Laser Simulation Encompassing Molar Fraction Variation via *DevEdit*

This article addresses the creation of semiconductor laser double heterostructures, and the subsequent simulation of laser output with **DevEdit** from Silvaco. A laser consists of a gain medium sandwiched between two mirrors forming the laser cavity. This is necessary for effective laser operation because the round trip gain of the device, including the material and mirror losses, is unity. In addition, there is an integer number of half-wavelengths of light inside the optical length of the laser cavity.

A semiconductor laser consists of a PN junction made from direct bandgap semiconductor material; the N-doped side contains excess electrons and there is an excess of holes on P-doped side. Across this junction is a built-in potential barrier that prevents or hinders electron-hole recombination. Forward bias application lowers this barrier and facilitates carrier recombination. If forward bias is particularly high, the result is a population inversion that yields the required gain for laser operation.

The interaction between the gain medium and the laser light is optimized through the use of of double heterostructures that fabricate a laser from a combination of semiconductor materials with different band gap energies. This provides confinement for current and different refractive indices for optical confinement. The use of these confinement techniques improves laser efficiencies and lower the laser drive's current.
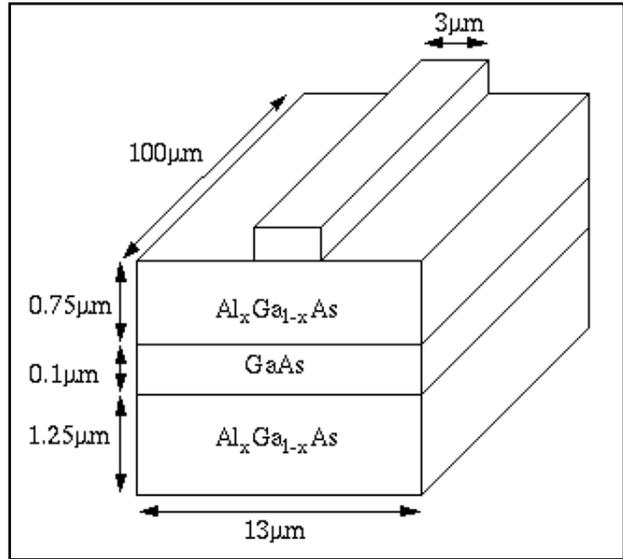

Figure 1. The AlGaAs/GaA/AlGaAs stripe laser structure used in this article.

The semiconductor materials used for the structure in this example include GaAs with direct bandgaps of 1.43eV, and $Al_xGa_{1-x}As$. $Al_xGa_{1-x}As$ is dependent on the x concentration (molar fraction). The x concentration is the relative number of atoms for which Ga is replaced by Al. Although x concentration < 0.38 $Al_xGa_{1-x}As$ is a direct bandgap material, the concentration is higher and the mertial becomes indirect[1,2]. A variation of the x concentration is demonstrated here with Silvaco's **DevEdit** device structure editor. Laser simulation of the device is performed with **Laser** in conjunction with **Blaze**, Silvaco's 2-D device simulator for III-V, II-VI materials.

Figure 1 illustrates the heterostructure stripe laser that the program is to create. The active layer and photon generating region is GaAs. Above and below this region is a cladding layer comprised of $Al_xGa_{1-x}As$, which features a greater bandgap than GaAs. The resulting discontinuity in the conduction and valence band edges at the junction of the active layers leads to confinement of the carrier. The refractive index of the GaAs region is greater than the $Al_xGa_{1-x}As$ region, resulting in an optical confinement in the active layer that also acts as a slab waveguide. A good quality heterojunction depends on spacing the crystal lattice of the cladding layer so that it matches the active layer as closely as possible. This is easily obtained in the AlGaAs/GaAs structure.
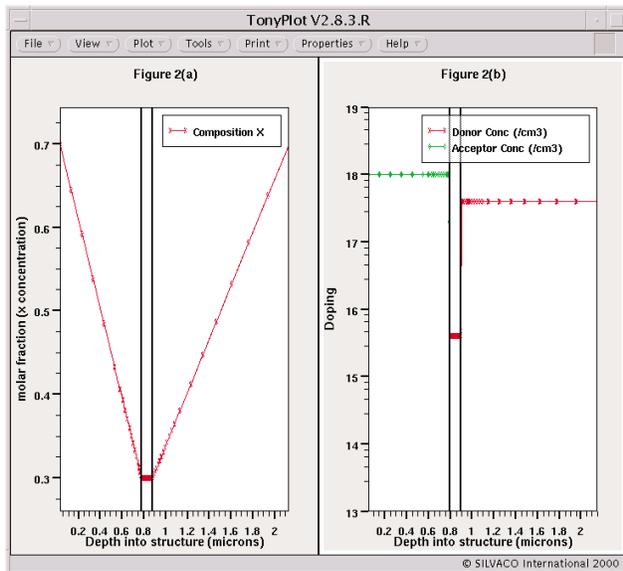

Figure 2. A 1D cutline through the stripe laser shows the x-composition fraction varying with depth (y) and the donor and acceptor concentration.
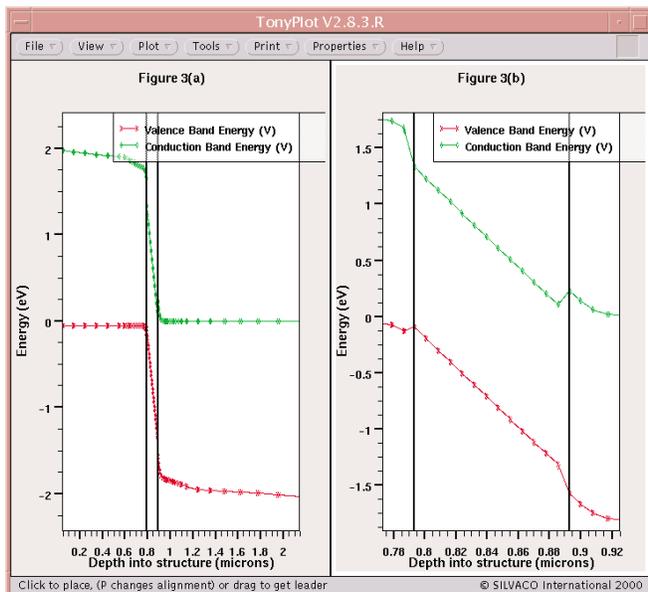
Figure 3. At zero bias on the strip laser a 1D cutline can plot the conduction and valence bands; (a) shows the full depth and (b) is zoomed in to the GaAs layer,

There are several options that reduce the electrical current required for the lasing operation. One option makes use of a stripe contact that effectively limits the lateral extent of the current injection, and yields a smaller lasing region of the active material. The injection current flows through a narrow stripe contact so that even a moderate injection current yields a high current density within the active layer. Since gain is achieved only in the high current density regions, such an arrangement is termed gain guiding. In the figure, the stripe width of the laser is 3 microns, the cavity length is 100 microns, while the x concentration of the $Al_xGa_{1-x}As$ is graded from 0.7 at the outer edge of the layer to 0.3 at the GaAs junction

Creating the Structure with *DevEdit*

The initial structure is created with Silvaco *ATLAS* and includes the mesh, doping concentrations and electrical contact. The structure contains no x concentration at this point. The initial structure is saved for later import into *DevEdit*, where the various x concentrations are then added. The structure is defined by means of a doping profile written separately the user. It's important to clearly define x concentrations prior to adding them to the initial structure. Our example profile, illustrated below, is saved as example_profile.dat.

0	0.7
0.75	0.3
0.85	0.3
2.1	0.7

The left column indicates the boundary at which the doping level, listed in the right column, originates. The next doping value is found upon reaching the next boundary (in this example at 0.75 microns). The differing values between the two points require a linear interpolation that results in a linear doping profile. It is possible to define the entire x concentration for the structure this way. The x concentrations are then added into the structure only after these doping profiles are written.

The following are important steps for this process:

1. Use *ATLAS* to create an initial structure without x concentration.

2. Write a doping profile to use in *DevEdit*. Save this as a separate data file.

3. Load the initial *ATLAS* -designed structure into *DevEdit*.

4. Use *DevEdit* to click on impurities, and then on doping profile.

5. Load the doping profile (the data file written during stage 2)

6. Click on add impurities.

7. Choose start x=-2, start y=0, end x=11, end y=0. On a Y roll off choice, choose the user profile that was created in step 2.

8. Save the structure with a valid name.

The values chosen for the x fields in Stage 7 are the beginning and the end value of the x dimension. The value for the beginning and end of the y field matches the start value of the y dimension.
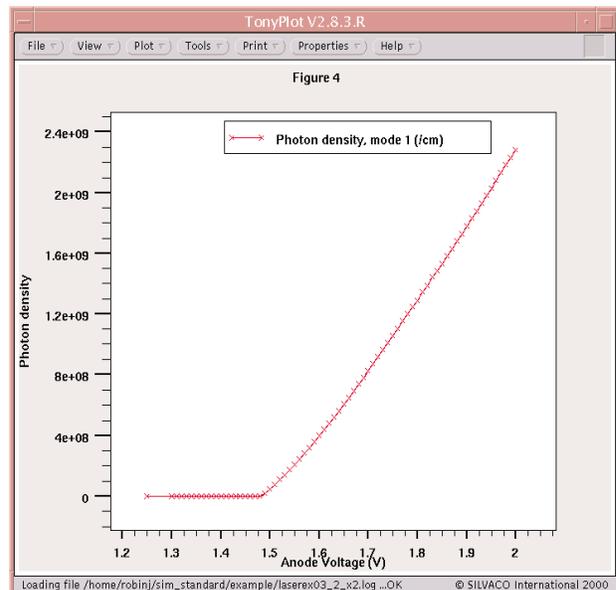

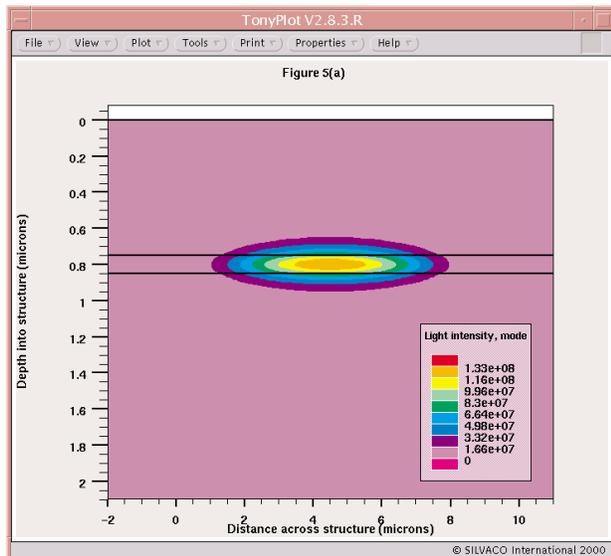Figure 4. Simulated photon density versus anode voltage for the stripe laser.

Figure 5a. Simulated light intensity of the fundamental mode of the stripe laser.
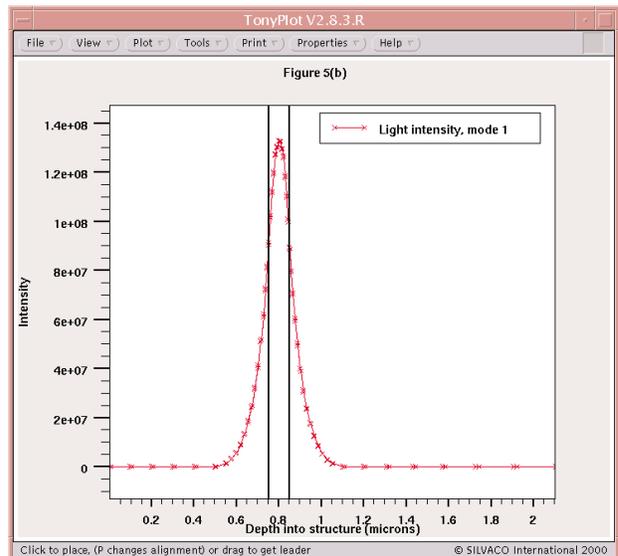

Figure 5b. A 1D cutline through the center of the light intensiy at x-5μm.

Figure 2(a) illustrates a structure that is divided with a one dimensional cut line that directly follows the doping profile and exposes the x concentration. Figure 2(b) presents additional information, such as doping concentration, acceptors and donors, within the structure.

Initial Simulation

The complete structure is obtained from *DevEdit* and is then imported into *ATLAS* for simulation. An important parameter in a heterostructure device is the bandgap alignment. The bandgap difference is distributed between the conduction and valance bands with great

Figure 6. Simulated laser gain versus the anode voltage showing "leveling" of the gain that indicates successful lasing.

impact to the charge transport. To align the bandgaps, use the MATERIAL statement's ALIGN parameter. This specifies the fraction of bandgap difference that appears as conduction band discontinuity. *Blaze* creates the desired conduction band and offsets it by modifying the electron affinity of the material specified in the ALIGN parameter.
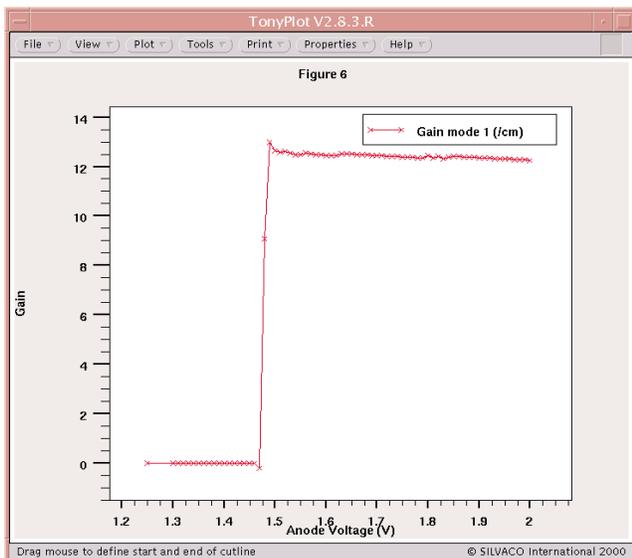
The example assumes a value of ALIGN=0.6 that results in the assignment of 60% of the bandgap to the conduction band offset. To save simulation time when modeling the Fabry-Perot laser, gradually increase the device bias until the laser threshold voltage is nearly reached before executing the laser simulation. Only the electrical properties are modeled. Figure 3 shows the zero bias (thermal equilibrium) conduction and valence bands for (a) the entire structure and (b) magnified view of the alignment region. Once the zero bias condition is solved, forward bias is put across the structure in order to turn on characterization.

LASER Simulation

Laser is a module within the *ATLAS* device simulator that performs coupled electrical and optical simulation of semiconductor lasers. *Laser* works in conjunction with *Blaze* in order to solve the two dimensional Helmholtz equation that calculates the transverse optical field profile. It also calculates of the carrier recombination rate due to light emission, optical gain, and laser output power. The modal gain spectra for several longitudinal cavity modes is also readily available.

To initiate a laser simulation, specify an independent rectangular mesh for the Helmholtz solution that covers the entire active region. The rectangular grid is extend to include an area slightly larger than the active region in order to contain any light that might escape. Turn-on characteristics (Figure 4) indicate that forward bias voltage output increases dramatically for charges that approximate or exceed 1.4V.

Figure 5(a) is a side view of the laser structure's light emission. Figure 5(b) is a transverse mode profile obtained from Figure 5(a) by placing a 1 dimensional cut line across the active region. Good optical confinement is evident in Figure 5(b). Figure 6 displays a 'gain=loss' lasing condition success indicated by the levelling off of local optical gain. *Laser* features two gain calculation models. One model takes frequency dependence into account and is ideal for spectral analysis[3]. Figure 7 is a longitudinal lasing spectrum for a bias of 1.79V. One dominant mode corresponds to the GaAs bandgap energy.
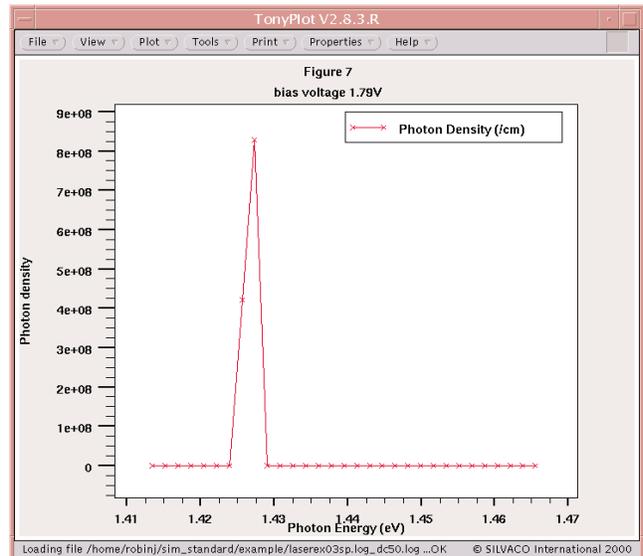

Figure 7. Simulated photon density versus photon energy for a multiple longitudinal mode simulation.

Conclusion

This article focuses on a detailed description of a relatively simple semiconductor laser structure created with Silvaco *DevEdit*. In addition, the structure's lasing characteristics were simulated. Results indicated that very good transverse optical confinement was achieved for this structure.

References

[1] 'Laser Diode modulation and Noise', K. Petermann, Kluwer Academic publishing, 1988

[2] 'Composition dependence of the AlxGa1-xAs direct and indirect energy gaps', H. C. Casey and M. B. Panish, J. Appl. Phys., Vol. 40, pp. 4910-4912, 1969.

[3] *ATLAS User's Manual* and references therein.