(\omega)|^2 = R_0 + \frac{A+Bx}{1+x^2} \tag{2}$$

where: $X = \frac{\omega - \omega_0^*}{\Gamma}$, $R_0 = r_{01}^2$

$$A = t_{01}t_{10}S[t_{01}t_{10}S - 2r_{01}(1 + S^*)cos2\varphi]. \quad (3)$$

According to the Fresnel's formula, at normal incidence of the light on the crystal surface we have:

$$r_{10} = -r_{01} = \frac{n_b - 1}{n_b + 1}, \quad t_{01}t_{10} = \frac{4n_b}{(n_b + 1)^2}. \quad (4)$$

The A and B coefficients can take values of different signs depending on the distance between the centers of the quantum well and the external surface and, particularly, they can alternately vanish. At A = 0, B<0, the resonance contour consists of a maximum at $\omega < \omega_0^*$ and a minimum at $\omega > \omega_0^*$. At B = 0, there is a maximum (A > 0) or a minimum (A < 0) in the spectrum. Figure 1 shows the reflection spectra with two layers with QW for VCSEL lasers. As it is evident form the figure, reflection spectra maxima are visible, i.e. the A<0 coefficient. Interband transitions hh1-e1, hh2-e2 and hh3-e3 are observed in the QW layer for the 1 - 1.3eV energy region. Particularities are revealed in the energy interval 0.6 - 0.9eV, which are conditioned by QD in the studied structure. The reflection spectra contours are calculated basing on dispersion correlations for excitonic transitions in QW [2].

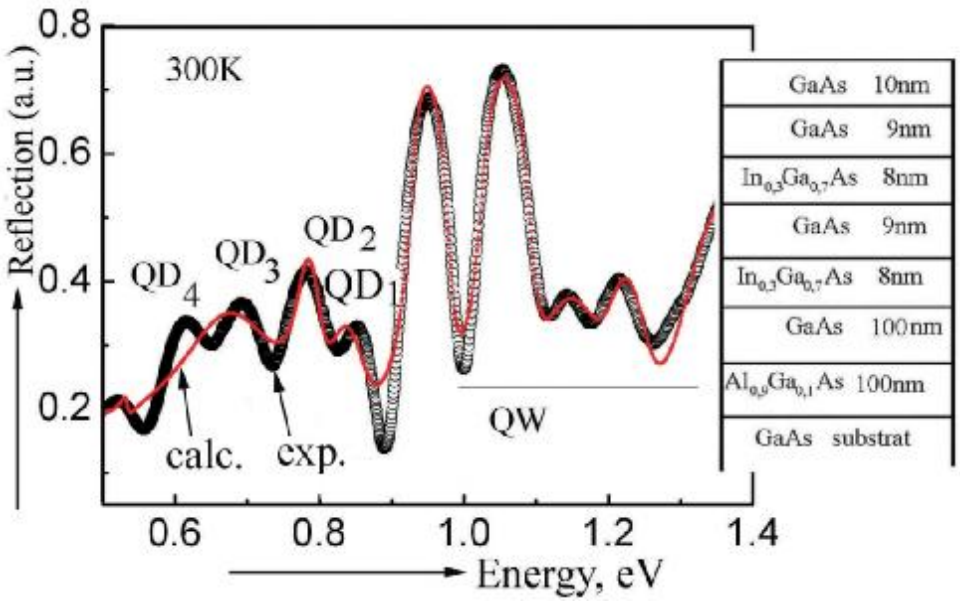


Fig. 1 Reflection spectra of VCSEL laser structures with QW layers limited by barriers. The layers' structure is presented in the right part of the figure.

The knowledge of semiconductor band structure parameters, particularly the effective mass of carriers, as well as the dependence of these parameters on the composition of layers and temperature is necessary for the determination of parameters of quantum well structures. The valence band of III-V compounds is four-fold degenerated at k= 0. The application of an axial deformation leads to the appearance of two maxima of the valence band with a small energy separation (the heavy and the light holes). The different maxima (minima) shift to a different degree with the application of an

axial deformation in an arbitrary direction. These extremums shift in a higher degree with the temperature change. It is difficult to determine the temperature coefficient of the heavy and light holes valence bands shift. These difficulties are partially overcome in bulk semiconductors by investigating the exciton absorption spectra and the interband magneto-optic effect. For the determination of the temperature coefficient of the heavy and light holes valence bands in $In_{0,3}Ga_{0,7}As/GaAs$ heterostructures, we measured the transmission spectra of quantum well structures at temperatures of 30 K and 300 K (Fig. 2). The digital values on Fig. 6 indicate energy position of the observed transitions in the investigate quantum well structure. The temperature coefficients of the quantized energy levels as well as the electron and hole bands responsible for these transitions were estimated from these data. The results presented in Table 1 show that the light holes valence bands have a large value of the temperature coefficient, for which $\beta=\Delta E/\Delta T$ varies in the limits of $(5.7\text{-}7.9)x10^{-5}$ eV/K. The temperature coefficient of the heavy holes valence bands varies in the limits of $(4.4\text{-}5.0)x10^{-5}$ eV/K. The splitting of the 1S states of light and heavy holes ($\Delta E_1$=lh1-hh1) at 300K equals to 1.7 meV, while it is equal to 3.7 meV at 30 K. The splitting of the $\Delta E_{12}$=lh2-hh2 equals to 4.3 meV and 10.1 meV at 300K and 30K, respectively. The same value of splitting is observed for the $\Delta E_2$=lh2-hh2 interval at both the 300 K and 30 K temperatures. The splitting of the $\Delta E_{33}$=lh3-hh3 transitions is larger, it being equal to 7.6 meV and 16.6 meV at 300 K and 30 K, respectively.

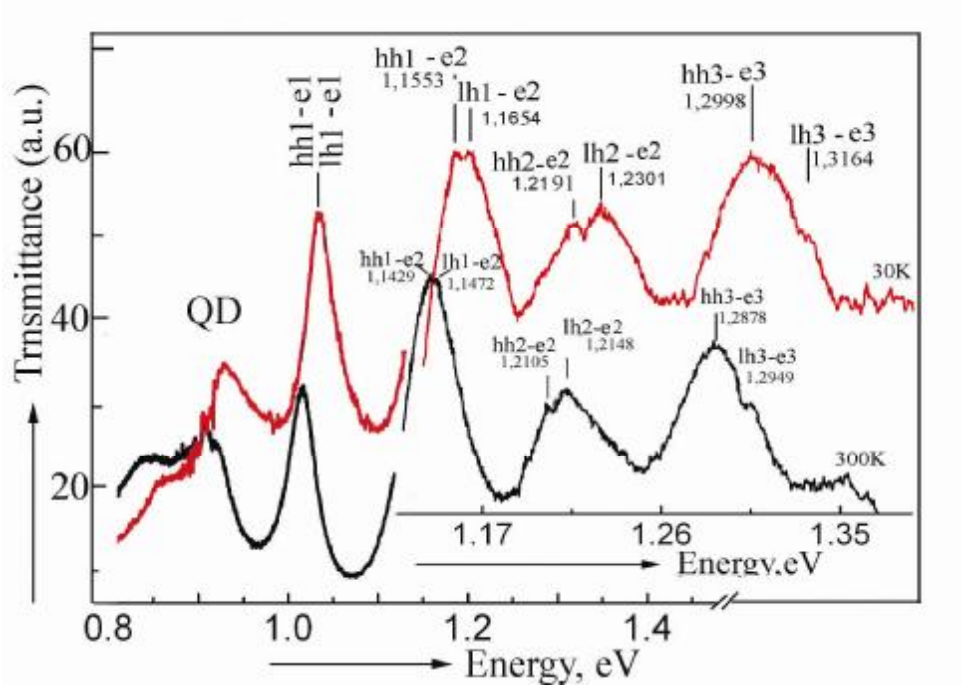


Fig. 2 Transmission spectra of a $In_{0,3}Ga_{0,7}As/GaAs$ quantum well structure measured at 30K and 300 K, and the energy of electronic transitions in quantum wells. The high-energy part of the spectrum is presented in a larder scale for the sake of clarity.

**Table 1 The energy of electronic transitions in quantum wells of a $In_{0,3}Ga_{0,7}As/GaAs$ structure.**

| Transitions (1s) | $E_i$ (300K) eV | $E_i$ (30K) eV | $\Delta E=E_i^{30K}-E_i^{300K}$ | $B=\Delta E_i/\Delta T$,[eV/grade] |
|---|---|---|---|---|
| lh1 - e1 | 1,0249 | 1,0405 | 0,0156 | $5,8x10^{-5}$ |
| hh1 - e1 | 1,0232 | 1,0368 | 0,0136 | $5,0x10^{-5}$ |
| $\Delta E_1$=lh1-hh1 | 1,7meV | 3,7meV | | |
| lh1-e2 | 1,1472 | 1,1654 | 0,0182 | $6,7x10^{-5}$ |
| hh1-e2 | 1,1429 | 1,1553 | 0,0124 | $4,6x10^{-5}$ |
| $\Delta E_{12}$=lh1-hh1 | 4,3meV | 10,1meV | | |
| lh2-e2 | 1,2148 | 1,2301 | 1,0153 | $5,7x10^{-5}$ |
| hh2-e2 | 1,2105 | 1,2191 | 0,0086 | $3,2x10^{-5}$ |
| $\Delta E_2$=lh2-hh2 | 4,3meV | 11,0meV | | |
| lh3-e3 | 1,2949 | 1,3164 | 0,0215 | $7,9x10^{-5}$ |
| hh3-e3 | 1,2878 | 1,2998 | 0,0120 | $4,4x10^{-5}$ |
| $\Delta E_3$=lh3-hh3 | 7,0meV | 16,6 meV | | |

The change of the crystal temperature as well as of quantum well structures leads to the change of the crystal lattice parameter as well as of the quantum well structure. The change of the lattice parameter (at low deformation potentials) leads to the change of electronic energy levels which are described by the deformation potential tensor. The change of the level energy in a point r of the crystal is given by the following expression [6, 7].

$$\delta E(r) = \sum_{ij} E_{ij} W_{ij}(r) \tag{5}$$

where $W_{ij}(r)$ is the deformation tensor. Uni-axial or bi-axial deformation can cause complicated effects due to the change of the crystal symmetry. In the case of uni-axial deformation, the energy of the band edges $E_c$ and $E_v$ of a cubic crystal subjected to the deformation $\Delta$, can be written in the following form

$$E_i(\Delta) = E_l(0) + E_1(\Delta). \tag{6}$$

At a given temperature and pressure,

$$E_i(T,P) = E_i(T) + E_1\Delta(P), \tag{7}$$

where $\Delta(P)$ is the deformation caused by the applied pressure $P$, and $E_l(T)$ is the energy of the band edge at normal pressure, which is given by the following expression

$$E_1(T) = E_l(0) + E_{5l}(T) + E_1\Delta(T). \tag{8}$$

Here $E_{s,l}$ are the energy levels, and $\Delta(T)$ is the temperature deformation. One can write further

$$E_1(T, P) = E_1(0) + E_{s,l}(T) + E_1\Delta(T, P). \tag{9}$$

For the energy levels determining the bandgap we have

$$E_g(T,P) = E_в(0) + [E_{s,c}(T) - E_{s,v}(T)] + (E_{1,c} - E_{1,v})\,\Delta(T,P) \tag{10}$$

where $\Delta(T, P) = \int_0^T \left(\frac{\partial \Delta}{\partial T}\right)_{Po} dT + \left(\frac{\partial \Delta}{\partial P}\right)_T (P - Po)$.

Here the first partial derivative is the temperature coefficient of expansion, and the second partial derivative is the compressibility taken with a negative sign. These macroscopical values have been measured for some semiconductors. From the last equation we have

$$\left(\frac{\partial Eg}{\partial T}\right)_P = \left(\frac{\partial E_{g,c}}{\partial T}\right)_P - \left(\frac{\partial E_{g,v}}{\partial T}\right)_P + [E_{1,c} - E_{1,v}]\left(\frac{\partial \Delta}{\partial T}\right)_P \quad (11)$$

$$\left(\frac{\partial E_g}{\partial P}\right)_T = (E_{1,c} - E_{1,v})\left(\frac{\partial \Delta}{\partial P}\right)_T \quad (12)$$

Therefore, the temperature coefficient of the energy level shift consists of the electron-phonon and the deformation components. Different temperature coefficients of the quantum well exciton energy level shift where found from optical transmission spectra of the investigated hetero-junctions. This is due to different temperature coefficients of the light and heavy holes bands shift, as well by difference of the light and heavy holes effective masses. The energy of the QD transition is equal to 0.9056 eV and 0.9289 eV at 300 K and 30 K, respectively. The temperature coefficient of the QD energy shift $\beta=\Delta E/\Delta T$ is equal to $8.3x10^{-5}$ eV/K. This value does not differ from the temperature coefficient of the energy level shift in QW in the limits of the experimental errors (±1 meV). This observation suggests that, in this structure, the shift of the light and heavy holes bands is determined mainly by the temperature component, not by the deformation one.

There is an ambiguity in literature concerning the determination of band parameters in the $In_yGa_{1-y}As$–GaAs system. The published data concerning the conduction band offset at the $In_yGa_{1-y}As$–GaAs interface $\Delta E_c/\Delta Eg$ ($\Delta E_c$ is the difference of the conduction band bottoms of GaAs and $In_yGa_{1-y}As$, $\Delta Eg$ is the difference of their bandgaps) are different: 0.52 [8], 0.6 [9], 0.7 [9], 0.83[9]. The situation with the data about the heavy holes effective mass in GaAs is similar: $0.62m_0$ [8], $0.52m_0$ [9] ($m_0$ is the free electron mass). There is also a discrepancy concerning the dependence of the bandgap $E_g(y)$ of stressed $In_yGa_{1-y}As$ layers in the GaAs–$In_yGa_{1-y}As$–GaAs system on the In content (y) [8, 9]. When considering the energy spectrum of QW based on the системы ***GaAs–$In_yGa_{1-y}As$–GaAs*** system, we used a mean value of Ec/Eg=0.7 and a linear approximation of the dependence of electron and hole effective masses on the In content (y). The electron effective mass of ***$In_XGa_{1-X}As$*** solid solutions was determined from the relation $m^*_e/m_0 = 0.067-0.0603+0.0163x^2$. The effective masses of electrons $m^*_e$, heavy $m_{hh}^*$ and light $m_{lh}^*$ holes equal to $0.050m_0$, $0.312m_0$, and $0.074m_0$, respectively, at x = 0.3. the bandgap at 300 K was estimated from the relation $E_g = 1.425-1.501x + 0.436\ x^2$ [30,31], and it was found to be equal to 1.014 eV for an $In_XGa_{1-X}As$ layer with x=0.3. At 10 K, the bandgap was determined from the relation $E_g = 1{,}515 - 1{,}584x + 0{,}489x^2$, which is used for the determination of the bandgap at 0K [30, 31]. The bandgap of an $In_XGa_{1-X}As$ layer with x=0.3 was determined to be equal to 1.024eV at 10 K.

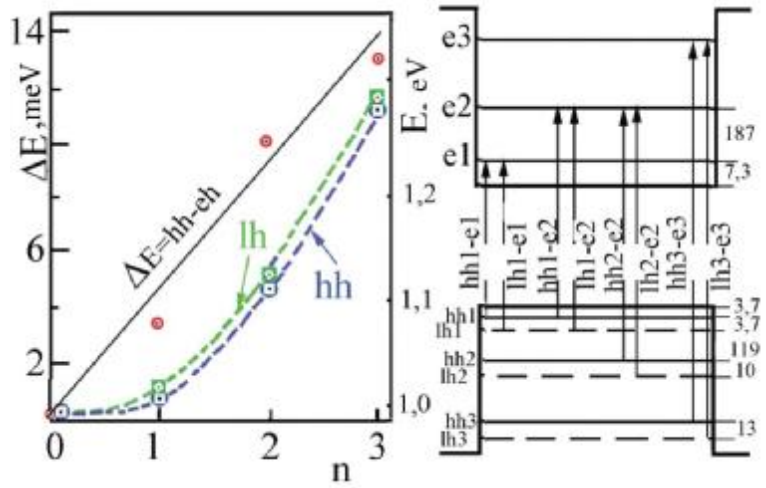


Fig. 3 The dependence of energy position of hh, lh bands and the difference ΔE=hh-eh on the quantum number n (left part of the graph), and the scheme of electron transitions and the energy intervals between the energy levels in QW (right part of the graph).

The temperature coefficient β of the quantum levels hh2-e2 and hh1-e2 equals to $3.2 \times 10^{-5}$ and $4.6 \times 10^{-5}$ eV/K, respectively. The value of $\Delta\beta = \beta(hh1\text{-}e2) - \beta(hh2\text{-}e2) = 1.4 \times 10^{-5}$[eV/K] means that the level hh1 lies below the top of the valence band with an energy separation of 3.7 meV. The energy interval $E(hh1\text{-}e1)\text{-}E_g$ equals 0.011 eV. Consequently, taking into account the energy position of the hh1 level, one can deduce that the e1level is situated 7.3 meV above the conduction band. One can find from the data presented in Table 1 that the energy interval hh1-hh2 equals 119 meV, while the interval e1-e2 is equal to 187 meV.

For the structure considered in this paper, the optical characteristics of the quantum well and the barrier (the coefficients of refraction and exctinction, as well as the real and imaginary parts of the dielectric constant) were calculated from the reflection coefficient by means of the Kramers-Kronig relations.

Fig. 4 presents the spectral dependences of the refractive index n, the extinction coefficient k, the real $\varepsilon_1$ and the imaginary $\varepsilon_2$ parts of the dielectric constant for S-P and P-P light wave polarization calculated from the reflection spectra by means of the Kramers-Kronig relation. $\varepsilon_2$ reaches a value near 270 at the energy of 1.085 eV in the P-P light wave polarization, which suggests that the highest absorption is observed at the resonance value of e1-hh1(1s) transitions.

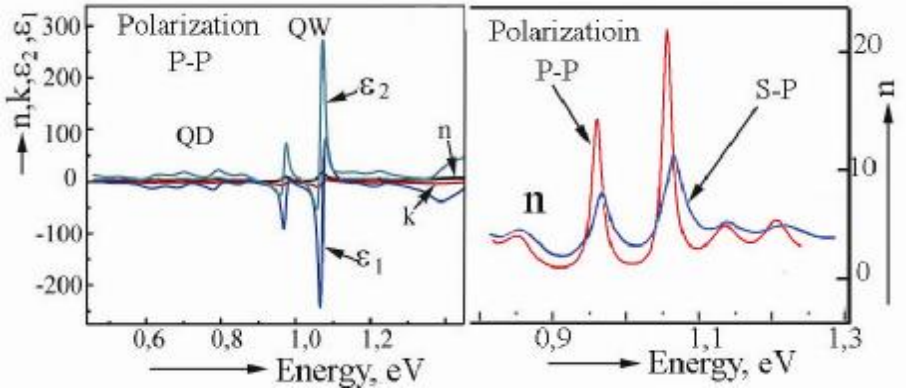


Fig.4 Spectral dependence of the refraction coefficient n, the excitonctions coefficient k, the real $\varepsilon_1$ and the imaginary parts of the dielectric constant for the S-P and P-P light wave polarizations calcu-

lated from the reflection spectra by means of Kramers-Kronig relations.

The obtained results suggest that the highest value of the real part of the refraction coefficient is observed in the P-P polarixation at the resonace energy of 1.085 eV. The spectral dependencies of the refractive index for P-P and S-P polarized lightwaves at resonant values of light frequency are shown in the right part of figure 4.

## IV. Conclusions

The experimental investigations of $In_{0.3}Ga_{0.7}As/GaAs$ heterojunctions with quantum wells revealed the presence of narrow and intensive lines in optical absorption and reflection spectra which are due to the ground states of exciton polaritons in quantum wells. Features caused by quantum dots (QD), formed at the interface of nanolayers and the buffer, have been observed in optical spectra. The contours of the reflection and transmission lines have been calculated both with a single-oscillator, and many-oscillator models. The spectral dependencies of the refractive index n extinction coefficient k, the real $\varepsilon_1$ and imaginary $\varepsilon_2$ parts of the dielectric constant for S-P and P-P polarizations had been determined using the Kramers-Kronig correlations.

## V. References


1. N. A. Maleev, A.E. Zhukov, A.R. Kovsh, S.S. Mihrin, V.M. Ustinov, D.A. Bedarev, B.V. Volovik, I.L. Krestinov, I.N. Kayander, V.A. Ondobljudov, A.A. Suvorova, A.F. Tsatsulinikov, Yu.M. Shernjakov, N.N. Ledentsov, P.S. Kopiev, Zh.I. Alferov, D. Bimberg, Semiconductors physics and techniques, Vol. 34 (2000) , edition 5.
2. E. L. Ivchenko. Optical spectroscopy of semiconductor nanostructures (Alpha Science International, Harrow, UK, 2005).
3. L.E. Vorobjev, E.L. Ivchenko, D.A. Firsov, V.A. Shalygin, Optical Properties of Nanostructures, in: V.I. Iljin, A.Ja. Shik (Eds.), Nauka, Sankt-Petersburg, 2001.
4. A. Dorogan, N. Dragutan, T. Vieru, N. Syrbu. Exciton luminescence in In0.3Ga0.7As/GaAs quantum well heterostructures. Proceedings of Inter. Conf. on Nanotechnologies and Biomedical Engineering (ICNBME-2011). Chisinau, Moldova, July 7-8, 2011. P.83-85.
5. A. Dorogan, N. Dragutan, T. Vieru, N. Syrbu, V. Zalamai. Interband Optical Transitions in the Region of Excitonic Resonance in In0.3Ga0,7As/GaAs Quantum Wells. Proceedings of Inter. Conf. on Nanotechnologies and Biomedical Engineering (ICNBME-2011). Chisinau, Moldova, July 7-8, 2011. P.142-144.
6. J. Bardeen, W. Shockley, Phys. Rev. 80, 72(1950).
7. E. Djonson, Semiconductors and Semimetals, edit. R. K. Willardson, Albert C. Beer, Academ Pres, NEW YORK AND LONDON, 1967, vol.3, p.167-277.
8. I.A. Avrutskii,V.A. Sychugov, B.A. Usievich, Fizika i Tekhnika Poluprovodnikov 25(1991), 1787.
9. G. Ji. D. Huang, U.K. Reddy, T. S. Henderson, R. Houdre, H.Morkoc. J. Appl. Phys., 62, 3366 (1987).