Ultrafast (GaIn)(NAs)/GaAs vertical-cavity surface-emitting laser for the 1.3 μm wavelength regime

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(GaIn)(NAs) vertical-cavity surface-emitting lasers for room-temperature emission at 1.3 μm wavelength are designed and grown by metal-organic vapor-phase epitaxy using dimethylhydrazine and tertiarybutylarsine. Room-temperature operation at wavelengths up to 1.285 μm is achieved with low optical pumping thresholds between 1.6 and 2.0 kW/cm^2. Stimulated emission dynamics after femtosecond optical pumping are measured and compare favorably with results on (GaIn)As/Ga(PAs)-based structures. © *1999 American Institute of Physics.* [S0003-6951(99)03416-6]

Vertical-cavity surface-emitting lasers (VCSELs) are of increasing interest for high speed optical fiber communication due to performance advantages such as single longitudinal mode operation, high optical coupling efficiency into fibers, and low-cost fabrication.[1–4] VCSELs emitting at the optical fiber windows of 1.3 or 1.55 μm have progressed far more slowly than 0.85 μm VCSELs which are already commercially available. The (GaIn)(PAs)-InP material system is most common for edge emitters in this long wavelength regime[5] but for VCSELs the lack of epitaxial layers with a high enough refractive index contrast to form highly reflecting distributed Bragg Reflectors (DBRs)[6] is most detrimental. One approach to better Bragg mirrors is the deposition of dielectric DBRs after backside etching,[7] but this requires lateral electrical contacts due to the insulating mirrors. Promising results have been achieved using wafer fusion of the (GaIn)(PAs) active layer with GaAs/AlAs DBRs grown on separate GaAs substrates.[8,9] But this method requires a very complicated preparation using multiple steps of epitaxy, bonding, and etching. A different approach is to use an alternative material system for the DBRs and the active layers. Recently a GaSb/(AlGa)Sb VCSEL for the 1.5 μm range has been realized on GaAs substrate.[10] But new problems arise there due to the high lattice mismatch of GaSb and GaAs.

A novel alternative is using (GaIn)(NAs) quantum well (QW) active layers.[11,12] This material system offers the possibility to realize 1.3 μm or even 1.5 μm wavelength emission[12] and can be grown lattice matched on GaAs. Edge-emitting lasers for a wavelength of 1.3 μm have already been made with this material system both under pulsed[13] and cw operation.[14] The (GaIn)(NAs)/GaAs QWs have stronger electron confinement compared with conventional (GaIn)(PAs)/InP structures due to the large conduction-band offset yielding the potential for better high temperature performance of devices.[11] First optically and electrically pumped VCSELs have been grown with this material system by gas-source molecular beam epitaxy,[15,16] but only a small content of nitrogen was incorporated (0.4%) leading to emission wavelengths near to 1.2 μm, only.

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We have realized VCSELs with (GaIn)(NAs)/GaAs QWs emitting close to 1.3 μm and report here on the lasing properties of these structures after pulsed optical excitation. In particular, the emission dynamics at room temperature is studied as an interesting issue for high-speed performance of future devices.

The VCSEL structure with (GaIn)(NAs) QWs was grown by metal-organic vapor-phase epitaxy (MOVPE) using 1,1-dimethylhydrazine (UDMHy) in combination with tertiarybutylarsine (TBAs) as group-V precursors. Trimethylaluminum (TMAl), triethylgallium (TEGa), and trimethylindium (TMIn) have been used as group-III sources. First MOVPE growth experiments in the (GaIn)(NAs) material system have already been reported.[12] By optimizing the MOVPE growth conditions, in particular the room-temperature luminescence-efficiency could be improved drastically. Details of this optimization will be published elsewhere.[17] The structure designed for room-temperature operation with fast emission dynamics is shown in Fig. 1. The layer sequence is similar to our (GaIn)As/Ga(PAs) structure optimized for fast dynamics in the 0.93 μm wavelength regime.[18,19] The top and the bottom AlAs/GaAs DBR mirrors consist of 16 and 20.5 layer pairs, respectively. GaAs is used as barrier material in the $2\frac{1}{2}\ \lambda$ cavity. The active region is composed of four stacks of three 7 nm (GaIn)(NAs) QWs, placed in the antinode positions of the internal field (Fig. 1).

In the following, we report on threshold and emission dynamics of the new material system and compare them with results obtained on our (GaIn)As/Ga(PAs)-based structure.

We use optical excitation with a mode-locked Ti:sapphire laser with a pulse width of 100 fs at a repetition rate of 80 MHz for the measurement of the room-temperature lasing properties and the emission dynamics of our structure. The pump wavelength is 0.92 μm in order to avoid reflection losses as well as absorption in the Bragg mirrors or in the barriers. The time-integrated VCSEL emission is investigated with an optical spectrum analyzer. Figure 2 shows the intensity of the time-integrated emission as a function of excitation density at two different positions on the sample. For densities higher than about 2 kW/cm^2 we find a steep rise of the emission intensity with increasing excitation

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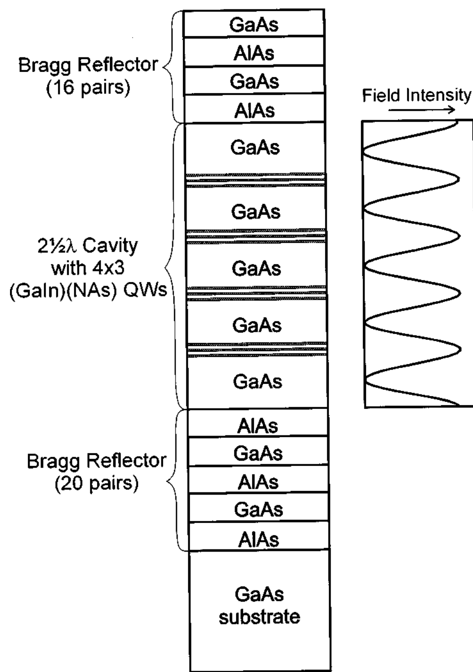

FIG. 1. Schematic layer sequence of the (GaIn)(NAs) multiquantum well vertical-cavity surface-emitting laser with a $2\frac{1}{2}\lambda$ cavity.

power, indicating threshold excitation densities between 1.6 and 2.0 kW/cm^2 in the center and near the edge of the (GaIn)(NAs) sample, respectively. The reflection losses, varying between 30% and 38% of the pump beam, are already taken into account. The threshold is by a factor of two lower than the values recently reported for a (GaIn)(NAs) VCSEL emitting at 1.22 μm.[15] It is important to note, however, that both the active layer as well as the design of the DBR mirrors are different. Therefore, a direct comparison of the layer quality is difficult. A more comparable structure is our (GaIn)As/Ga(PAs) VCSEL designed for fast room-temperature emission at 0.93 μm.[19] This structure contains the same number of QWs as the (GaIn)(NAs) VCSEL but

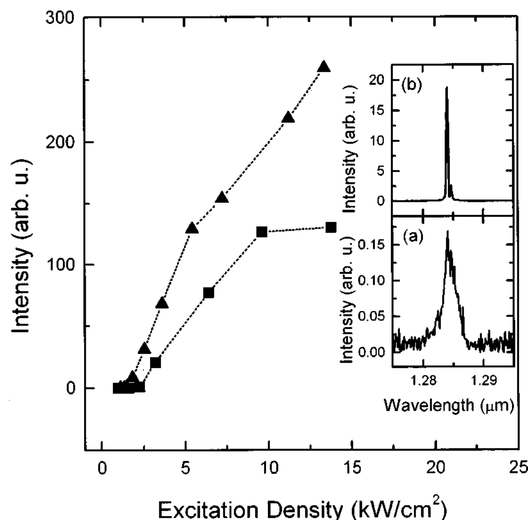

FIG. 2. Intensity of the time-integrated emission as a function of the internal excitation density in the center (triangle) and near the edge of the sample (square). Insets (a) and (b) display emission spectra close to threshold near the edge of the sample. For (a) the excitation density is 0.8 times threshold, for (b) it is 1.1 times threshold.

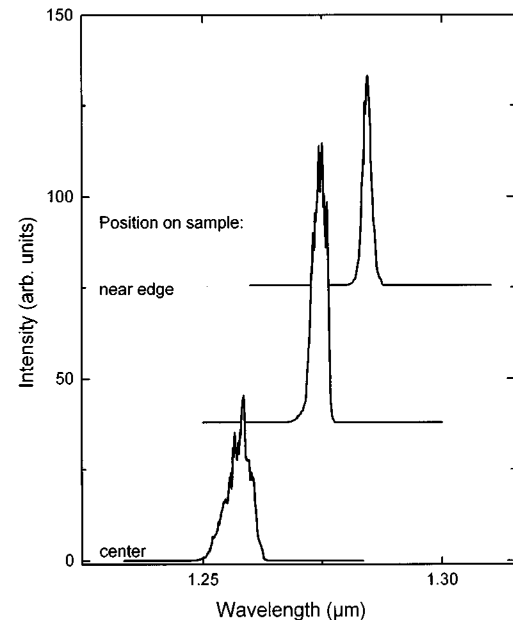

FIG. 3. Emission spectra of the (GaIn)(NAs) VCSEL at three different positions on the sample at room temperature. The emission wavelengths are 1.26, 1.275, and 1.285 μm, while the excitation wavelength for all three spectra is 0.92 μm at internal densities of 11, 11, and 10 kW/cm^2, respectively.

has a threshold excitation density of 4.5 kW/cm^2 (also corrected for the reflection losses). The threshold value of the (GaIn)(NAs) VCSEL is thus more than a factor of two smaller than the threshold of the (GaIn)As/Ga(PAs) structure, demonstrating the very good material quality of our (GaIn)(NAs) VCSEL.

The linewidth narrows drastically at the threshold underlining the onset of laser emission, as can be seen from the emission spectra slightly below [Fig. 2(a)] and above threshold [Fig. 2(b)]. At higher excitation densities multiple transverse modes rise up, leading to a broadening of the lineshape, as expected for planar VCSEL structures. The lasing wavelengths vary between 1.26 μm in the center and 1.285 μm near the edge of the sample as shown in Fig. 3. This small wavelength shift underlines the high layer homogeneity in the growth process using the alternative group-V precursors.

Next, we measure the dynamical response of the (GaIn)(NAs) VCSEL at room temperature after optical excitation at 0.92 μm (i.e., with 360 meV excess energy) using a femtosecond up-conversion technique with a time resolution of 100 fs.[19] The results at an emission wavelength of 1.26 μm are depicted in Fig. 4. The peak delay time after the excitation and the full-width at half-maximum (FWHM) of the peak decrease with increasing excitation density and reach a saturation at excitation densities of about 8 times the threshold value. This behavior is similar to the case of (GaIn)As VCSELs.[20,21] The fastest dynamics is measured at an internal excitation density of 13.4 kW/cm^2, i.e., at 8.4 times the threshold value, with a peak delay time of 15.5 ps and a peak width of 10.5 ps (inset of Fig. 4).

Recently, the room-temperature dynamics of an (GaIn)(PAs) VCSEL after femtosecond optical excitation has been investigated.[7] A peak delay of 32.5 ps and a width of the pulses of 16 ps were reported. This structure was not particu-

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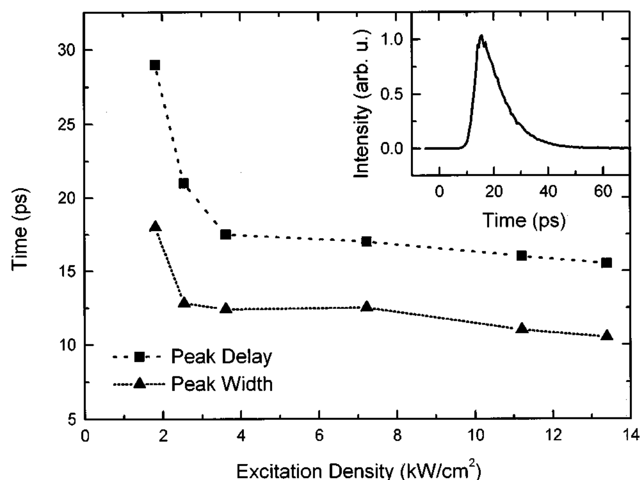

FIG. 4. The peak delay time (square) and the peak width (triangle) of the VCSEL emission after excitation with 100 fs optical pulses at 0.92 μm at different internal excitation densities at room temperature. The lasing wavelength was 1.26 μm. The time evolution of the emission at 13.4 kW/cm^2 internal excitation density is shown in the inset.

larly optimized for fast dynamics. Nevertheless, the comparison with our novel (GaIn)(NAs) VCSEL supports the high performance of our new material system.

For further comparison, we look again at the (GaIn)As/Ga(PAs) VCSEL emitting at 0.93 μm after femtosecond excitation with 120 meV excess energy. Excitation densities of about 5 times the threshold value result in a peak delay time of 9 ps and a peak width of 13 ps for the (GaIn)As/Ga(PAs) VCSEL and a peak delay time of 17 ps and a peak width of 12.5 ps for the (GaIn)(NAs) VCSEL. The decay times of the falling tail of the peak are 13.7 and 7.1 ps for the (GaIn)As/Ga(PAs) and for the (GaIn)(NAs) VCSEL, respectively. We relate the longer peak delay of the (GaIn)(NAs) VCSEL to a longer thermalization process[21] due to the higher carrier excess energy after the optical excitation. But the peak width of the long-wavelength VCSEL is slightly shorter and the decay time is drastically reduced, again demonstrating the excellent dynamical properties of the (GaIn)(NAs) material system.

In conclusion, we have succeeded in the realization of a (GaIn)(NAs) VCSEL emitting in the 1.3 μm wavelength range at room temperature. The structure exhibits low lasing thresholds between 1.6 and 2.0 kW/cm^2 at room temperature and at emission wavelengths between 1.26 and 1.285 μm. Picosecond dynamics after femtosecond optical excitation are demonstrated with a peak delay of 16 ps and a peak width of 11 ps for an excitation density of 8 times above threshold with an excess energy of 360 meV. Our results underline that (GaIn)(NAs) is a very promising material system for 1.3 μm VCSELs. Future studies will concentrate on the realization of even longer wavelength emission in the 1.55 μm spectral range as well as on electrically pumped structures.

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