# LATERAL VARIATION AND CONTROL OF THE REFRACTIVE INDEX AND THE TWO-DIMENSIONAL BOUND STATES IN GaAs/GaAlAs SUPERLATTICE STRUCTURES*

E. LENDVAY

Research Institute for Technical Physics,
Hungar. Acad. Sci. Budapest

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## Abstract

In multiquantum-well and superlattice structures the physical properties — e.g. the energy of bound states and the refractive index — strongly depend on the superlattice periodicity. On the other side, the growth rate of the GaAs and GaAlAs is very sensitive to the crystallographical orientation. Applying these properties using nonplanar substrates multiquantum-well structures were grown, where the lattice periodicity were different in the different directions. The structures grown into GaAs grooves or onto linear mesa-structures have boundary planes along their axis where the refractive index perpendicular to the axis was lower than along the axis. This results in a strong wave-guiding making possible to develop a new type of semiconductor laserdiode.

Investigations on III—V semiconductor crystal growth on nonplanar surfaces give important and very useful data for device technologies. In optoelectronics, the widely used GaAs/GaAlAs system is one the most important and interesting heteroepitaxial systems, where this problem has been investigated in detail. For GaAs it was found that the thickness of epitaxial layers depends significantly on the substrate orientation (Chang and Cho, 1977; Nishizawa and Kimura, 1986). Similar orientation dependence was found for GaAlAs, too. The layer thickness variation over a nonplanar substrate surface makes possible to produce the so called buried heteroepitaxial laser structures necessary e.g. for high power and long life-time *LD* devices, as well as the growth of different structures used for III—V sensors, detectors and planar devices. Previous studies of orientation dependent growth rate, however, were limited to relatively thick epitaxial layers, and only a few papers dealt with quantum well structures (Kapon, Tamargo and Hwang, 1987; Kamon, Shimazu, Kimura, Mihard and Ishii, 1986; Kahen and Leburton, 1987). On the other hand, in superlattice (*SL*) structures the physical properties in the semiconductor system very strongly depend on the *L* periodicity. It was expected, e.g. that the variation of the *SL* period (layer thickness) with

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orientation gives rise to effects which are significantly different from those resulting from thickness variations of thicker ($L > 50$ nm) epitaxial layers. In particular, the change of $L$ results in the change of the refractive index according to the equation (1)

$$n(\omega) = \left\{ \frac{\varepsilon_1(\omega)}{2} + \frac{1}{2}\varepsilon_1(\omega)^2 + \varepsilon_2(\omega)^2 \right\}^{1/2} \tag{1}$$

where $\varepsilon_1$ is the real, $\varepsilon_2$ is the imaginary part of the dielectric constant. $\varepsilon_1$ is strongly dependent on $L$ periodicity and owing to this fact, the refraction index is very sensitive to the superlattice parameters. The variation of $n_{SL}/n_{GaAs}$ is seen in Fig. 1. In the range of thin ($10a_0 - 50a_0$, e.g. 5.6 nm—28.0 nm) *SL* layers, where a local maximum in the $n_{SL}/n_{GaAs} - L$ function can be found, the change of the refractive index is very strong, and at about $40a_0$ ($\sim 20$ nm) has a minimum value of $n_{SL}/n_{GaAs} \sim 0.95$ meaning a $\Delta n \sim 5\%$ variation sufficient for optical guiding.

Similar effects in the bound state energies can also be expected. According to Fig. 2 bound states formed in the quantum wells have energies of

$$E_n = \frac{n^2\pi^2}{2m_e^x}\left(\frac{n}{L}\right)^2 J(m_e^x, L, V_0) \tag{2}$$

where $n = 1, 2, 3 \ldots$; $V_0$ is the depth of the quantum well and function $J$ takes account of finite depth value of $V_0$ in the box.

To study the guiding and recombination properties, different nonplanar *SL* structures were grown by an improved LPE technique (Lendvay, Görög and Rakovics, 1985; Görög, Lendvay and Rakovics, 1987; Smith, Derry, Morgalit and Yariv, 1985). A vertical rotating LPE system was applied to prepare patterned *SL* structures.

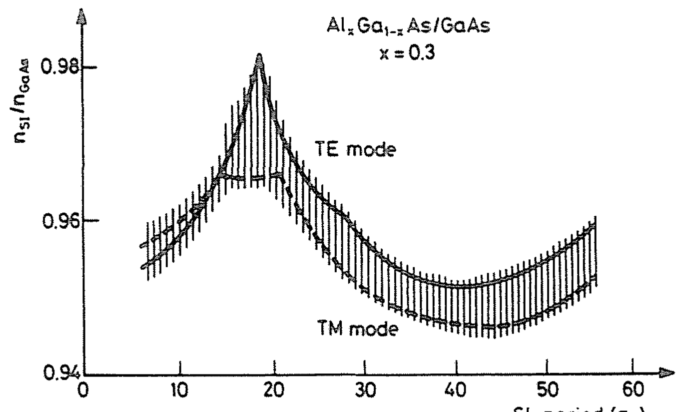


*Fig. 1.* Variation of $n_{SL}/n_{GAs}$

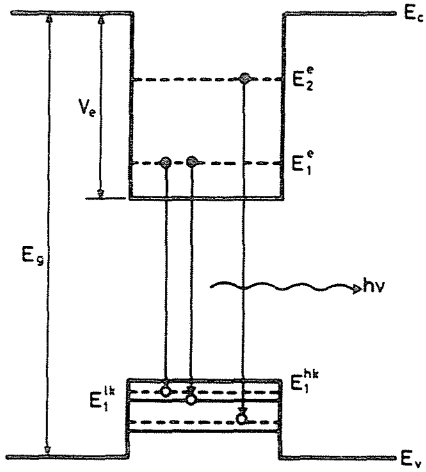


*Fig. 2.* Bound states formed in the quantum wells

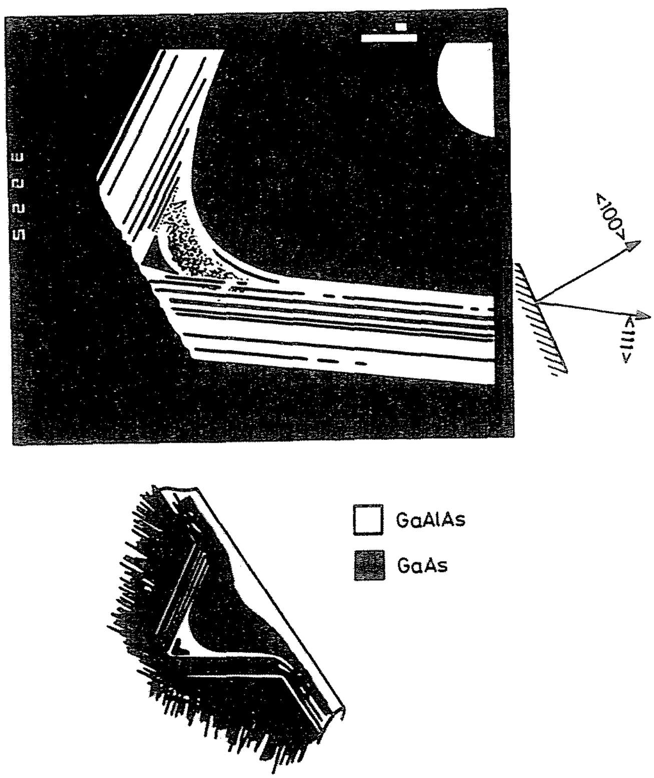


*Fig. 3.* Superlattice confinement grown by LPE technique in a GaAs groove

Growth temperatures ranging from 700°C to 960°C were used. The (100) GaAs substrates were chemically-mechanically polished prior to growth. Masking patterns were formed by chemical etching using conventional photolitography. Lines and spaces aligned in the ⟨110⟩ direction were investigated. The mesa and groove structures were etched using an etchant of $4H_2SO_4:H_2O_2:H_2O$ at room temperature. Superlattices consisting of 15—60 periods of alternate (20—50 nm thick) GaAs and GaAlAs layers were grown onto the patterned substrates. The growth was performed above the oxide desorption temperature (680°C). Figs 3, 4 and 5 show cleaved and etched cross sections of *SL* wafers, where the *SL* region was grown by LPE onto the

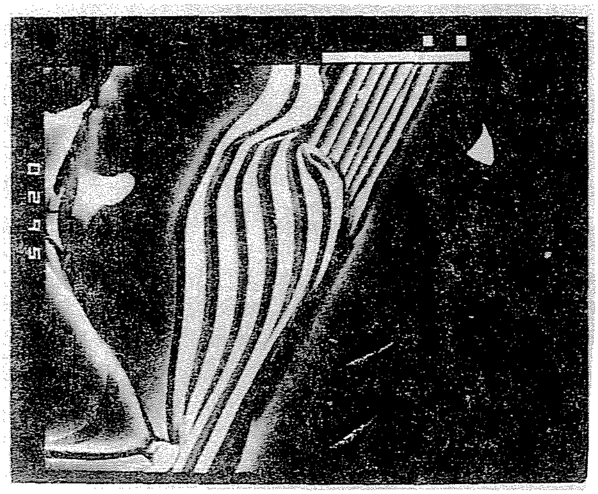

*Fig. 4.* *SL pn* junction grown on *SL* mesa structure

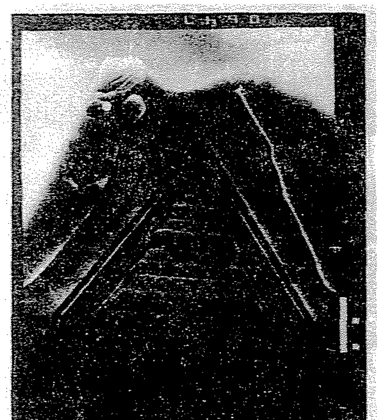

*Fig. 5.* Quantum-wire structure grown by liquid phase epitaxy (LPE) A strong growth rate anisotropy was found in the ⟨100⟩ and the ⟨111⟩ direction: $V_{100}/V_{111}=25—28$

patterned regions. In Fig. 3 superlattice grown into an etched groove is seen. Similar picture for mesa-substrates is illustrated in Fig. 4, where the mesa itself is a *SL* region. On surfaces defined by oxide stripe quantum-wire structures can also be grown: a characteristic sample is seen in Fig. 5. As the figures show the superlattice period changes significantly by changing the tilt angle of the growth plane and increases with increasing angle. Generally, the transition between different faces in the *SL* region is smooth and occurs within a few nm period, according to the previously investigated MBE layers (Kapon, Tomargo and Hwang, 1987; Smith, Derry, Margalit and Yariv, 1985). The strongest anisotropy was found when *SL* structures formed on oxide defined stripes (Fig. 5). In Table I characteristic tilt angles found on patterned (100) GaAs surfaces are listed.

**Table 1**

Tilt angles relative to the 100 plane

| $\Theta_m$ measured (deg) | $\Theta_c$ calculated (deg) | Crystal plane | period $\frac{Lz}{\cos\Theta}$ (nm) |
|---|---|---|---|
| 22 | 19,47 | 411 | 19,4 |
| 53 | 54,74 | 111 | 19,1 |
| 10 | 10,02 | 811 | 19,3 |
| 12 | 11,42 | 711 | 11,4 |
| 59 | 60,0 | 544 | 16,2 |

The period variation is probably caused partly by the difference in sticking coefficients, partly by the difference between component fluxes across the different planes. The problem is complicated for *SL* structures by the fact that the surface migration (diffusion) length of Ga and Al atoms is about 20—30 nm on the growth surface, i.e. it is in the order of magnitude of the *L* period in the *SL* structure. The growth anisotropy experimentally found on nonplanar surfaces combining with the change in refractive index and bound state energy makes possible to develop new optoelectronic devices. In these structures grown on nonplanar substrates lateral variations in properties associated with *SL* periods can be expected. E.g., the change in $n(\omega)$ makes possible to form optical wave guiding along the cavity axis. In structures shown in Fig. 5 e.g. modus selection and a strong confining effect can be expected. Similarly, *SL* structures grown into GaAs grooves can also be applied for modus selection giving, in principle, new directions for semiconductor laserdiode developments.

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E. LENDVAY Research Institute for Technical Physics Hung. Acad. Sci.
Budapest