# Excitonic waveguiding and lasing in wide bandgap semiconductor matrices

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New type of structures for optoelectronics, we refer to as excitonic waveguides, is proposed and realized. As opposite to conventional waveguides and double heterostructure lasers, no significant defference in the average refractive index between the cladding and the active layers is necessary, and these regions can be fabricated from the same matrix material (homojunction laser). In this aproach: (i) the waveguiding effect has a resonant nature and appears on the low energy side of the strong exciton absorption peak in agreement with the Kramers–Kronig transformation; (ii) the absorption peak is induced by nanoscale island-like insertions of narrow gap material in a wide bandgap matrix (quantum dots), preventing free carrier screening of excitons and, simultaneously, allowing lasing resonant to the spectral range of the enhanced refractive index.

Currently the structure of semiconductor lasers is defined by the double-heterostructure concept [1]. A using of thick layers of a wider bandgap material having a lower refractive index is assumed to be necessary. However, this wider bandgap material, lattice matched to the active layer, does not always exist, or, if exists does not necessarily provide sufficient conductivity. The interest in using of a wider range of materials and an ultimate shift towards blue and UV spectral region requires a search of alternative approaches for efficient waveguiding. An attractive idea is to use resonant waveguiding, which originates of the low energy side of the absorption peak due to Kramers–Kronig equation which relates the absorption with the dielectric susceptibility.

Exction absorption can be considered as a possible candidate to realize excitonic waveguiding [2]. In conventional III–V bulk or quantum wells (QWs), however, excitons are effectively screened at excitation densities well below threshold. On contrary, high exciton binding energies and oscillator strengths, and high densities required to screen exciton in II–VI and III–N materials (around $10^9\,\mathrm{cm}^{-3}$) make these excitons stable. However, exciton-induced lasing, resonant to the range of strongly enhanced refractive index, can be hardy realized [2] as free excitons with finite $k$-values dominating at high excitation densities and observation temperatures cannot recombine radiatively, as it was demonstrated first by Gross et al. [3] and an additional particle (LO-phonon) is required for lasing.

As opposite, excitons in quantum dots (QDs) cannot be screened, and also provide exciton or biexciton luminescence and gain resonant to the waveguiding region at any lattice temperature. As large QDs trap carriers more effectively and, at finite temperature there always exists recapture of thermally excited carriers from smaller dots by larger ones, gain initially appears on the low energy side of the QD exciton resonance, and, unless the main QD absorption peak remains, the waveguiding effect remains. The crucial point to realize excitonic waveguides is thus related to a possibility to create arrays of uniform QDs either isolated or electronically-coupled and providing a lateral confinement of a scale of the order of exciton diameter. Recently, ultrathin submonolayer [4] or monolayer (ML) [5] insertions were proposed to be used in excitonic waveguides. These insertions are proved to form dense array of nanoscale 2D islands which can efficiently localize excitons. The structures composed of stacked ultrathin insertions result both in lifting of $k$-selection rule and in strong increase in the exciton oscillator strength, providing a new possibility for lasing and waveguiding [6–9]. At the same time we underline that different approaches can be used for QD fabrication [10].

The cross-section local lattice parameter image of the stack composed of 1 ML CdSe insertion separated by 3 nm-thick ZnSe layers is presented in Fig. 1. White color corresponds to CdSe lattice parameter in the growth direction, while the black spots indicate the ZnSe lattice parameter in the growth direction. As it can be clearly seen, the CdSe

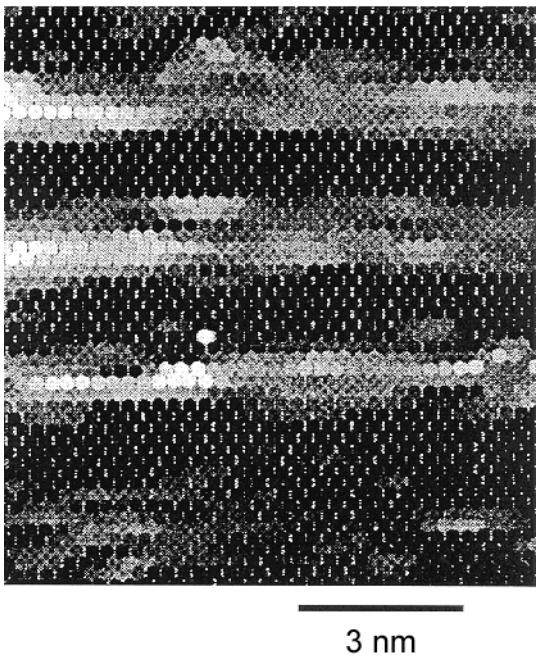


**Figure 1.** Local lattice parameter image of the structure with CdSe insertions in a ZnSe matrix.

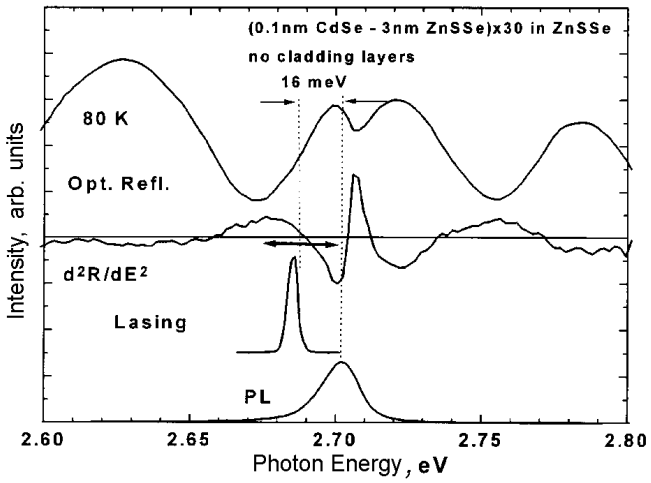


**Figure 2.** Photoluminescence, lasing, and optical reflectance spectra of the excitonic waveguide structure.

deposition results in islands having a lateral size of about 4 nm. The average thickness of the CdSe insertion in the island area obtained from numerical analysis of the local lattice parameter image is about 1.6 ML and significantly exceeds the average thickness of the deposit.

Photoluminescence, optical reflection and lasing spectra of the structure with 30 stacks of CdSe insertions grown on top of a thick ZnSSe layer and covered by ZnSSe cap are shown in Fig. 2. The important result which follows from Fig. 2 is an extremely pronounced modulation of the optical reflection spectra at the SL heavy-hole exciton energy, which indicates the high exciton oscillator strength and, hence, effective refractive index modulation in the active region. Increase in the exction oscillator strength in the array of QDs with respect to that for QWs has been demonstrated in [11]. To describe the exciton peculiarity in optical reflection spectrum we use the model of resonant modulation of dielectric susceptibility [12]

$$\varepsilon(\omega) = \varepsilon_b \left(1 + \frac{\omega_{LT}}{\omega_0 - \omega - i\Gamma}\right), \qquad (1)$$

where $\varepsilon_b$ — dielectric constant without exciton resonanse; $\hbar\omega_0$, $\hbar\omega_{LT}$, $\hbar\Gamma$ — exciton resonant, longitudinal-transverse splitting and damping energies, respectively. Fitting of the calculated optical reflection spectrum to the experimental one gives the following values: $\hbar\omega_0 = 2.701$ eV, $\hbar\omega_{LT} = 1.9$ meV and $\hbar\Gamma = 3.5$ meV. The region of the exciton-induced enhancement of the refractive index and, thus, of the exciton-induced waveguiding is placed on the low-energy side from the exciton resonant energy [2]. The antiwaveguiding region is, consequently, placed on the high energy side from this energy. As it follows from Fig. 2, the lasing spectrum recorded in the waveguide geometry is 16 meV Stokes shifted with respect to the surface photoluminescence peak and the exciton resonance energy in the optical reflection spectrum. The refractive index enhancement at lasing wavelength is estimated to be of 0.15. This value is comparable with the refractive index enhancement provided by thick (Zn,Mg)(S,Se) cladding layers.

$ZnS_{0.06}Se_{0.94}$–$Zn_{0.8}Cd_{0.2}Se$ quantum well laser structures with comparable cavity length lase at energies $\sim \hbar\omega_{LO}$ (30 meV) below the exction transition revealed by photo-

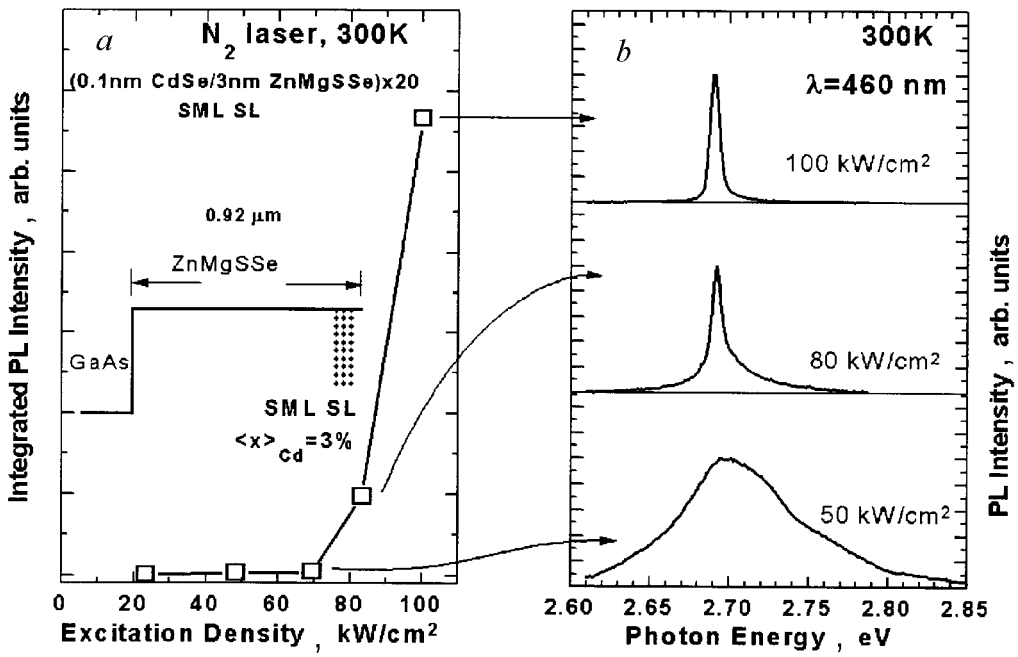


**Figure 3.** Dependence of integrated *PL* intensity versus excitation density (*a*) and luminescence spectra (*b*) of the excitonic waveguide structure.

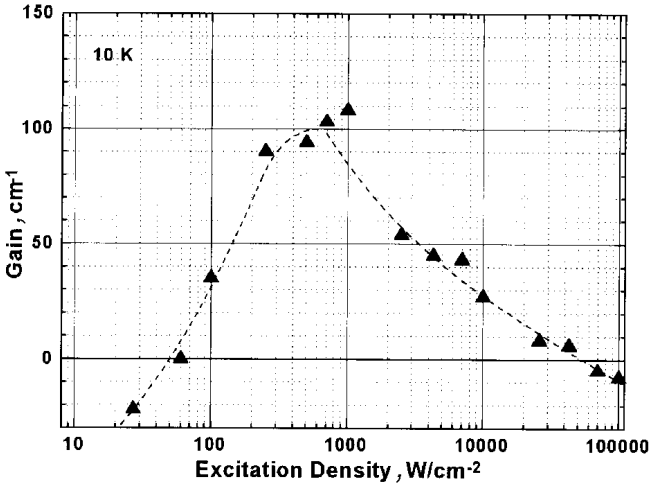


**Figure 4.** Gain *vs* excitation density in the structure with excitonic waveguide.

luminescence and optical reflection spectra, in agreement with the exciton-*LO* phonon lasing model [13,14]. At room temperature this shift increases to about 100 meV [2]. For ultrathin CdSe insertions, exciton localization makes the interaction with another particle (*LO*-phonon, or another exciton) unnecessary, allowing the lasing to occur without additional many body interactions directly in the region of the exciton-induced waveguiding.

For CdSe insertions in a (Zn,Mg)(S,Se) matrix we were able to realize entirely exciton-induced waveguiding and lasing up to 300 K ($\lambda = 460$ nm) without using wider bandgap cladding layers (Fig. 3). The upper limit estimated for internal losses is comparable to that in structures with optimized cladding layers and is below 18 $cm^{-1}$. As a highly absorbing GaAs substrate is used, and the active layer is separated by only $\sim 0.9\,\mu$m from the substrate, the efficient confinement of the optical mode in the excitonic waveguide is, thus, proven. Lasing has been realized also in structures with only $0.4\,\mu$m thick buffer layers and in very diluted arrays of QDs with 8 nm-thick spacers.

Gain studies under pulsed excitation using a variable stripe length method demonstrate fast saturation of the absorption at the low energy side of exciton luminescence with excitation density ($P_{exc}$) and a development of a gain peak at energies $\sim 3-4$ meV below the exciton resonance energy in the optical reflection spectrum. Further growth in $P_{exc}$ results in monotonic increase in gain up to values of 100 $cm^{-1}$. For further excitation density increase the most of QD excitons convert to biexcitons, and the excitonic gain decreases (Fig. 4). At the same time biexcitonic gain being Stokes-shifted by 7–10 meV develops and dominates the spectrum at high excitation densities.

To conclude, excitonic waveguides represent a unique system with high device potential, particularly in wide gap materials. The recent progress became possible due to application of self-organized growth of quantum dots in III–V and II–VI materials systems.

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