# Extremely broadband AlGaAs/GaAs superluminescent diodes

Ching-Fuh Lin[a] and Bor-Lin Lee
*Institute of Electro-Optical Engineering and Department of Electrical Engineering,*
*National Taiwan University, Taipei, Taiwan, Republic of China*

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Extremely broadband AlGaAs/GaAs superluminescent diodes are fabricated on substrate with four quantum wells of different widths. By choosing 20, 33, 56, and 125 Å, respectively, for the four quantum wells, the spectrum could be broadened to several times that of the conventional superluminescent diodes. The measured spectra of the fabricated devices with such quantum-well structure show that the full-width at half-maximum spectral width could be as large as 915 Å. © *1997 American Institute of Physics.* [S0003-6951(97)02238-9]

Superluminescent diodes (SLDs) are important light sources for applications in areas such as optical gyroscopes and sensors, multichannel optical amplifiers, mode-locking semiconductor lasers, and wide-range tunable external-cavity semiconductor lasers. Small spectral modulation and large spectral width are important features for SLDs. Reduction of spectral modulation has been attempted by many efforts, including antireflection coating the facet,[1] tilting the stripe,[2] polishing,[3] or dry etching[4] the facet at an angle to the pumping stripe, and bending the mesa stripe.[5] On the other hand, relatively fewer works were devoted to broadening the spectral width. We recently reported that, by choosing 40 and 75 Å for the two quantum wells, a bell-shaped emission spectrum with a spectral width 2 to 3 times that of the conventional SLDs is achieved.[6] In this letter, we report that the spectral width of the (SLA) could be engineered to be even broader with a proper design of the quantum-well structure. Using four quantum wells with widths of 20, 33, 56, and 125 Å, respectively, for the four quantum wells, the spectrum could be significantly broadened. At the low injection current, wells with widths of 56 and 125 Å contribute to the emission. At the large injection current, all four wells contribute to the emission. The measured spectra show that, at 350 mA pumping current, the full-width at half-maximum (FWHM) spectral width could be as large as 915 Å. To our knowledge, this is the broadest spectrum measured from AlGaAs/GaAs superluminescent diodes.

The idea for broadening the spectrum of SLD is very simple. From quantum mechanics, the first quantized energy level of a quantum well is elevated from the bottom of the well potential. As a result, the emitted photon energy of the semiconductor quantum well is a function of the well width. By stacking quantum wells of different widths, the emitted photon energy should cover a wide range of spectrum. Because the gain bandwidth of the GaAs material for each quantized level corresponds to about 50 meV, we expect that the overlapped energy spectrum is maximized without a dip if the energy level for each well is separated from one another by 50 meV. Using $Al_{0.2}Ga_{0.8}As$ as the well barrier and GaAs as the well material and choosing 20, 33, 56, and 125 Å as the well widths, the corresponding transition energies could separate for 50 meV. As a matter of fact, the transition energies for those wells are about 25, 75, 125, and 175 meV larger than the energy of the well bottom, respectively. Therefore, the overall gain spectrum of the material with four such wells stacked together will be four times wider than that of the single-width quantum well.

It is worth noting that the band gap of the $Al_{0.2}Ga_{0.8}As$ barrier is 250 meV larger than that of the GaAs material, so the addition of another well with the first quantized energy 225 meV larger than the GaAs band gap is expected to further expand the energy spectrum. However, the corresponding well width is only 9 Å, around which the quantized energy level significantly varies with the well width. Because no multiple atomic layers could be grown to have this width for the desired energy level, the quantum well of such narrow width is not used. Therefore, four quantum wells will probably be the maximum number for the expansion of the gain spectrum. On the other hand, the widest well has a second quantized level corresponding to an energy 97 meV larger than the GaAs band gap, but this level contributes to the transition only under certain conditions.[7] From our spectrum measurements of the devices fabricated on the designed substrate, this second quantized level has no adverse effects on the shape of the spectrum.

The designed quantum-well structure is shown in Fig. 1. The graded index separate confinement heterostructure (GRINSCH) is formed in connection with the wells. The wells are separated by the wide $Al_{0.2}Ga_{0.8}As$ barrier to ensure that the quantized states in each well do not couple to each other and so the transition occurs at the desired energy level. Otherwise, the energy level in each well will be shifted and

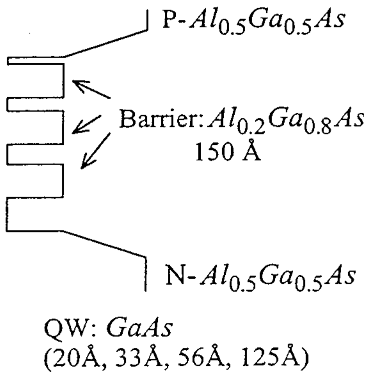

FIG. 1. The band structure of the designed quantum-well epitaxial layers.

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[a] Electronic mail: cflin@cc.ee.ntu.edu.tw

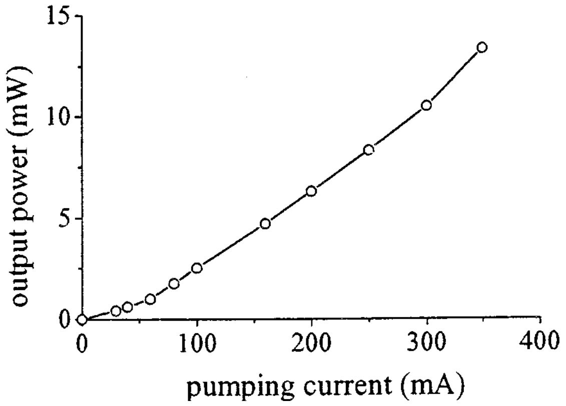

FIG. 2. A measured $L-I$ curve of the SLD.

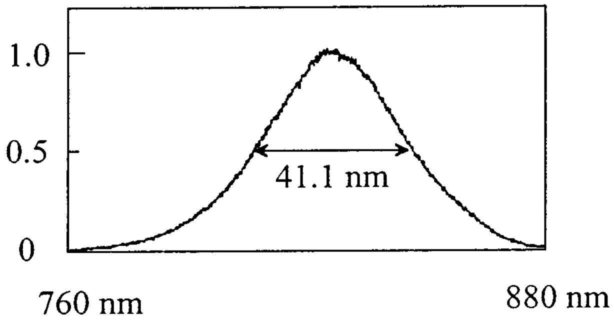

FIG. 4. Spectrum of SLD at the pumping current of 30 mA.

the gain spectrum will not behave according to our design. Metal organic chemical vapor deposition (MOCVD) is applied to grow this quantum-well structure. Although the transition energy can also be altered by different material gradients in the wells,[8] for fine tuning the transition energy MOCVD epitaxial growth usually has better control of well width than material gradients.

The tilted-stripe SLDs[2] are fabricated on the MOCVD grown substrate with the designed quantum-well structure. Because the tilted-stripe structure could well eliminate the Fabry–Perot resonance, the broad spectrum could easily be realized. The 5 $\mu$m ridge waveguide of the SLDs is tilted at 5° from the normal to the cleaved facet. The length is about 500 $\mu$m. Typical processing techniques were applied for the device fabrication. The ridge waveguide was created by wet etching. Etching was stopped at $\sim$200 nm above the GRIN-SCH layer. The fabrication was completed by $n$-contact metallization and then the devices were cleaved apart. No facet coatings were applied to the devices.

The $L-I$ curves were measured. Figure 2 shows a measured $L-I$ curve. The spectra were also measured. Very little spectral modulation is observed because both facets have a very small retroreflectivity. From the measured spectra, the spectral modulation is estimated to be less than 20 dB even for the injection current up to 350 mA. With increasing pumping current, the spectrum is broadened, but remains bell shaped. The broadening is mainly toward the short wavelength, as shown in Fig. 3. At the low injection current, the spectrum at the long-wavelength side dominates, indicating that the injected carriers fill up the wider well first. Figure 4 shows the spectrum of the device pumped at 30 mA. Even at this low injection current, the spectral width is still larger than the gain bandwidth of the individual well, so transitions in the two widest wells should occur simultaneously. This observation is consistent with the measurement from SLDs fabricated on the substrate with asymmetric dual quantum wells,[6] where transitions in both wells also occur simultaneously at the low injection current.

At the low injection current, the Fermi level is far away from the quantized energy level of the narrower wells, so very few carriers exist therein. With increased injection current, the Fermi distribution of the carriers shifts toward the large-energy level, leading to a significant increase of the population in the narrower wells. As a consequence, transition due to the quantized energy level of the narrower wells occurs, resulting in a broadening of the spectrum toward the short wavelength. At 350 mA pumping current, all four wells have significant carriers for the transitions, so the spectrum is very broad, as shown in Fig. 5. The FWHM of the spectrum is as large as 915 Å, which spans 42 THz in the frequency domain. Because this spectral width has already been reduced due to the exponential growth of the amplified emission,[6] the original overall gain bandwidth of the four quantum wells could be more than 1000 Å, as expected from our design of the quantum-well structure. In addition, the flat plateau of the spectrum in Fig. 5 implies that all the four wells have comparable transitions at the large injection current. Therefore, as four wells are all highly populated, there

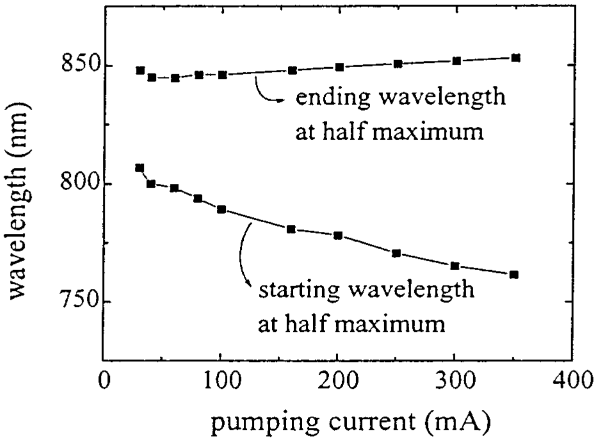

FIG. 3. The starting and ending wavelengths of the spectrum at half-maximum magnitude vs the pumping current.

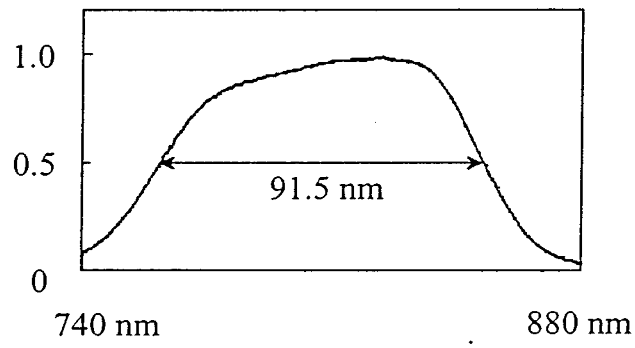

FIG. 5. Spectrum of SLD at the pumping current of 350 mA.

is no obvious preference on the transition in any well. On the other hand, the large injection current also causes a slight broadening toward the long wavelength, as shown in Fig. 3. It is possibly due to the band gap renormalization effect.[9]

In conclusion, extremely broadband SLDs are fabricated on AlGaAs/GaAs substrate with a proper design of the quantum-well structure. By choosing 20, 33, 56, and 125 Å, respectively, for four quantum wells, the spectrum could be broadened to several times that of the conventional SLDs. The spectral width increases with the injection current. At low injection current, the spectrum at the long-wavelength side dominates, but still larger than the gain bandwidth of the material with a single well. With increased injection current, the spectrum is broadened due to the transitions occurring at the narrower wells. At pumping current of 350 mA, the measured spectrum has a FWHM as large as 915 Å. In addition, the spectrum has a pretty flat plateau, indicating that all the four wells have comparable transitions at the large injection current. We expect that the wide and flat spectrum could extend the applications of SLDs.

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