

# Simultaneous two-level lasing in GaInAsSb/GaSb strained quantum-well lasers

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Simultaneous two-level lasing, corresponding to ground level and excited level transitions in GaInAsSb/GaSb quantum well lasers under continuous wave operation is reported. The effect is attributed to a slowed-down intersubband relaxation in the quantum wells due to buildup of hot phonon population resulting in an incomplete clamping of the excited state population above the ground level lasing threshold. © 2009 American Institute of Physics. [DOI: 10.1063/1.3207826]

Simultaneous two-state lasing has already been observed in quantum dot lasers,<sup>1-3</sup> where it was attributed to a “phonon-bottleneck” effect resulting in an increased carrier relaxation time between the excited state and the ground state due to combined effects of limited density of states in quantum dots and inefficient relaxation by phonon emission when interlevel energies do not match energies of the optical phonons. Such an inhomogeneous broadening by retarded relaxation in quantum dots has been also predicted theoretically.<sup>4,5</sup> Slow intersubband relaxation in quantum wells has also been observed previously in asymmetric and coupled quantum well systems,<sup>6,7</sup> however, up to now, it has never been observed experimentally to result in simultaneous two-level lasing.

In this letter, we present experimental evidence of simultaneous two-level lasing in quantum well (QW) lasers under continuous wave (cw) operation. We attribute the excited level lasing to a slow interaction between the subbands.

The structure investigated in this work was grown on an *n*-type GaSb substrate. The layer sequence is as follows. First, a 2  $\mu\text{m}$  thick cladding layer of  $\text{Al}_{0.50}\text{Ga}_{0.50}\text{As}_{0.04}\text{Sb}_{0.96}$  with a Te doping of  $2 \times 10^{18} \text{ cm}^{-3}$  was grown. This was followed by a 400 nm undoped  $\text{Al}_{0.10}\text{Ga}_{0.90}\text{As}_{0.01}\text{Sb}_{0.99}$  waveguide layer, which also serves as a separated confinement layer. Then, the active region with two 20 nm thick  $\text{Ga}_{0.57}\text{In}_{0.43}\text{As}_{0.14}\text{Sb}_{0.86}$  QWs, separated by 8 nm thick GaSb barriers was deposited. The *p*-side consists of a 400 nm wide undoped  $\text{Al}_{0.10}\text{Ga}_{0.90}\text{As}_{0.01}\text{Sb}_{0.99}$  waveguide layer and a 2  $\mu\text{m}$  thick  $\text{Al}_{0.50}\text{Ga}_{0.50}\text{As}_{0.04}\text{Sb}_{0.96}$  cladding layer, which is *p*-doped with Si to the concentration of  $5 \times 10^{17} \text{ cm}^{-3}$ . The QWs are 1.7% compressively strained.

Ridge waveguide lasers with stripe widths of 30  $\mu\text{m}$  were processed, cleaved at different lengths, and mounted episode up on copper heat sinks. The laser facets were left as cleaved and no coating was applied.

From spectral measurements, it was observed that devices with longer resonator lengths ( $>400 \mu\text{m}$ ) started lasing with an emission wavelength of 2720 nm, corresponding to the ground level transition of 0.456 eV. On the other hand, shorter devices started lasing at 2490 nm, corresponding to the second QW level transition of 0.5 eV (see Fig. 1). The latter is due to the fact that mirror loss is directly proportional to the inverse cavity length, therefore, by changing the cavity length the total loss is also changed and, at some

point, gain in the ground level becomes smaller than the total loss and lasing is prohibited.

A more detailed investigation was carried out on 500  $\mu\text{m}$  long devices, which showed simultaneous lasing from both QW levels under cw operation (Fig. 2). It was observed that the wavelength switching from the ground level to the excited one has “digital” character (Fig. 3) and that simultaneous lasing takes place only in a limited range of current densities (see Figs. 3 and 4). At low current densities (below 1.22  $\text{kA/cm}^2$ ), only the ground level lasing is observed. By increasing the current, second level lasing appears as well and simultaneous lasing from both levels takes place. By increasing the current further, the ground level transition ceases and only lasing at the second level transition is observed (above 1.32  $\text{kA/cm}^2$ ). Figure 4 shows the evolution of the measured laser emission spectra as a function of increasing current densities.

Switching from ground level lasing to excited level lasing was found to have no hysteresis effect. This behavior is reproducible not only for the devices from the same wafer, but also for devices from different epitaxial runs.

“Digital” switching behavior was observed experimentally<sup>1-3</sup> and explained theoretically<sup>1,2,8</sup> in quantum dot lasers. Nevertheless, in quantum well lasers, the situation is different. First, if the gain saturation in the ground level would be the result of a decreasing number of available electron states in the subband due to filling, then, one would expect to observe uniform filling due to a two-dimensional

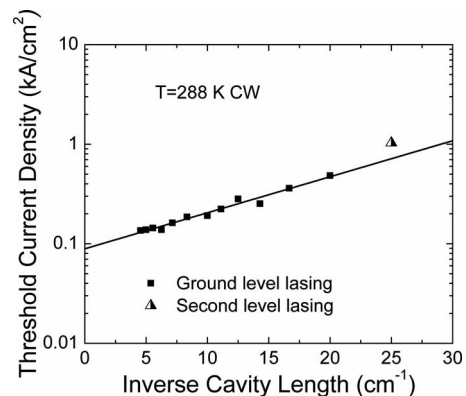


FIG. 1. Measured threshold current density as a function of inverse cavity length. Solid squares indicate devices that start lasing at the ground level and the triangle represents the 400  $\mu\text{m}$  long device, which starts lasing from the second quantum well level.

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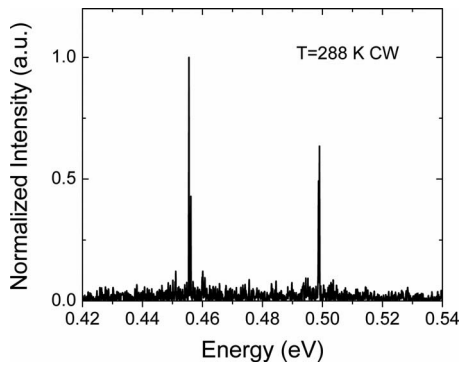


FIG. 2. Measured emission spectra of 500  $\mu\text{m}$  long device with a 30  $\mu\text{m}$  wide ridge at a current density of 1.3  $\text{kA}/\text{cm}^2$  at 288 K under cw operation. The laser line at 0.456 eV corresponds to the ground level transition, whereas the laser line at 0.5 eV corresponds to the excited level transition.

continuum of states, which would result in a continuous shift of the emission wavelength toward higher energies. Second, the higher number of available states in a quantum well makes retarded relaxation due to filling a less likely mechanism. Our experimental observations also clearly indicate that no filling takes place. The population of the ground level gets clamped immediately after the threshold is reached. This can be seen from a nearly constant laser emission wavelength with increasing current (Fig. 3). The appearance of the excited level lasing indicates that the population in the second level does not clamp when the lasing condition is reached in the ground level. Such filling eventually leads to population inversion in the second level as well. The observed behavior indicates that very slow scattering between the subbands exists. The exact origin of such a behavior is not clear. A most likely mechanism for the retarded relaxation can be the buildup of a significant nonequilibrium LO phonon population (hot phonons). It is well known that phonon reabsorption considerably slows down the electron relaxation.<sup>7,9</sup> Another possible mechanism could be the dynamical screening effect,<sup>10</sup> where the electron-phonon interaction is screened by free-carriers. It has been shown to play a minor role<sup>7,11</sup> up to electron densities of  $n = 10^{17} \text{ cm}^{-3}$ . On the other hand, the carrier densities are much higher since two levels simultaneously reach the population inversion condition and such an effect might become significant.

We would attribute the disappearance of the ground level stimulated transition with increasing current density (see Figs. 3 and 4) to several effects. First, due to slow intersubband relaxation, the free-carrier density strongly increases as

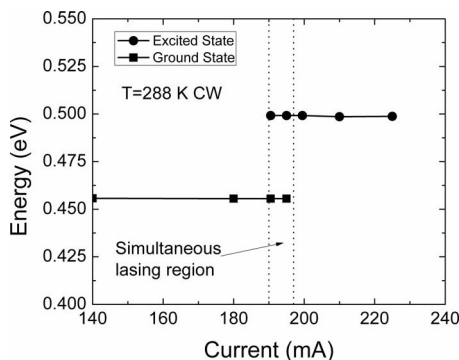


FIG. 3. Wavelength switching as a function of laser current for a 500  $\mu\text{m}$  long device, with a 30  $\mu\text{m}$  wide ridge.

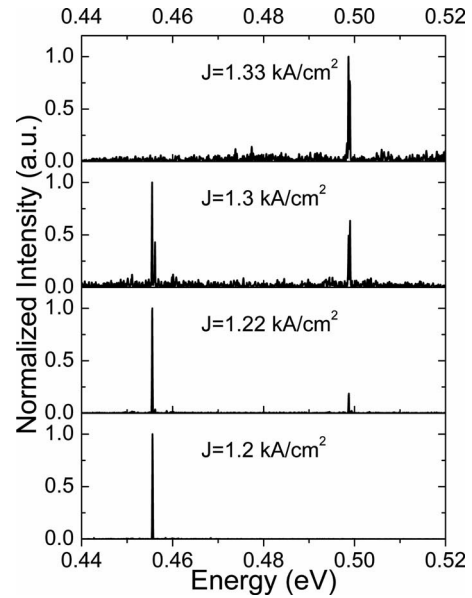


FIG. 4. Evolution of the measured emission spectra for a 500  $\mu\text{m}$  long device, with a 30  $\mu\text{m}$  wide ridge, under cw operation, at 288 K.

the second quantum level is being filled. This leads to increased free-carrier absorption, to which the ground level lasing is more sensitive as the efficiency of this absorption mechanism increases proportionally to the square of the emission wavelength.<sup>12</sup> Second, nonradiative Auger recombination is also stronger for the ground level transition due to the smaller energy gap. In long wavelength GaInAsSb lasers, the dominant Auger mechanism is CHCC<sup>13,14</sup> which is proportional to  $n^2p$ . Apparently, this Auger recombination mechanism is not clamped at the ground level lasing threshold and heavy-holes make a major contribution. This is because the second heavy-hole subband is being filled after the ground level starts to lase. The separation between the two heavy-hole subbands is only 6 meV (as simulated by nextnano<sup>++</sup>),<sup>15</sup> thus, both can effectively participate in CHCC Auger process. The CHSH (Ref. 16) mechanism can be ruled out, as it was shown to be strongly suppressed<sup>14</sup> for GaInAsSb laser with radiative transitions below 0.6 eV. This is because the separation between spin-orbit split-off band and heavy-hole band exceeds the bandgap energy. Finally, the fact that the second level starts to lase also leads to a dramatically decreased carrier lifetime in that subband (typically in the range of several picoseconds for stimulated emission). In such situation, events of carrier scattering to the lower subband and stimulated emission from the second level compete for the same carriers. As the population in the second level gets clamped with increasing injection, the radiative rate increases due to decreasing stimulated emission lifetime from that level, whereas the scattering rate to the lower subband is clamped. Therefore, with increasing injection, the gain in the ground level gets saturated. The combination of all these effects leads to the ceasing of the ground level lasing with increasing current.

The dynamics described above can be observed in the optical output power-current ( $P$ - $I$ ) characteristics of a 500  $\mu\text{m}$  long laser which shows two-level simultaneous lasing (see Fig. 5). It can be seen from Fig. 5 that the optical power corresponding to the stimulated ground level transition starts to saturate as the current density approaches the

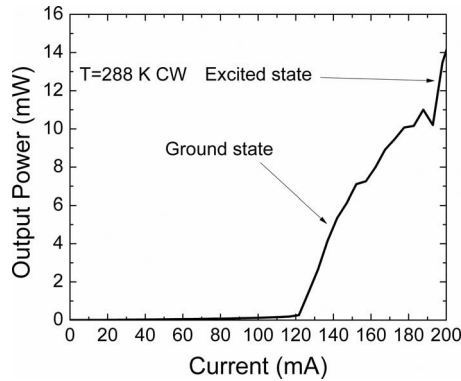


FIG. 5. Measured  $P$ - $I$  characteristic of a  $500\ \mu\text{m}$  long laser with a  $30\ \mu\text{m}$  wide ridge under cw operation.

value at which population inversion is reached in the second quantum level (corresponds to 190 mA in Fig. 5). The appearance of second level lasing is followed by a kink in the  $P$ - $I$  curve, and, when the ground level lasing disappears, the output power starts to rise with an increased external efficiency.

To summarize, we have demonstrated simultaneous lasing from two QW laser levels under cw operation. We attribute the effect to the slowed down intersubband relaxation which we explain by possible buildup of nonequilibrium LO phonon population and dynamical screening effect. No band filling was observed, therefore, we ruled out retarded relaxation due to a reduced number of available electron states in the lowest subband. We also observed ceasing of the stimulated emission from the ground level with increasing current density. We attribute this to nonradiative loss mechanisms, which are more efficient for the lower energy transition, and to the competition between events of stimulated recombina-

tion from the excited level and scattering of carriers to the lower subband.

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- <sup>15</sup>For obtaining the Nextnano executables and related publications [online] <http://www.wsi.tum.de/nextnano>.
- <sup>16</sup>CHSH—the recombination of a conduction band electron with a heavy-hole is accompanied by the excitation of another heavy-hole to the spin-off band.