Polarization mode switching and tuning in *p*-AlGaAs/GaAsP/*n*-AlGaAs diodes by compressive stress

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Introduction

The strained heterostructures with quantum wells are the main working materials for semiconductor laser diodes and other optoelectronic devices. They offer wide flexibility for band structure engineering and device modeling and show high sensitivity to both external hydrostatic [1] and uniaxial [2] compression. Thus, under [110] uniaxial compression at P ≈ 5 kbar the electroluminescence spectrum in *p*-$Al_xGa_{1-x}As/GaAs_{1-y}P_y$/*n*-$Al_xGa_{1-x}As$ laser diode demonstrated a blue shift up to 27 meV [3]. Much more dramatic changes take place under uniaxial compression in correlation between transverse electric TE and transverse magnetic TM polarization modes of emitting light [4].

Experimental and calculation details

In this work we present experimental and computational results for strained *p*-$Al_xGa_{1-x}As/GaAs_{1-y}P_y$/n-$Al_xGa_{1-x}As$ laser diode structures. Experimentally investigated structures were grown on Si doped (001)-oriented GaAs substrates by metalorganic vapor phase epitaxy system. The method of uniaxial compression has been described in a special issue [5].

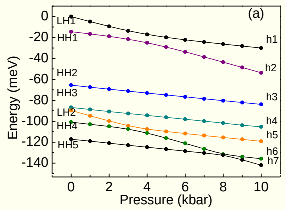
The numerical calculations were performed under uniaxial stress up to 10 kbar along [110], [100] and [001] directions at the temperature of 77 K. The Luttinger-Kohn Hamiltonian with strain terms was self-consistently solved together with Poisson's equation for the electrostatic potential using the finite difference k•p method in the vicinity of the Γ point. The Heterostructure Design Studio software was used to perform the calculations [6].

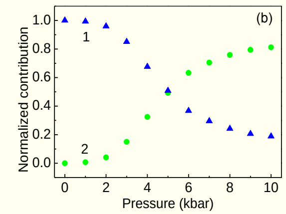
The numerical calculations of uniaxial stress influence on the energy spectrum, wave functions, momentum matrix elements, optical gain of TE and TM polarization modes have been performed for a set of samples with different combinations of the phosphor content y = 0 ÷ 0.20 (with 0.02 interval) and the quantum well width d = 4, 10, 14 and 20 nm.

Results and discussions

The increase of applied uniaxial compression leads to the strong change of the energy spectrum of light hole LH and heavy hole HH quantized levels h1, h2,… h7 in the quantum well (QW), see Fig. 1a. The results of calculations show that at P = 0 the uppermost level h1 is a pure LH state and the next level h2 is a pure HH state (Fig. 1b,c). After h1-h2 anti-crossing at P ≈ 4 kbar, the share of HH states dominates on the level h1, see Fig. 1b. So the topmost level h1 becomes almost of HH nature. As the result, the change of the ground state symmetry in the QW removes the prohibition on the interband transitions only with the TM mode. We can make a conclusion that the stronger the HH states admixture to LH states at the upper level, the larger the advantage of the TE mode. This describes an essential change in the TE/TM mode intensity ratio that occurs under uniaxial compression.

The results of calculations for the experimentally investigated structure demonstrates that in the 14 nm quantum well with phosphor fraction of 0.16 the ratio g_{TM}/g_{TE} of optical gain in the TM and TE modes at zero compression is equals to 8 (Fig. 2). This is quite usual for a structure designed for TM emitting laser diodes. Under compression P = 5.1 kbar in [110] direction the g_{TM}/g_{TE} ratio strongly drops to approximately 5, i.e. in 1.6 times, that is in a good agreement with the experimental data on decrease of relative TM/TE intensity ratio with about 5% of variance, see Fig. 3a. This agreement makes the results of numerical calculations for structures with other QW compositions, thickness, and other directions of applied stress, quite reliable.





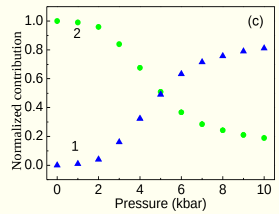


FIG.1. Calculated energy shifts of seven hole levels at the zone center under uniaxial compression (a) and pressure dependence of normalized contribution of basis functions with different angular momentum projection $|m_J|$ = 1/2 (1) and $|m_J|$ = 3/2 (2) into wave functions of h1(b) and h2 (c) hole levels for the $GaAs_{0.84}P_{0.16}$ QW of 4 nm width.

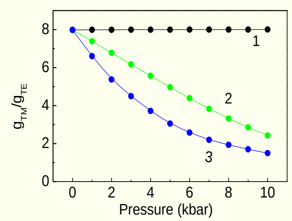
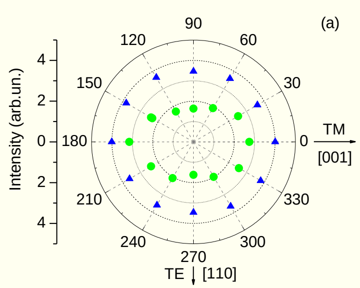


FIG.2. Pressure dependence of the g_{TM}/g_{TE} ratio for the $GaAs_{0.84}P_{0.16}$ QW of 14 nm width under uniaxial compression along [001] (1), [110] (2) and [100] (3) directions.



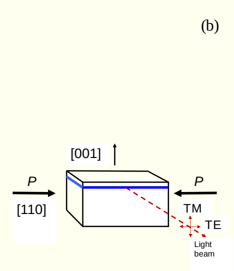
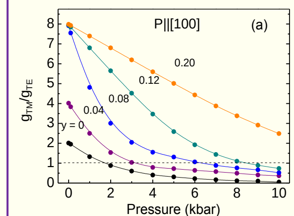
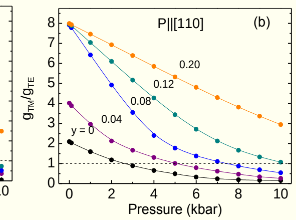


FIG.3. The light intensity dependence on polarizer turn angle for the $GaAs_{0.84}P_{0.16}$ QW of 14 nm width under uniaxial compression along [110] at P = 0 (●) and 5.1 kbar (▲) (a) and the experiment geometry (b).

Fig. 4 shows the results of calculated g_{TM}/g_{TE} ratio in the structures with QWs of two different width and which phosphor concentration *y* varies from 0 to 0.2. The results indicate strong change of g_{TM}/g_{TE} ratio under compression in the plane of the heterostructure both for P || [110] and P || [100] (Fig. 4a,b). This effect is connected with the change of the energy spectrum and wave functions of initially light hole LH and heavy hole HH quantized levels in a QW (Fig. 1). We would like to mention that TM → TE polarization mode switching is possible under moderate pressure if energy difference between the LH1 and HH1 states at P = 0 is rather small.

It should be noted that for structures with a HH ground level in a QW, TE → TM mode transition is possible under compression in [001] direction (Fig. 4c). This is connected with the character of the confinement levels shift in a QW: under compression along [001] direction the levels with initial HH nature move down at the energy scale stronger than the levels with initial LH nature.





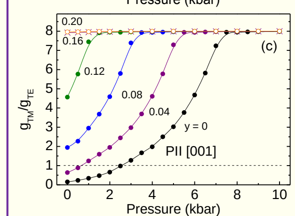


FIG.4. Pressure dependence of g_{TM}/g_{TE} ratio in $GaAs_{1-y}P_y$ QWs under uniaxial compression with phosphor concentration y varies in range of 0-0.2. a) 10 nm QW with compression along [100], b) 10 nm QW with compression along [110] and c) 4 nm QW with compression along [001] .

References

1. Trzeciakowski W, Bercha A, Dybala F, Bohdan R, Adamiec P and Mariani O 2007 *Phys. Stat. Sol. (b)* 244, 179
2. Kolokolov K I, Savin A M, Beneslavski S D, Minina N Ya and Hansen O P 1999 *Phys. Rev.* B 59 7537.
3. Berman I V, Bogdanov E V, Kissel H, Minina N Ya, Shirokov S S and Yunovich A E 2009 *Phys. Stat. Sol. (b)* 246 522
4. Bogdanov E V, Minina N Ya, Tomm J W and Kissel H 2012 *J. Appl. Phys.* 112 093113
5. Minina N Ya, Brandt N B, Savin A M and Bogdanov E V 2008 *J. Phys. Conf. Ser.* 121 032002
6. http://www.optronicsdesign.com - Heterostructure Design Studio, nanostructure semiconductor quantum simulation software