Observation of stimulated emission in an ultrashort-period nonsymmetric GaAs/AlAs superlattice

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Nonsymmetric short-period GaAs/AlAs superlattices, for which the well thickness is at least a factor of 2 larger than the barrier thickness, have been shown to exhibit a direct band gap for any well thickness. These superlattices are characterized by an enhanced intensity of the luminescence as compared to their symmetric indirect-gap counterparts with the same well width, and, thus, may be used as light-emitting devices, in particular, as low-threshold lasers in the red visible spectrum. This conjecture is supported by the observation of stimulated emission at $T=80\,\mathrm{K}$ for a GaAs/AlAs superlattice with six monolayers well and three monolayers barrier width. [DOI: 10.1063/1.1379985]

It is well known that semiconductor superlattices (SLs) are characterized by enhanced luminescence efficiency and are very promising candidates for application in various light emitting devices. However, for symmetric GaAs/AlAs SLs with equal well and barrier thickness, a reduction of the layer thickness below 12 monolayers (MLs), i.e., a SL period of 6.8 nm (1 ML corresponds to 0.283 nm), results in an indirect band gap.[1] The X minimum of AlAs in the conduction band becomes lower than the respective Γ state in GaAs. In this case, the electron-hole transitions become indirect in both, real and momentum space. Staggered band alignment leads to inferior light emitting properties of indirect-gap SLs as compared to their direct-gap counterparts. Thus, short-period GaAs/AlAs SLs are not very suitable for light-emitting devices, although their energy gap falls into the red part of the visible spectral region.

We have shown previously that this drawback may be overcome by using nonsymmetric SLs with different well and barrier thicknesses.[2] If the ratio of well to barrier thickness becomes 2 or larger, short-period GaAs/AlAs SLs with any well thickness below 3.4 nm will always exhibit a direct energy gap, resulting in a significant enhancement of the photoluminescence (PL) intensity. In this letter, we are reporting the observation of stimulated emission in a short-period nonsymmetric GaAs/AlAs SL with 6 MLs well and 3 MLs barrier width at 80 K. Therefore, short-period nonsymmetric GaAs/AlAs SLs may be used for light-emitting devices in the red part of the visible spectrum.

Two $(\mathrm{GaAs})_n/(\mathrm{AlAs})_m$ SLs with $n=6$ MLs and $m=3$ and 4 MLs were grown by molecular beam epitaxy on (001) GaAs substrates. We will label these SLs n/m. The SL periods of 200 (6/3) and 50 (6/4) and the composition have been confirmed by x-ray diffractometry. The difference between the nominal and actual layer thicknesses was about 1%. The PL experiments at low excitation levels were performed at 5 K using an Ar^+-laser (515 nm) for excitation. To observe stimulated emission, the second harmonic of a Nd:yttrium–aluminum–garnet laser (532 nm) was used. In the experiment, the laser beam was focused by a cylindrical lens onto the top surface of the sample on a narrow stripe. The stripe width was about 50 μm, and its length could be varied by a slit. The experimental results presented here were obtained with a stripe length of 1 mm. The spontaneous PL signal I_{spont} was detected from the surface of the sample, while the stimulated PL signal I_{stim} was detected from a cleaved edge.[3,4] The optical gain spectra were determined by measuring I_{stim} and I_{spont}. Using the optical gain coefficient g and the length of the excitation strip l, their product $g\,l$ can be derived from the following equation

$$\frac{I_{\mathrm{stim}}}{I_{\mathrm{spont}}}=\frac{\exp(g\,l)-1}{g\,l}, \tag{1}$$

where I_{stim} and I_{spont} are taken at the same wavelength.

In Fig. 1, the PL spectra recorded at 5 K and low excitation level of the 6/3 and 6/4 SLs are compared. This figure

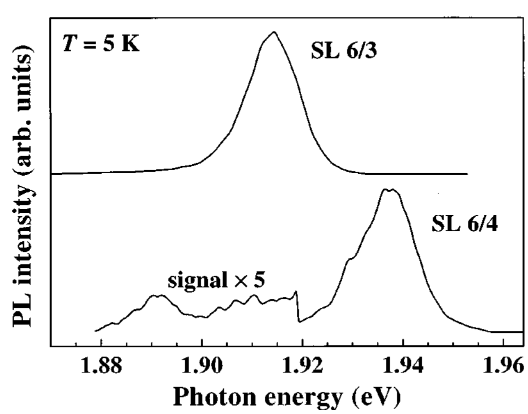

FIG. 1. PL spectra of the 6/3 (top) and 6/4 (bottom) SLs at 5 K and low excitation power. The spectra are normalized to their respective maximum. The spectrum for the 6/3 SL has been shifted vertically.

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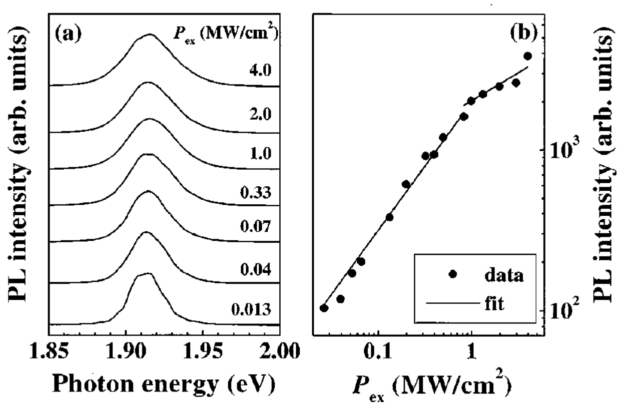

FIG. 2. (a) PL spectra of the 6/3 SL at 80 K for different optical pumping powers P_{ex} as indicated. (b) Dependence of the PL intensity on the optical pumping power P_{ex}. The dots are the experimental data, the solid lines are least square fits to the data points.

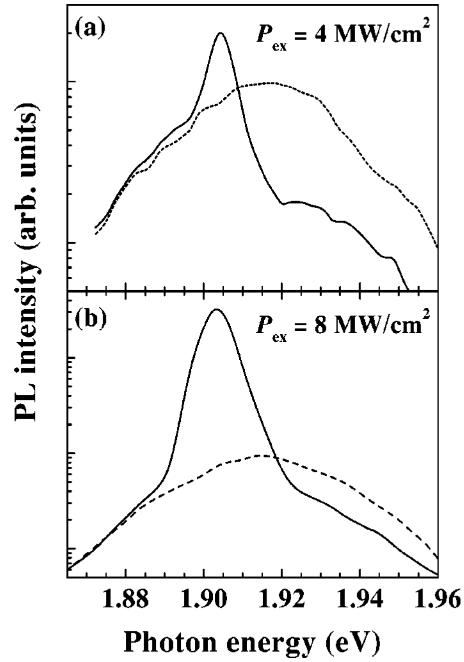

FIG. 3. Spontaneous (dashed) and stimulated (solid) PL spectra of the 6/3 SL at 80 K for excitation powers P_{ex} of (a) 4 and (b) 8 MW cm^{-2}.

clearly demonstrates the difference in the type of energy gap of the two samples, which is caused by the different barrier width. The PL spectrum of the 6/4 SL is typical for quasi-direct SLs and consists of an intense zero-phonon line due to recombination of the $X_z-\Gamma$ excitons and two phonon satellites on the low-energy side of the zero-phonon line. However, only one PL line is observed for the 6/3 SL. This difference demonstrates that this sample exhibits a direct energy gap, in which photoexcited electrons and holes are confined within the GaAs layers. Therefore, recombination occurs via the respective Γ levels in the conduction and valence bands.

In Fig. 2(a), PL spectra of the 6/3 SL taken at 80 K are shown for different excitation powers. The increase of the optical excitation results in a broadening of the PL line without a remarkable change of its energy position. This behavior is typical for radiative recombination in quasitwo-dimensional electron-hole plasmas. Despite a relatively small splitting between the Γ and X levels in the conduction band of the SL (31 meV according to our calculations), no additional PL line, which could be assigned to the indirect electron-hole transition, is observed. The dependence of the PL intensity on the excitation power P_{ex} is shown in Fig. 2(b). This dependence may be fitted by a power law $I_{PL} \propto P_{ex}^n$ using two different exponents n_1 and n_2 at low and at high intensities. For $P_{ex} \leqslant 1$ MW cm^{-2}, the PL intensity varies almost linearly with increasing excitation power, whereas at higher excitation intensity the dependence becomes sublinear. The change of the slope indicates the appearance of an additional channel of nonradiative recombination, i.e., Auger recombination, which is the most likely process for large carrier concentrations. However, the properties of Auger recombination in two-dimensional (2D) systems differ from those for bulk crystals. In particular, the increase of the PL intensity with increasing excitation level is weaker in the 2D case.[5] The value of $n_2 \approx 0.35$ indicates[5] that the Auger recombination occurs via local centers, which could be induced by interface roughness.

Stimulated emission from the 6/3 SL appears at 80 K for optical pumping powers of 4 MW cm^{-2} and higher. The spectra of the spontaneous and stimulated emission signal for two values of pumping power are shown in Fig. 3. It should be noted that no stimulated PL signal was detected from the 6/4 SL for similar experimental conditions because of the indirect character of the energy gap in this sample.

In Fig. 4, the gain spectra obtained according to Eq. (1) are plotted together with respective fits for two values of pumping power. The fits were obtained using an approach described in Refs. 6–8 assuming that the recombination occurs only via the lowest electron and the highest heavy-hole subband. By fitting the experimental gain spectra, the density of electron-hole pairs, the effective temperature and the energy gap can be derived. In particular, for an excitation power of 4 and 8 MW cm^{-2}, the two-dimensional plasma density was determined to be 3.7×10^{11} and 6.4

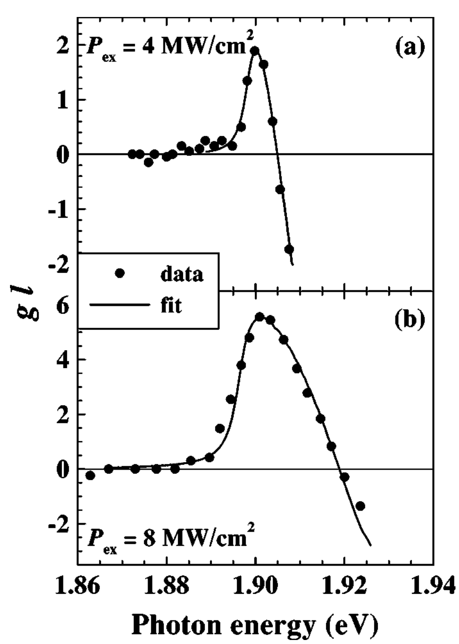

FIG. 4. Optical gain spectra of the 6/3 SL at 80 K determined using Eq. (1) for excitation powers P_{ex} of (a) 4 and (b) 8 MW cm^{-2}. The solid lines are fits to the data points.

$\times 10^{11}\,\mathrm{cm}^{-2}$, respectively. With increasing laser power, the gain increases superlinearly with a power law exponent of about 1.5. The gain coefficients g were determined to be in the range of 20 and $55\,\mathrm{cm}^{-1}$ for $P_{ex}=4$ and $8\,\mathrm{MW\,cm}^{-2}$, respectively.

In principle, Eq. (1) should be modified when applied for quantum well (QW) structures with thin wells. This equation was originally developed for isotropic, bulk semiconductors. In this case, the spontaneous emission measured from the surface of the sample is polarized in-plane (x and y polarization), while the stimulated emission detected from the cleaved edge (in y direction) is polarized in the $x-z$ plane. Equation (1) can also be used as an approximation for QW structures with rather large well widths (10 nm and more), for which the PL signal polarized along the SL direction (z polarization) is prominent due to the mixing of the heavy- and light-hole subbands. However, for very thin QWs, the splitting between these subbands becomes rather large so that the light-hole subband does not affect the spectral shape of the PL anymore. In this case, both spontaneous and stimulated emission are caused by recombination of electrons with heavy-holes alone. From the anisotropic character of the heavy-hole subband, it follows that no z-polarized luminescence signal should be present.[9] Measuring the intensity of the spontaneous emission signal for both polarizations (x and y), we thus underestimate the ratio of the stimulated to the spontaneous emission intensity. In order to properly account for this effect, a multiplicative factor should be added to the denominator of Eq. (1). In the ideal case (no z polarization), this factor will have a value of 2. However, in our experiments, the z-polarized component of the heavy-hole PL becomes observable due to, e.g., interface corrugations, resulting in an actual value of this factor between 1 and 2. For the semiquantitative estimates in this letter as well as for qualitative results on the gain coefficient, this difference is not very important, because at high excitation levels the intensity of the stimulated emission exceeds the intensity of the spontaneous emission by more than one order of magnitude (cf. Fig. 3). Taking into account the polarization effect would actually increase this ratio. Nevertheless, additional theoretical and experimental investigations are necessary to obtain a detailed understanding of the polarization dependence.

In conclusion, stimulated PL has been observed at 80 K for a $(GaAs)_6/(AlAs)_3$ SL. The appearance of stimulated PL in such a short-period SL becomes possible because of the larger thickness of the well with respect to the barrier layer. For a ratio of well to barrier thickness of at least 2, a transition from a quasidirect to a direct band gap occurs. Since non-symmetric GaAs/AlAs SLs exhibit a direct energy gap, they can therefore exhibit superior emission properties even for very small well widths. This observation opens additional perspectives for the utilization of ultrashort-period SLs in light-emitting devices operating in the red region of the visible spectrum, in particular for the development of low-threshold lasers.

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