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Optically pumped (GaIn)As/Ga(PAs) vertical-cavity surface-emitting lasers with optimized dynamics

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We present a vertical-cavity surface-emitting laser structure optimized for fast intrinsic emission dynamics, using the strain-compensated (GaIn)As/Ga(PAs) material system with a 2λ sin-type cavity. The high quality of the epitaxial growth is revealed by the large normal mode splitting of 10.5 meV found in reflectivity measurements. The fast dynamical response of our structure after femtosecond optical excitation at 30 K yields a pulse width of 3.2 ps and a peak delay of only 4.8 ps. A structure designed for laser emission at higher temperatures exhibits picosecond dynamics at room temperature. © *1999 American Institute of Physics.* [S0003-6951(99)00610-5]

Over the past few years vertical-cavity surface-emitting lasers (VCSELs) have attracted an increasing interest of research and applications[1–5] due to their numerous favorable properties, as, e.g., the potential for generation of short pulses by gain switching[6–10] which is essential especially for high-speed optical communications. Previous work showed that the emission dynamics of a VCSEL depends on design parameters like the photon lifetime, the photon density, and the differential gain.[9,10] A high differential gain can be achieved by tuning the cavity towards the high energy tail of the gain spectrum[9] or with strained quantum wells (QWs).[11] Often compressively strained (GaIn)As/GaAs quantum well heterostructures (QWH) are therefore incorporated as active material in GaAs-based VCSEL structures. The other two parameters for fast response, i.e. photon lifetime and photon density, cannot be optimized independently: Longer cavities with periodic gain structures, on the one hand, lead to higher photon densities due to larger longitudinal confinement factors but also to longer photon lifetimes. On the other hand, shorter photon lifetimes but also lower photon densities are obtained with lower reflectivity of the distributed Bragg reflectors (DBRs). The parameters for fastest dynamical response and shortest pulses were optimized, using a rate equation model[10] and led to a VCSEL structure with a 2λ sin-type cavity with 4*3 QWs. The field has a node at the interfaces between the DBRs and the cavity resulting in a sin type of cavity which has an additional antinode position in the cavity compared to cos-type structures of the same length. A higher number of QWs can then be coupled effectively to the light field, i.e., a larger confinement factor can be realized without increase of the cavity length.

We have realized this VCSEL structure with a 2λ sin-type cavity in the material system (GaIn)As/Ga(PAs). The concept of the strain-compensated quantum well layers enabled us to grow as many as 12 strained QWs with high crystalline quality, which is one key point of our VCSEL design for fast emission dynamics. This design cannot be realized in the (GaIn)As/GaAs material system. There the total number of QWs is severely limited due to strain accumulation leading to strain relaxation mechanisms and defect formation. Strain-compensated (GaIn)As/Ga(PAs) QWH, in contrast, are free of this restriction and offer new possibilities in the design of the gain region in VCSEL structures. For example, a higher indium concentration in the wells can be realized in comparison with (GaIn)As/GaAs QW structures. This leads to both a larger strain and stronger confinement of the carriers in the wells. The consequences are a higher differential gain and a lower laser threshold. First electrically pumped continuous wave (cw) VCSELs with very low threshold have been realized with this material system.[12]

A further important advantage of the Ga(PAs) cavity spacer material is, that it has a slightly lower refractive index than GaAs, the high index material of the DBRs. A sin-type cavity, which is another key point of our VCSEL design, can therefore be realized, in contrast to the (GaIn)As/GaAs material system.

The VCSEL structures were grown by metal-organic vapor-phase epitaxy (MOVPE). Trimethylaluminum (TMAl), -gallium (TMGa), and -indium (TMIn) have been used as group-III sources in combination with the liquid group-V precursors tertiarybutyl arsine (TBA) and tertiarybutyl phosphine (TBP), which are less hazardous than arsine and phosphine. The background doping densities are assumed to be in the lower $10^{14}\,\mathrm{cm}^{-3}$ range as in high purity GaAs samples that are grown under the same conditions. A structure designed for low temperature operation is shown in Fig. 1. The top and the bottom AlAs/GaAs DBR mirrors consist of 12.5 and 15 layer pairs, respectively. $\mathrm{GaP_{0.09}As_{0.91}}$ is used as spacer material in the 2λ cavity. The active region is composed of four stacks of three 8.2 nm $\mathrm{Ga_{0.9}In_{0.1}As}$ QWs with 9.9 nm GaAs barriers in between, placed in the antinode positions of the electric field (Fig. 1). The cavity resonance of the low-temperature sample is around 887 nm (1.398 eV). A more detailed description of the growth process will be published elsewhere.[13]

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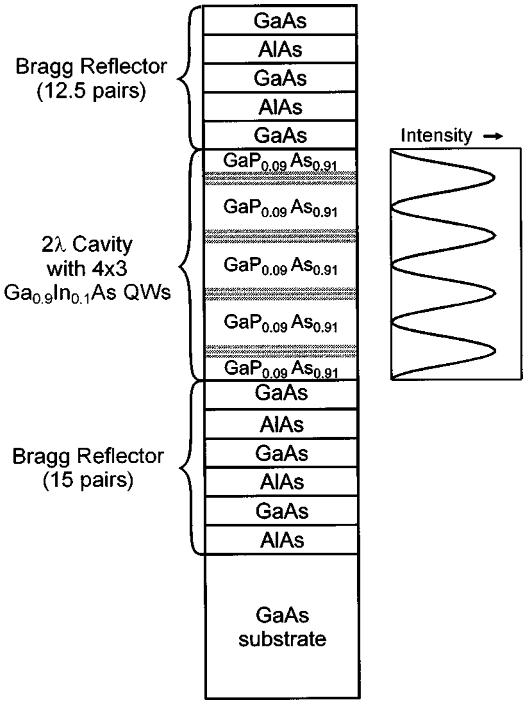

FIG. 1. Schematic layer sequence of the (GaIn)As/Ga(PAs) multiple-quantum-well vertical-cavity surface-emitting laser with a 2λ sin-type cavity.

Reflectivity spectra at low densities are measured to characterize the quality of the epitaxial layers. The samples are cooled to 10 K in a He gas flow cryostat. A halogen lamp serves as the light source. The reflected light is spectrally resolved in a monochromator and detected with a cooled Ge detector. Figure 2 shows the reflectivity spectrum of the VCSEL. We obtain a wide stopband with a width of about 170 meV. In the center of the stopband two pronounced resonance dips are observed at 1.390 and 1.402 eV. This splitting of the resonances is due to the normal mode coupling, which is caused by the interaction between the QW excitons and the cavity mode.[14] We changed the temperature from 5 to 180 K tuning thereby the exciton energy versus the cavity mode.[15] The minimum splitting of the mixed exciton-cavity modes is 10.5 meV being the highest value of normal mode coupling in GaAs-based microcavities reported so far and demonstrating the high quality of our structure. This strong coupling between the active material and the light field in the cavity should also yield a high photon density under lasing conditions, and therefore fast emission dynamics is expected.

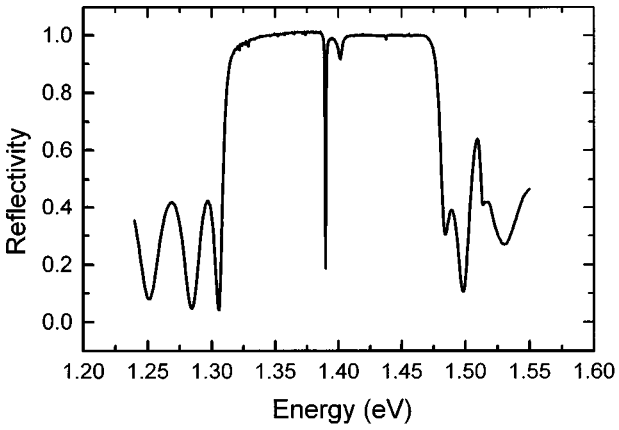

FIG. 2. Reflectivity spectrum of a strain-compensated (GaIn)As/Ga(PAs)-VCSEL structure at 10 K.

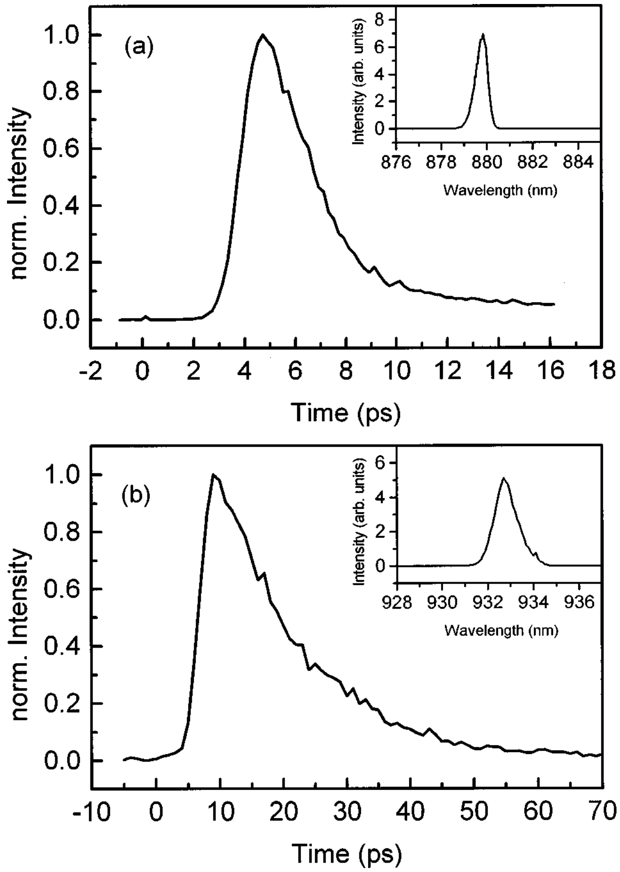

FIG. 3. Time evolution of the VCSEL emission at 30 K after excitation with 100 fs optical pulses at 825 nm (a) and at 300 K after excitation at 853 nm (b). The time-integrated spectra of the low-temperature sample and the room-temperature sample are shown in the inset of (a) and (b), respectively.

We measure the dynamical response of our VCSEL using femtosecond optical excitation with a mode-locked Ti:sapphire laser with a pulse width of 100 fs and at a repetition rate of 80 MHz. The pump wavelength is 825 nm in order to avoid reflection losses as well as absorption in the Bragg mirrors or in the barriers. The excitation power is 450 mW, corresponding to 9 times the threshold value. The emission of the VCSEL structure is focused onto a β-bariumborate crystal by two parabolic mirrors together with a time-delayed fraction of the pump beam. The generated sum-frequency light is separated from the scattered light by a double monochromator and detected with a photomultiplier. Variation of the time delay between the upconversion and the excitation laser gives the temporal variation of the VCSEL emission.[16] The dynamical response of the sample at 30 K is depicted in Fig. 3(a). The peak delay time after the excitation is 4.8 ps and the full-width at half-maximum (FWHM) is 3.2 ps. This is the fastest dynamics reported for VCSELs so far.[9,10] The comparable values for a 2λ cos-type cavity with 3*2 (GaIn)As/GaAs QWs are 8.2 ps for the peak delay and 3.3 ps for the pulse width.[10] Particularly, the peak delay is reduced for our structure. A reduction of the peak delay time to 6.8 ps for a 3*3 QWs configuration has already been predicted using rate equation calculations in Ref. 10. Our result of 4.8 ps for the peak delay is even faster than this prediction. This further improvement is due to the sin-type cavity in our structure which yields an additional antinode position of the electric field in the cavity compared to the cos-type design. The additional gain region with three QWs in the additional antinode position leads to a higher confinement factor without an undesired increase of the photon lifetime.

Rate-equation calculations show that longer cavities do not further improve the dynamics since the increase of the confinement factor is compensated by an increase in the photon lifetime.[10] More than three QWs in each antinode of the electric field also do not improve the dynamics since for a given barrier width only three QWs can be coupled efficiently to one antinode.[9] Therefore, our cavity design can be regarded as the optimum structure for fastest intrinsic dynamics in the framework of a simple rate-equation analysis. However, it should be mentioned that the rate equation description does not include nonequilibrium effects like carrier relaxation dynamics. In particular, carrier relaxation plays an important role for the emission dynamics, as was shown recently.[17] Therefore, a complete understanding of the picosecond emission dynamics cannot be obtained from rate equations but requires a detailed microscopic modeling including nonequilibrium effects.[18] A further improvement of the VCSEL design can, if at all, only be obtained on the basis of such a microscopic theory.

We have also realized a sample designed for operation at higher temperatures up to 300 K. The layer sequence is the same as that in Fig. 1, only the layer thicknesses are adapted for an emission wavelength of 930 nm at room temperature leading to 8.35 nm for the width of the (GaIn)As QWs and 10.4 nm width for the barriers. The number of the top and bottom mirror layers is increased by two pairs to overcome the lower gain at higher temperatures. We use femtosecond optical excitation at 853 nm with a power of 670 mW, corresponding to 4.8 times the threshold value. The fastest emission dynamics at room temperature are with a FWHM of 13 ps and a peak delay of 9 ps slower than at low temperatures [Fig. 3(b)], indicating slower carrier relaxation and slower gain dynamics at room temperature.

In conclusion, we have presented here the consequent realization of a VCSEL structure optimized for fast emission dynamics. We take advantage of the strain-compensated (GaIn)As/Ga(PAs) material system that yields the possibility on one hand to grow as many as 4*3 strained QWs and on the other hand to design a sin-type cavity. The high quality of the epitaxial layers is revealed by the large normal mode splitting of 10.5 meV. The optimum dynamical response of our structure after femtosecond optical excitation is characterized by the very short pulse width of 3.2 ps and a short peak delay of 4.8 ps at 30 K. Picosecond dynamics of another sample are also demonstrated at room temperature, with slightly longer values obtained for peak delay and pulse width.

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