APPLIED PHYSICS LETTERS VOLUME 72, NUMBER 12 23 MARCH 1998

High-gain excitonic lasing from a single InAs monolayer in bulk GaAs

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(Received 7 July 1997; accepted for publication 23 January 1998)

We report the observation of highly efficient laser emission from a single InAs layer with an effective thickness of 1.5 monolayers (ML) embedded in bulklike GaAs. Lasing action is obtained at the wavelength of the InAs thin-layer luminescence (870 nm) by cw optical pumping with a threshold power density of 0.9(3) kW/cm^2 at 10 K. Gain measurements yield a very high material gain of $1.0(5)\times10^4$ cm^{-1} for the InAs layer when pumped with $\sim$10 kW/cm^2 at low temperatures. The 0 dimensional character of the emission as determined from cathodoluminescence and the absence of band-gap renormalization with increasing pump level speak for an excitonic mechanism of population inversion. © *1998 American Institute of Physics.* [S0003-6951(98)00812-2]

Nowadays, much effort is being devoted to the fabrication of optoelectronic devices based on low-dimensional semiconductor nanostructures,[1–5] because of the recently demonstrated improvement in device performance, for example by the δ-function density of states in zero dimensions.[6,7] This advantage of low-dimensional systems is often partly impaired by large fluctuations in size and shape, which lead to strongly inhomogeneously broadened emission lines. A structure consisting of a very thin InAs layer in GaAs, whose thickness is in the monolayer (ML) range, presents several peculiarities which make such structures very promising candidates for device applications. Monolayer-thick InAs/GaAs structures exhibit an isomorphic epitaxial growth despite the high built-in strain ($\sim$7%) which affects the energies of confined electron and hole states.[8,9] Furthermore, monolayer-width fluctuations play a fundamental role in localizing free carriers in the plane of the monolayer[10] with the consequent enhancement of excitonic effects. One would also expect that the optical properties of the ML samples will resemble that of quantum dots systems.[11] In fact, this structure exhibits a very strong but narrow [full width half maximum (FWHM)$\approx$8 meV] photoluminescence (PL) line.[8–10] Although lasing action in thin InAs/GaAs ML structures has been previously reported,[12,13] no investigation of the lasing performances in relation to an excitonic kind of mechanism for population inversion or in connection to zero-dimensional (0D) characteristics of the emission was undertaken.

In this letter we report the observation of stimulated emission from *excitons* in a single InAs monolayer in bulklike GaAs. Laser emission occurs at constant energy, independent of the pump power, at about 100 meV below the GaAs band gap involving radiative recombination processes from ground-state excitons bound to the InAs layer.[10] Cathodoluminescence measurements show that these excitons are localized in the InAs plane by layer-width fluctuations. Very striking is the large material gain of $1.0(5)\times10^4$ cm^{-1} achieved at 12 kW/cm^2 excitation power (10 K), which is higher for InGaAs/InGaAsP multiple quantum wells (QWs),[14] but comparable to the values measured recently in InAs/GaAs quantum dot lasers.[15] The very high gain values obtained for the InAs/GaAs ML sample, the insensitivity of its emission energy upon pump power levels and the localized nature of the exciton states all together give strong evidence for an excitonic mechanism of stimulated emission similar to that observed in quantum dots.

The sample was grown by metalorganic chemical vapor deposition (MOCVD) on a semi-insulating (001) GaAs substrate as described elsewhere.[16] The laser structure consists of a single InAs layer (effective thickness about 1.5 ML) sandwiched between 300 nm thick GaAs layers. A waveguide is formed by two cladding layers of undoped Al$_{0.5}$Ga$_{0.5}$As. Short cavities from 250 to 400 μm in length with mirrorlike surfaces perpendicular to the plane of the InAs ML were obtained by cleaving the sample after it was mechanically thinned from the backside to a total thickness of 150 μm.

Standard PL was excited with the 514 nm line of an Ar$^+$-ion laser. Gain measurements were performed in 90°-scattering geometry at low temperatures between 2 and 120 K. Light emission was excited by a continuous wave (cw) Ti:sapphire laser tuned to 750 nm, which is absorbed only by the GaAs. The pump laser was incident on the (001) growth surface and was focused to a 40 μm wide stripe of variable length. Light emitted from one of the cleavage mirrors was analyzed.

Figure 1 shows representative PL spectra of the InAs/GaAs ML sample measured in backscattering from the (001) growth surface at different excitation powers and at 2 K. The optical emission is dominated by a single intense and narrow line (FWHM$\approx$10 meV), which is redshifted by 93 meV from the GaAs gap energy. The much weaker structures at around 1.48–1.50 eV correspond to transitions involving carbon impurities in bulk GaAs. The energy level scheme is also shown in Fig. 1. Tight-binding calculations indicate that only a single electron state and two almost-degenerate hole levels are bound to the InAs layer. Their wave functions are the largest at the InAs, but penetrate up to 10 ML's in GaAs.[9] The main PL peak was demonstrated to arise from a radiative recombination of excitons bound to the thin InAs layer.[8,9,17] We noted that the energy position and the bandwidth of the main PL peak remain unchanged even though

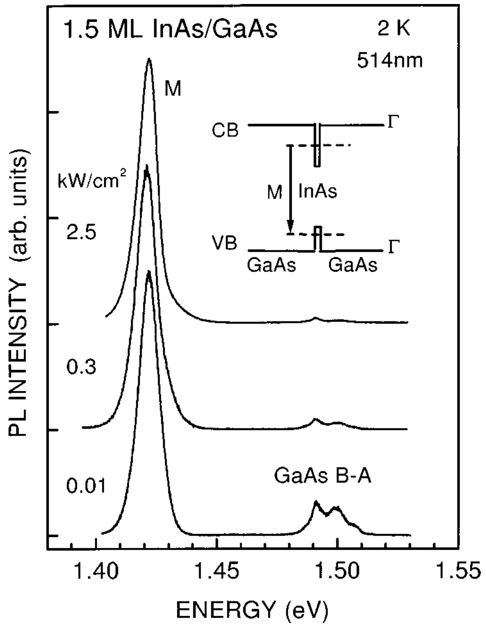

FIG. 1. PL spectra of the 1.5 ML InAs/GaAs sample at different excitation power densities and at 2 K. A sketch of the Γ-point band edge profiles of the structure is shown in the inset. Arrow indicates the observed optical transition.

the pump power density has been increased by a factor of about 300, as expected for an excitonic type of emission.

The nature of the observed luminescence peak has been studied further by spectrally and spatially resolved cathodoluminescence (CL) at low temperatures between 5 and 50 K and using moderate excitation (7 kV, 2.5 nA). CL spectra taken from a single spot of the sample clearly show that the PL peak consists of an ensemble of δ function like lines; each line can be attributed to the recombination of an individual localized 0D exciton. The spectral linewidth of the δ-like CL lines is determined by the resolution of the experimental setup (0.27 meV). As shown in Fig. 2, no broadening of the single CL lines occurs up to 50 K in contrast to what is expected for a 3D or 2D system. This demonstrates the zero-dimensional character of the underlying recombination process[18] as a consequence of the localization of excitons by width fluctuations in the InAs layer.

Figure 3 shows TE-polarized emission spectra from the cleaved edge measured in 90° geometry at 2 K and using different power densities below and above lasing threshold (P_{th}). Here the spot length for optical pumping just matched the resonator length $L = 250\ \mu$m of that sample. At low excitation levels the main feature in the spectra corresponds to excitonic emission from the InAs ML, which appears to be modulated by the interference pattern of longitudinal modes. With increasing pump power the emission becomes sharper with only a few longitudinal modes gaining exponentially in intensity. The maximum peak intensities are plotted in the inset to Fig. 3 as a function of pump power density. For this resonator length the threshold for stimulated emission occurs at 0.9(3) kW/cm^2 for cw operation at low temperatures. We point out that neither a redshift nor a broadening of the stimulated emission was observed for all power densities, as recently found in self-organized InAs/GaAs quantum dots.[19] This speaks against band gap renormalization effects due to buildup of photoexcited free carriers, which is characteristic for QW lasers.[20] We therefore conclude that the lasing mechanism is of excitonic nature.[21]

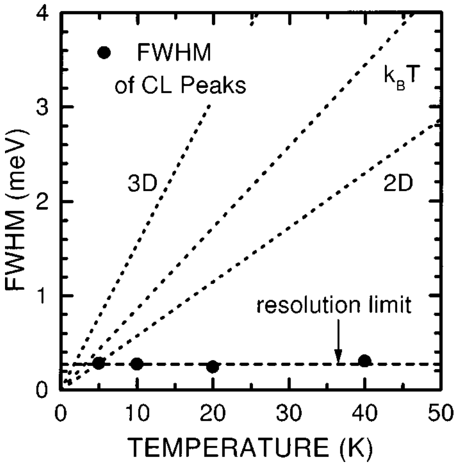

FIG. 2. Spectral width of CL lines corresponding to individual localized excitons as a function of temperature. Dashed lines are thermal energy and theoretical widths for ideal bulk (3D) and quantum well (2D) material.

The net gain was measured by the stripe excitation method.[22] The sample is optically excited from the (001) surface with a stripelike focus of variable length, while the stimulated emission from one of the cleaved edges is detected. For very short stripe lengths l as compared with the length of the resonator (1.5 mm in this case) light is emitted after a single pass through the cavity and the discrete spectrum of longitudinal modes is no longer observed. The emitted intensity from one edge can be then expressed as

$$I(\omega) = (1-r)\cdot\frac{I_{SP}}{G(\omega)}\cdot\left(e^{G(\omega)\cdot l}-1\right), \tag{1}$$

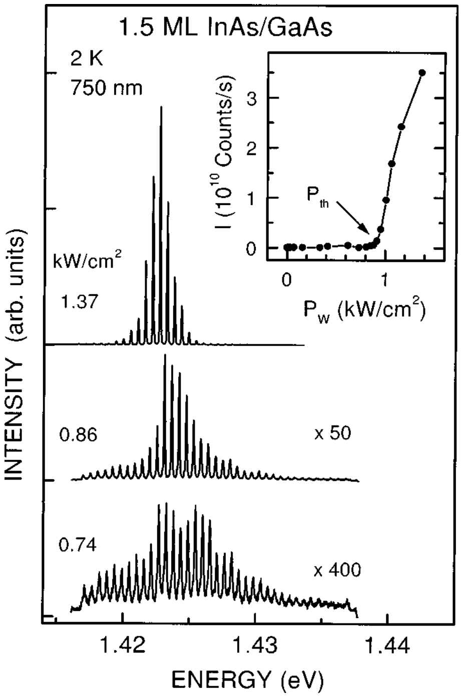

FIG. 3. Optical emission spectra of the 1.5 ML InAs/GaAs sample for different pump power densities below and above lasing threshold. The inset shows the maximum peak intensity as a function of incident power density. The lasing threshold P_{th} is also indicated.

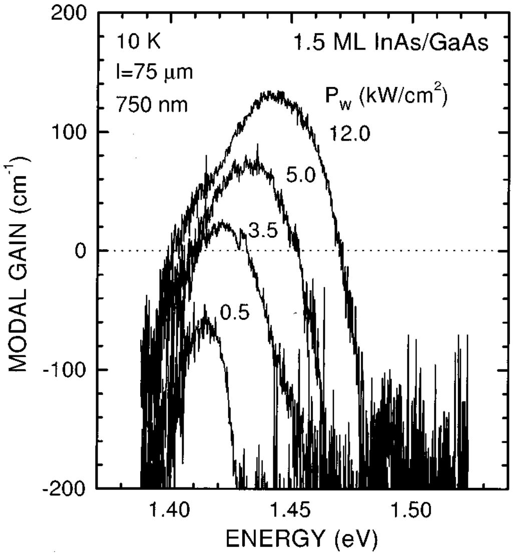

FIG. 4. Single-pass modal gain spectra of a 1.5 ML InAs/GaAs sample without resonator measured at different pump power densities and at 10 K using the variable stripe-length method with $l=75$ μm and 150 μm.

where $G(\omega)$ is the net optical gain (or modal gain) at given frequency, I_{SP} is the spontaneous emission rate, and $r=0.3$ is the reflectivity of the GaAs–air interface. The modal gain spectrum $G(\omega)$ can be determined using Eq. (1) from the ratio between emission spectra measured for a given stripe length $l=75$ μm and for its double value. The results obtained for different cw pump power densities at 10 K are shown in Fig. 4. These measurements yield a very high maximum modal gain of $G=130(20)$ cm^{-1} at 12 kW/cm^2. We obtain a broad gain spectrum with its maximum slightly blueshifted from the peak energy of the InAs ML luminescence. The increase of the gain-spectrum width in Fig. 4 is simply due to the existence of excited states which gradually exhibit positive gain as the pump power increases.[6]

The material gain $g=(G+\alpha)/\Gamma$ is related to the modal gain through the confinement factor Γ and the coefficient α of internal absorption loses of the laser cavity. The electric field power distribution for the TE modes has been calculated by solving the differential equations of transverse cavity modes[23] for our particular waveguiding stripe geometry. A confinement factor of $\Gamma=0.014$ is calculated from the ratio between the mode power confined to the narrow region determined by the lateral spread of the electron and hole wave functions in the direction perpendicular to the plane of the InAs layer (~5 nm from tight-binding calculations[9]) and the integrated intensity of the waveguide mode within the 600 nm thick GaAs layer. The coefficient α for internal losses is not well known but it is assumed to be less than 10 cm^{-1}, as typically found for similar InAs/GaAs nanostructures.[7] In this way we obtained for a single 1.5 ML thick InAs layer in GaAs a material gain of $g=1.0(5)\times 10^4$ cm^{-1} at low temperatures. This value is twice as large as for parented InGaAs/InGaAsP MQW structures emitting at similar wavelengths but when pumped with ten times larger power densities.[14] Our gains are actually comparable, though lower, than that of $\sim 10^5$ cm^{-1} reported recently for InAs/GaAs quantum dot injection lasers.[6,15]

We interpret such an increase in material gain for a monolayer as compared to quantum wells as due to the different lasing mechanism being active in each case. Lasing from excitons was reported previously for T-shape GaAs quantum wires[3] and interpreted to be due to an increased stability of 1D excitons. In the case of the InAs ML and as demonstrated by the CL measurements, width fluctuations lead to localization of excitons within the x,y plane of the InAs layer with the consequent quantization of their center-of-mass motion as in zero dimensions. Thus, the Coulomb interaction between electron and hole localized at the same site is enhanced and the ML excitonic emission aquires 0D character similar to quantum dots, which is reflected in the device performance.

In summary, we demonstrated that large material gain values were achieved for a structure consisting of a single InAs ML in bulklike GaAs due to the enhanced excitonic character of the optical emission like for a quantum dot system even at high pumping levels. Due to the close relation between the monolayer and self-organized dot structures these results would certainly contribute to the understanding of lasing processes in low-dimensional nanostructures.

The authors are grateful to O. Stier for helpful discussions. Parts of this work are funded by Deutsche Forschungsgemeinschaft in the framework of Sfb 296.

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