Lasing and electronic properties of a single InAs monolayer embedded in bulklike GaAs

Institut für Festkörperphysik, Technische Universität Berlin
10623 Berlin, Germany
Recibido el 10 de enero de 1998; aceptado el 14 de enero de 1998

We have studied the spontaneous and stimulated emission characteristics of a single 1.5-monolayers-thick InAs layer in bulklike GaAs. Lasing action is obtained by continuous-wave-optical pumping always at the wavelength of the InAs thin-layer excitonic luminescence (~ 870 nm) independent on pump power density. Gain measurements yield a very high material gain of 1.0(5) x 10^4 cm^-1 for the InAs layer when pumped with 12 kW/cm^2 at low temperatures. This value is twice as high as that obtained for related InGaAs/InGaAsP multiple quantum wells with much larger pump power densities, but comparable to the gains measured recently in InAs/GaAs quantum dot lasers. The large material gain and the absence of bandgap renormalization effects with increasing pump level speak for an excitonic mechanism of population inversion characteristic of low-dimensional lasing nanostructures. As clearly shown by cathodoluminescence measurements, exciton localization effects due to layer-width fluctuations play a fundamental role in determining the lasing mechanism for the InAs monolayer as compared to wider quantum wells.

Keywords: Semiconductor laser; low-dimensional structures; stimulated emission; excitons

En este trabajo se han estudiado las características de la emisión espontánea y estimulada de luz de una capa delgada de InAs con un espesor efectivo de 1.5 monolayer intercalada en GaAs. Mediante el bombeo óptico de onda continua se consigue la emisión laser siempre a la misma longitud de onda correspondiente al máximo de la fotoluminiscencia (PL), la cual proviene de procesos de recombinación excitónica en la monolayer de InAs. Mediciones de la ganancia material de esta estructura arrojan valores extremadamente altos de hasta 1.0(5) x 10^4 cm^-1 con 12 kW/cm^2 de potencia de bombeo y a bajas temperaturas. Esta ganancia es dos veces mayor que la obtenida en pozos cuánticos múltiples de InGaAs/InGaAsP para densidades de potencia de bombeo mucho más elevadas, resultando más bien comparable a los valores de ganancia recientemente alcanzados con láseres de puntos cuánticos de InAs/GaAs. La alta ganancia material y la ausencia de efectos de renormalización de la brecha de energía al incrementar el nivel de bombeo indican que, tal como es característico en estructuras de baja dimensionalidad, el mecanismo subyacente a la emisión estimulada es excitónico. Por otro lado, mediciones de catodoluminiscencia muestran claramente la localización de los excitones en el plano de la monolayer de InAs debido a las fluctuaciones en el espesor de la misma. Este hecho cumple un rol determinante para el mecanismo de laseo de la monolayer proporcionándole características propias de sistemas 0-dimensionales y lleva a que ésta se diferencie en sus propiedades ópticas de pozos cuánticos más anchos.

Descriptores: Laser de semiconductores; estructuras de baja dimensionalidad; emisión estimulada; excitones

PACS: 73.20.Dx; 78.45.+h; 78.55.Cr

1. Introduction

In recent years InAs/GaAs quantum well (QW) structures with well widths ranging in the monolayer (ML) regime have attracted much interest due to their unusual electronic and optical properties [1-7]. At low temperatures these structures exhibit, for instance, a very strong but narrow (FWHM ~ 8 meV) photoluminescence (PL) line [1,5,8] and lasing action in thin InAs/GaAs ML's has been already observed [2,9]. Another peculiarity of the InAs/GaAs system is the high built-in strain (~ 7%) which enables an isomorphic epitaxial growth up to a critical thickness of two ML's [1,3,4]. Beyond this limit the growth proceeds three dimensional but self-organized leading to the formation of quantum dots [10-13]. As a matter of fact, every quantum dot sample grown by this method contains a ML-thick wetting layer. Thus, for a better understanding of emission processes in quantum dots systems it is important to study the single layer case first. Furthermore, for thin-layer structures one would expect that their optical properties will resemble that of quantum dots systems [14] because of the localization of excitons in the plane of the monolayer due to fluctuations in its width. In spite of this, an investigation of the lasing performances of InAs/GaAs ML structures in connection to an excitonic kind of mechanism for population inversion and its 0D characteristics is still lacking.

Here we report on the spontaneous and 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 [8]. Cathodoluminescence measurements show that these excitons are localized in the InAs plane by layer-width fluctuations. The thin-layer samples exhibit a strikingly large material gain which is twice as high as the maximum gain ob-
tained for InGaAs/InGaAsP multiple quantum wells (QW) using much larger pump power densities [15], but comparable to the values measured recently in InAs/GaAs quantum dot lasers [16].

2. Experimental

The sample was grown by conventional MOCVD on a semi-insulating (001) GaAs substrate as described elsewhere [17]. 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.

Standard photoluminescence (PL) was excited in backscattering with the 514 nm line of an Ar+ ion laser, whereas for photoluminescence excitation (PLE) a tunable Ti: sapphire laser was used. Gain measurements were performed in 90°-scattering geometry at low temperatures between 2 and 120 K. Light emission was excited in continuous-wave (cw) mode with the Ti: sapphire laser tuned to 750 nm. The pump laser was incident on the (001) growth surface and was focused to a 40 μm wide stripe of variable length (as shown schematically in the inset to Fig. 3). Light emitted from one of the cleavage mirrors was analyzed by a triple-grating spectrometer and detected with a charge-coupled-device camera. Cathodoluminescence (CL) measurements were performed at low temperatures between 5 and 50 K and using moderate excitation (voltage 7 kV and beam current 2.5 nA). The luminescence is detected with a 512-channel infrared-intensified diode array. The spectral resolution was about 0.27 meV.

3. Results and Discussion

Figure 1 shows a low-temperature PL spectrum of the InAs/GaAs ML sample measured in backscattering from the (0,0,1) growth surface at low excitation power. The optical emission is dominated by a single intense and narrow line (FWHM ≈ 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 and bound excitons in bulk GaAs. The energy level scheme is also shown in Fig. 1.

Tight-binding calculations for strictly one ML including strain effects indicate that only a single electron state and two practically degenerate hole levels are bound to the InAs layer [5]. For our sample with 1.5 ML width a third hole level also become slightly bound [1, 6, 7]. We therefore assign the main PL peak to optical transitions between heavy-hole exciton states bound to the thin InAs layer. Optical transitions corresponding to the recombination of the 2nd heavy-hole excitons have been observed in PLE spectra at about 65 meV higher in energy [18].
Figure 3 shows TE-polarized emission spectra from the cleaved edge measured in 90° geometry for two different spot lengths at 2 K and using a pump power density of 1.3 kW/cm² (above lasing threshold). The spectra exhibit the characteristic Fabry-Pérot oscillations corresponding to the longitudinal modes of the cavity. With increasing excitation power level the emission becomes sharper with only a few longitudinal modes gaining exponentially in intensity. An important point is that for all the cw power densities used in these experiments the stimulated emission occurs at the energy of the PL peak without showing any redshift or broadening. A similar lasing behavior was recently found in self-organized InAs/GaAs quantum dots [20]. This speaks against band gap renormalization effects due to build-up of photoexcited free carriers, and we therefore conclude that the lasing mechanism is of excitonic nature [21].

For the determination of the net optical gain (or modal gain) of the ML structure we performed gain measurements by the stripe excitation method [22]. The sample is optically excited from the (001) surface with a stripelike focus of variable length \( l \), while the stimulated emission from one of the cleaved edges is detected (see inset to Fig. 3). The dependence of the maximum lasing intensity on stripe length \( l \) is displayed in Fig. 4 for a sample with a resonator length of \( L = 250 \, \mu \text{m} \). A careful analysis of the finesse of the Fabry-Pérot oscillations shows that the number of passes for amplified light in the resonator rapidly grows with the stripe length resulting in the abrupt increase in laser intensity above \( l \approx 220 \, \mu \text{m} \). For stripe lengths shorter than 170 \, \mu m, however, light oscillates back and forth only in the cavity, and the emitted intensity from the edge can be then expressed as

\[
I(\omega) = (1 - r) \frac{I_{sp}}{G(\omega)} \left( e^{G(\omega)l} - 1 \right) \\
\times \left( 1 + r e^{G(\omega)l} e^{-2\alpha(L-l)} \right),
\]

where \( G(\omega) \) is the modal gain (or net optical gain) at given frequency, \( \alpha \) is the coefficient of internal absorption losses, \( I_{sp} \) is the spontaneous emission rate and \( r = 0.3 \) is the reflectivity of the GaAs-air interface.

In order to be able to obtain the maximum modal gain \( G(\omega_m) \) from Eq. (1) we need to determine the internal absorption coefficient \( \alpha \) of the nonilluminated resonator region, i.e. where there is no active medium. For that purpose we have monitored the decay of the emitted intensity when a point focus for excitation in 90° geometry is moved away from the cleaved edge of a sample with a very long resonator (1.5 mm). In Fig. 5 we have plotted several spectra of the edge emission for different distances of the point focus from the cleaved surface. The emitted light intensity decreases with increasing distance being its exponential decay strongly dependent on photon energy. As an example, the inset to Fig. 5 shows this distance dependence of the intensity for a given energy which corresponds roughly to that of the PL maximum. The solid line represents a fit using an exponential-decay function; the corresponding absorption coefficient being in this case 45 cm⁻¹.

In this way, we have determined the modal gain by fitting Eq. (1) to the intensity data points in the range of \( l < 170 \, \mu m \) using \( I_{sp} \) and \( G \) as adjustable parameters (solid curve in Fig. 4). Measurements performed under a cw excitation of 10 kW/cm² at 2 K yield a very high maximum modal gain of \( G = 130(20) \, \text{cm}^{-1} \). The large modal gain enables single-mode operation in samples with short cavity resonator, for which the light oscillates back and forth in the cavity performing up to 10 passes. As indicated by the stimulated emission spectra of Fig. 3, we achieved highly efficient lasing for a few longitudinal modes (3 to 5) with a 250 \, \mu m long resonator.
LASING AND ELECTRONIC PROPERTIES OF A SINGLE InAs MONOLAYER EMBEDDED IN BULKLIKE GaAs

Figure 5. Spectra of the edge emission of the 1.5 ML InAs/GaAs sample for different distances of the point focus from the cleaved surface. The inset shows the decay of the emitted intensity at a given photon energy as a function of the point-focus distance from the sample edge.

The material gain $g = (G + \alpha_i)/\Gamma$ is related to the modal gain through the confinement factor $\Gamma$, which gives the fraction of the radiation field that overlaps with the exciton states in the InAs layer, and the internal power loss coefficient $\alpha_i$ of the laser cavity. By solving the differential equations of transverse cavity modes [23] for our particular waveguiding stripe geometry and by taking into account the lateral spread of the electron and hole wavefunctions in the direction perpendicular to the plane of the InAs layer ($\sim 5$ nm from tight-binding calculations [5]), the confinement factor is calculated to be $\Gamma = 0.014$. We assumed the coefficient $\alpha_i$ to be less than $10$ cm$^{-1}$, as typically found for similar InAs/GaAs nanostructures [10]. In this way we obtained for the 1.5 ML-thick InAs layer a material gain of $g = 1.0(5) \times 10^4$ cm$^{-1}$ at low temperatures. This value is twice as large as for InGaAs/InGaAsP MQW structures emitting at similar wavelengths but when pumped with 10 times larger power densities [15]. Actually, our gains become closer to that reported recently ($\sim 10^5$ cm$^{-1}$) for InAs/GaAs quantum dot injection lasers [13, 16].

We interpret such increase in material gain for a monolayer as compared to quantum wells as due to the different laser mechanism being active in each case. For the InAs ML, the 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 acquires 0D character similarly as for quantum dots, which is reflected in the device performance.

4. Summary

In summary, we demonstrated that large material gain values were achieved for a structure consisting of a single InAs ML in bulklike GaAs as compared to thicker QW's emitting at similar wavelengths. The very high gain values obtained for the thin InAs layer and the insensitivity of its emission energy upon pump power levels taken together with the direct proof of exciton localization from cathodoluminescence give strong evidence for an excitonic mechanism of stimulated emission similar to that observed in quantum dots.

Acknowledgments

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