Advanced design and simulation of semiconductor laser diodes

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Semiconductor laser diodes and telecommunication networks

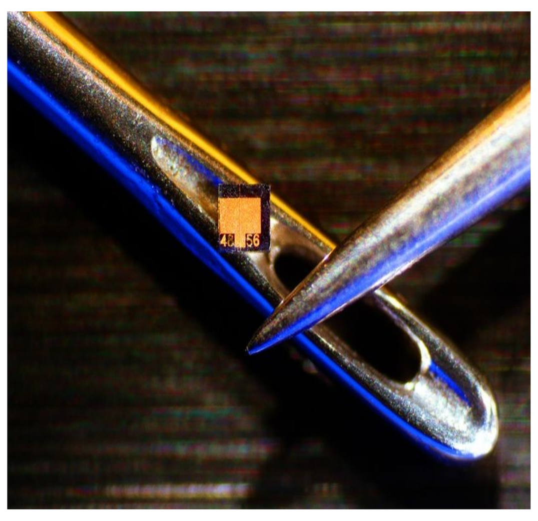


Figure 1. An example of a laser diode designed for use in severe environmental conditions such as on Mars

Image courtesy of NASA

- Laser diodes are the essential light source used in fiber optic networks which run throughout our cites and span the world forming the back-bone of our telecom network.
- Almost all information in our modern society is sent over high bandwidth fiber optic cables. These cables run throughout the world carrying information right up to the end of your street where they usually stop.
- At this point, the information is transferred to slow old 1970s copper phone cables for the remainder of its journey to your house thereby producing an information bottleneck between the end user and the network.
- Ultra high bandwidth internet and ultra high definition TV are not a reality because the cost of the laser diodes and associated active cooling elements are prohibitively high.
- This research aims to lower the cost of laser diodes to a level at which every home can afford a fiber modem – thus making cheep access to digital information a reality for all in our society.

Figure 2. A fiber optic bundle. Image used under the GNU document license from wikipedia.

Thermal performance of passively cooled 1.3µm InGaAsN/GaAs quantum well lasers

- Our research focuses on the new InGaAsN/GaAs material system.
  - The higher conduction band offset of the material system gives better device performance over wider range of temperatures 25-110^{o}C compared to the current InP devices, $T_{max} \approx$ 70^{o}C.
  - The improved performance eliminates the need for active cooling thus substantially reducing unit cost.
  - The devices grown by our project partners within the EU project FAST-ACCESS (IST-004772) have been shown capable of:
    - Direct modulation of up to 2.5Gb/s at a heat sink temperature of 110^{o}C (Figure 3)
    - Estimated quantum well temperature of in excess of 200^{0}C
    - Small variation in slope efficiency as a function of temperature.
  - The GaAs substrates used to grow dilute nitride lasers are considerably cheaper than the InP substrates used for current devices.

- **The primary challenge for these devices is to demonstrate improved reliability – reliability can be improved by decreasing operating temperature.**

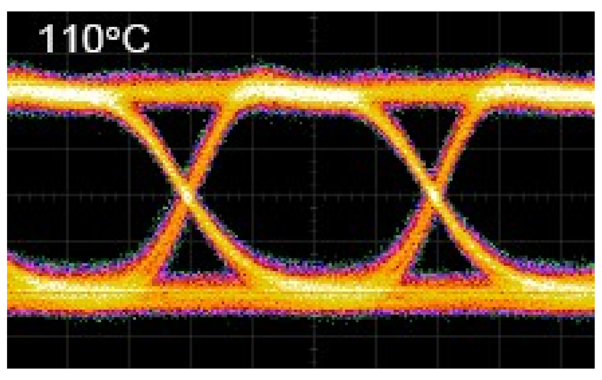
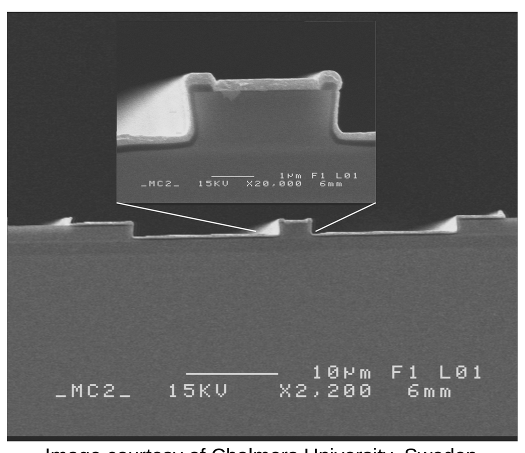


Figure 3. A measured eye diagram obtained at 2.5Gb/s at 110^{o}C for an InGaAsN/GaAs structure. Image courtesy of Chalmers University, Sweden

Simulation

- At Nottingham we run an advanced electro-opto-thermal device simulator on one of the UKs fastest supercomputers to optimize laser diode device designs.
- The simulation tool was designed and written at Nottingham
- Our optimized device designs are fed back to our European partners who grow the devices.
- The devices are characterized to provide performance data which is then fed back in to the models.
- Our most recent study produced much cooler device designs which are expected to increase reliability by a factor of two.



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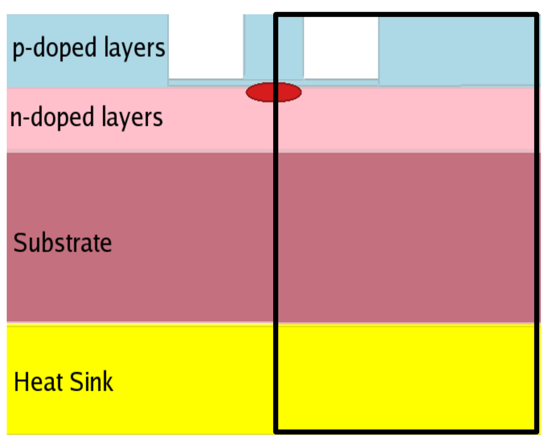
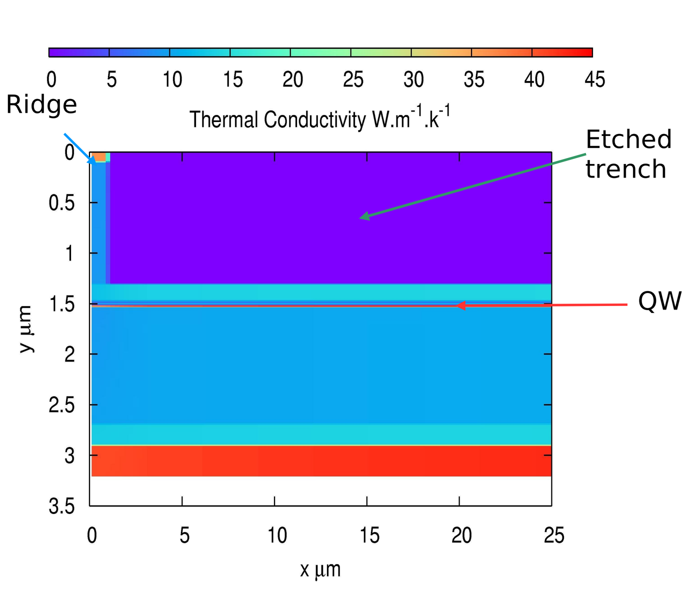
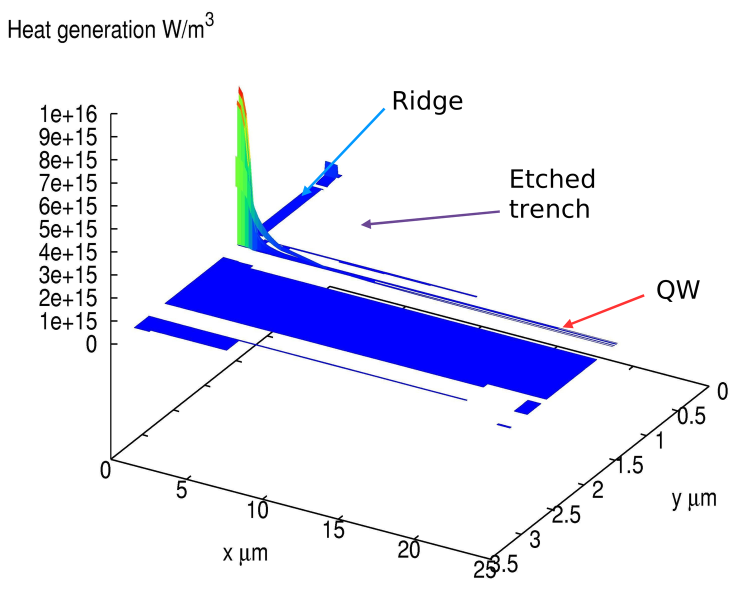
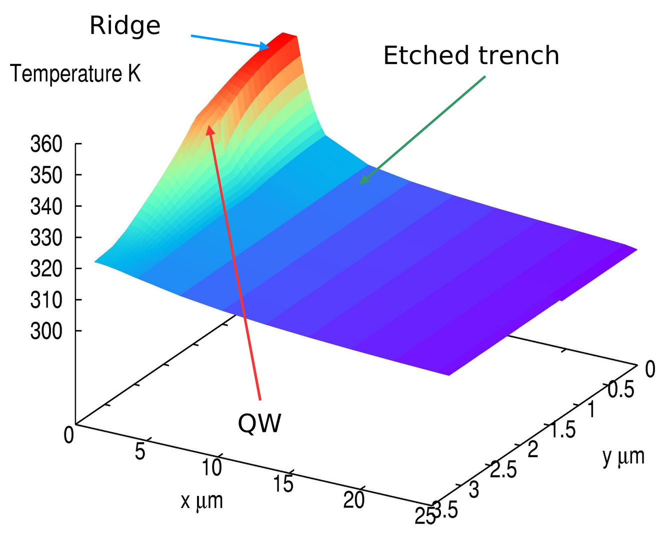


Black box indicates electrical half space simulation window







SEM image of a real 1.3µm laser → Structure of laser → Thermal conductivity → Heat sources → Device temperature profile

Optimize device parameters and re-simulate / re-grow device

The numerical model

The Electrical Model

- Bipolar 1D - 2D Drift Diffusion (DD) model (0th and 1st moments of the Boltzmann Transport Equation (BTE))
  - Includes thermal driving terms in current equation
- Poisson's equation
- QW capture/escape equations for each QW
- 2D lattice heat equation solved in external solver

The Optical Model

- Photon rate equation interacting with all QWs
- Gain and spontaneous emission calculated using 4x4 band ***k.p*** solver

Thermally dependent parameters

- Electron and hole mobilities
- Band gap
- Electron affinity
- Gain (through look up table)
  - Fermi-Dirac statistics
- Spontaneous emission
- SRH recombination
- Auger recombination
- Effective densities of states
- Thermal lattice conductivity
- Maxwell-Boltzmann statistics
- Heat capacity

Heat sources

- Shockley-Read-Hall
- Auger recombination
- Free carrier absorption
- Spontaneous emission
- Joule heating
- Peltier cooling/heating

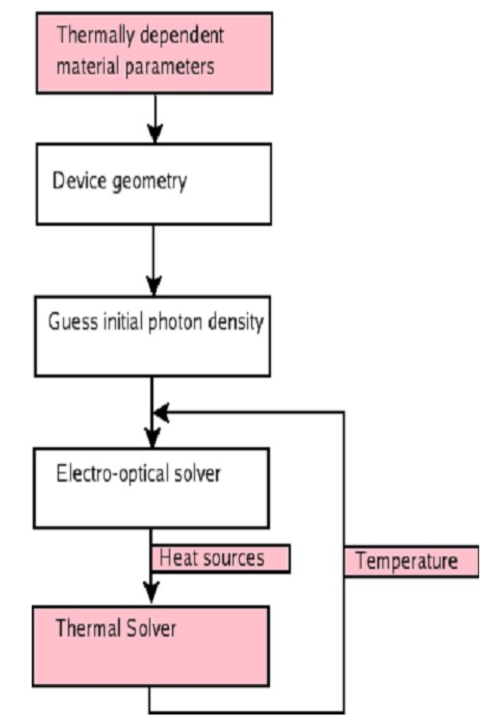
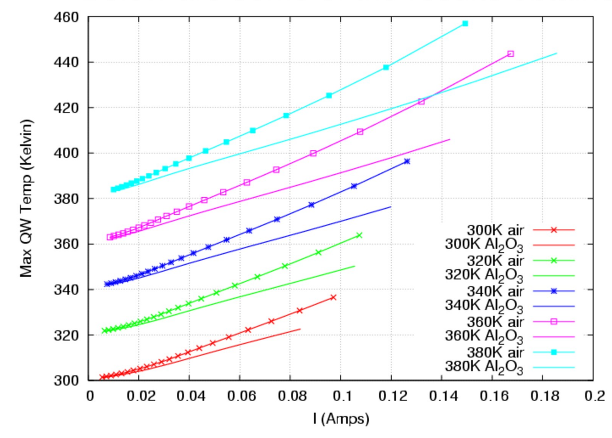


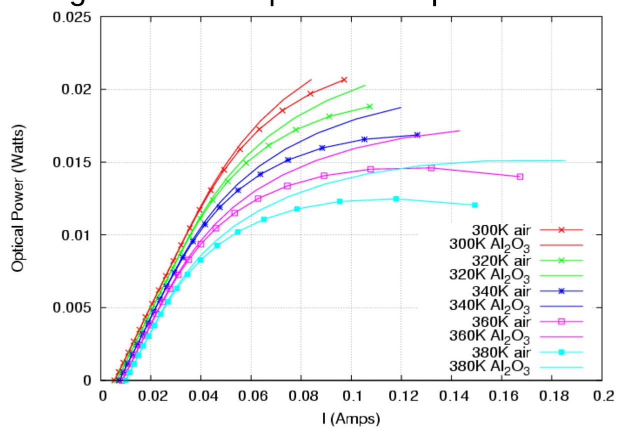
Figure 4. A flow diagram of the simulator used optimize the device

Results

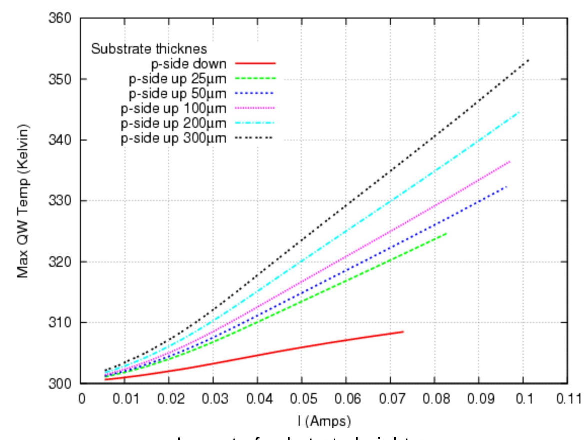
- Our in house CAD tools have been used to adjust device parameters to investigate and understand device performance.
  - A detailed understanding of device performance enables us to optimize device designs numerically
  - Below are some of the results obtained during the device optimization process.



Average QW temperature at different ambient temperatures for filled and unfilled trenches



LI curves for filled and unfilled etched trenches at variable temperatures



Impact of substrate height on average QW temperature

Conclusion

- Primary heat sources and main heat dissipation routes have been identified.
- The impact of the geometry of ridge waveguide has been investigated.
  - Waveguide width
  - Etch trench width
  - Etch trench filling
  - Substrate thinning
- A thermal evaluation of p-side up -vs- p-side down mounting has been carried out.
- The ridge has been found to be a major source of heat.
  - Optimized doping profiles, geometry changes and etch trench fillings have been recommended to our partners to elevate the thermal problem.

Our improved device designs will lower quantum well temperature by up to ten degrees and double the expected device lifetime.

EPSRC Engineering and Physical Sciences Research Council

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