Superluminescence diodes at 2.4 microns from GaInAsSb/AlGaAsSb quantum well heterostructures for optical glucose sensing

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SUPERLUMINESCENT DIODES AT 2.4 MICRONS FROM
GAINASSB/ALGAASSB QUANTUM WELL HETEROSTRUCTURES FOR
OPTICAL GLUCOSE SENSING

by

Michael Wootten

A thesis submitted in partial fulfillment
of the requirements for the Master of
Science degree in Physics
in the Graduate College of
the University of Iowa

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This is to certify that the Master's Thesis of

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for the thesis requirement for the Master of
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CHAPTER I
INTRODUCTION

The 2-2.5 micron range, the “combination region” of the electromagnetic spectrum, is the range where many biomolecules have characteristic absorption resonances due to the combination of vibrational stretching and bending modes associated with C-H, O-H and N-H bonds. As the absorption resonance of water is minimized in the combination region it is the ideal range for chemical sensing of these biomolecules in water based solutions.\textsuperscript{1,2} Absorption resonances span a broad range of wavelengths, requiring a broadband light source for detection coverage of the spectrum such as a room temperature diode.

High power, tunable GaInAsSb/AlGaAsSb quantum well lasers have been demonstrated as broadband sources in the combination region, however they are complex and potentially bulky as they require moving parts and external cavities.\textsuperscript{3} Another approach is the cascaded, room-temperature, mesa surface light-emitting diode from GaInAsSb/GaSb, which have tunable diode voltage and current characteristics to match batteries or control electronics, and provide broadband emission; but these have relatively low output powers (300 $\mu$W upper hemisphere at room temperature over a 1 mm diameter mesa).\textsuperscript{4} which results in a low signal-to-noise of the measurement. In this paper we have investigated superluminescent, edge-emitting diodes from GaInAsSb/AlGaAsSb quantum well heterostructures, which use amplified spontaneous emission to gain high output power, unlike surface emitters, while still emitting a broadband light source without the need for an external cavity, like tunable lasers.

Superluminescent diode heterostructures are basically identical to laser diodes in
layer design, and are fabricated as ridge waveguides for edge emission like laser diodes. However, SLDs operate below threshold to maintain a broad emission spectrum, unlike laser diodes. High output power is achieved without lasing by reducing feedback into the cavity, raising the threshold for lasing. This is done by using an absorbing facet,\(^5\) angling the facets,\(^6\) anti-reflection coating the facets, bending the waveguide,\(^7\) tapering the waveguide,\(^8\) or a combination of these approaches.\(^9,10\) Previous work on superluminescent diodes have focused on materials for communication wavelengths in the 800-900 nm, and 1.3 to 1.5 \(\mu m\) range using GaAs/AlGaAs,\(^5,6\) GaInAsP/InP quantum wells\(^10,11\) and InAs/GaAs quantum dots,\(^12,13\) as well as a report on a quantum cascade SLD in the 6-8 \(\mu m\) range.\(^14\) In this paper we report on the performance of GaInAsSb/AlGaAsSb quantum well heterostucture SLDs operating in the 2-2.5\(\mu m\) wavelength range at room temperature using simple straight ridge waveguides with angled facets. We also theoretically model the characteristics to analyze the device limitations and to inform future improvements.
CHAPTER II
EXPERIMENTAL AND THEORETICAL METHODS

Growth

A schematic of the heterostructure used in this study is shown in Fig. 1. The design was based on a report of high power, 2-2.5 μm GaInAsSb/AlGaAsSb quantum well, separate confinement heterostructure diode lasers using a novel waveguide design to reduce beam divergence. Our quantum wells consisted of a quaternary alloy estimated to be Ga$_{0.58}$In$_{0.42}$As$_{0.14}$Sb$_{0.86}$ based on calibrated growth rates of the group-III-limited growth, and fits to high-resolution x-ray diffraction (HRXRD) scans. Barriers consisted of the alloy Al$_{0.25}$Ga$_{0.75}$As$_{0.02}$Sb$_{0.98}$, which is lattice-matched to the GaSb substrate. For quantum wells of this composition, the 1.7% strain in the quantum wells has been determined to adequately confine holes.

Samples were grown in an Applied Epi EPI930 molecular beam epitaxy (MBE) chamber employing (Mark IV) valved crackers for the group V sources, and dual filament SUMO cells for group III sources. The quaternary Ga$_{0.58}$In$_{0.42}$As$_{0.14}$Sb$_{0.86}$ is not trivial to grow, because the alloy is thermodynamically unstable at the temperatures it was grown and the high compressive strain of 1.7% results in a layer critical thickness of only 6 nm, whereas quantum wells are 10 nm thick. However, it has been shown that metastable and unstable GaInAsSb quaternary alloys can be grown under nonequilibrium conditions of MBE by employing low growth temperatures to limit adatom diffusion length as well as strain to suppress phase separation.$^{15,16}$ Further it has been observed for GaInAsSb that single layers can be grown up to twelve times thicker than Matthew-Blakeslee critical thickness for an isotropic single layer without any observable
Figure 1. Stack diagram of the heterostructure grown for the superluminescent diode in this study. The structure is based on one used for a laser diode in another study.

relaxation, and that increasing strain improves material quality.\textsuperscript{16} Also, growing thick, lattice matched cap layers can increase the critical thickness by a factor of two.\textsuperscript{17} Figure 2 shows optical interferometric images (Wyko NT1100 optical profiling system, 2 nm vertical resolution) of the surface of two quantum well samples consisting of one 14 nm/20 nm Ga\textsubscript{0.58}In\textsubscript{0.42}As\textsubscript{0.14}Sb\textsubscript{0.86}/Al\textsubscript{0.25}Ga\textsubscript{0.75}As\textsubscript{0.02}Sb\textsubscript{0.98} quantum well with 100 nm Al\textsubscript{0.50}Ga\textsubscript{0.50}As\textsubscript{0.04}Sb\textsubscript{0.96} clads plus a 5 nm GaSb cap. One sample was grown at 475° C, and exhibited a low density of small defects, Fig. 2(a), perhaps due to phase separation, relaxation, or some combination. By reducing the growth temperature to 450° C, the defects were mostly eliminated, as shown in Fig. 2(b). Note growth temperatures were determined with an optical pyrometer calibrated to a GaSb RHEED surface reconstruction transition at 410° C.\textsuperscript{18}
A quantum well sample consisting of one 14 nm/20 nm Ga$_{0.58}$In$_{0.42}$As$_{0.14}$Sb$_{0.86}$/Al$_{0.25}$Ga$_{0.75}$As$_{0.02}$Sb$_{0.98}$ quantum well with 100 nm Al$_{0.50}$Ga$_{0.50}$As$_{0.04}$Sb$_{0.96}$ clads plus a 5 nm GaSb cap grown at temperatures (a) 475°C and (b) 450°C.

Parameters for lattice matching Al$_{0.50}$Ga$_{0.50}$As$_{0.04}$Sb$_{0.96}$ and Al$_{0.25}$Ga$_{0.75}$As$_{0.02}$Sb$_{0.98}$ were determined in separate growths. The bottom Al containing quaternary layers were grown at 520°C; after the sample was cooled to 450°C for the quantum well growth, it was not reheated for the top Al containing quaternary cladding layers to avoid degrading the quantum well. Because only a single Al and Ga cell was used, graded regions between the 25% buffer and 50% Al quaternary layers was achieved by stepping the alloys linearly in 10 nm, 5% Al steps, and with 60 second pause between steps to ramp cell temperatures. All layers in the structure were grown with true group V/III ratios.
between 1 and 2, where true V/III ratio is calculated by normalizing BEP V/III ratios by the minimum BEP V/III ratio needed to achieve group III limited growth rates.

**Fabrication**

Samples were wet etched in two runs using citric acid. The cathode etch was deep to the n-GaSb buffer layer. The waveguide was defined with a shallow channel etch, about 1 μm deep and not through the active region. Waveguides were then blanketed with polymide to passivate the sidewalls, and a window was opened along the ridge for the anode contact. Both contacts were established in a single run through e-beam evaporation of Ti/Pt/Au. The n-contact was enlarged to reduce contact resistance. Waveguides were 40 μm wide, and were cleaved to different lengths between 0.8-2.7 mm. Samples were flip chipped and pressure bonded to indium contacts on Si/SiO$_2$ headers.

Waveguides were either oriented parallel to the <010> crystal axes to give facets normal to the waveguide and 0.33 reflection for laser diode devices or they were oriented at a 12° angle to <010> to give angled facets with ideal effective reflection\textsuperscript{19} of about $3 \times 10^{-5}$ for suppressing lasing in superluminescent diodes.

**Measurements**

Power versus current and voltage measurements (LIV) were taken by integrating device output under quasi-CW conditions over a 0.64 str solid angle collected by $f/1$ parabolic mirrors. Samples were heatsinked to a copper block using indium foil in between the header and the copper. Current was injected by a 200 μs square pulse of varying currents at low duty cycles (1%-5%). Power was measured using a calibrated room temperature extended wave InGaAs detector. Data were taken at room temperature (295K) with no active temperature stabilization or cooling, and with no degradation noted
between 1% and 5% duty cycles.

Spectra was measured using a Nicolet 560 FTIR spectrometer using a double signal modulation approach.\textsuperscript{5}

**Modeling**

Modeling of LI data was done by numerically solving the rate equations (Eqs. 1-5)\textsuperscript{6} at equilibrium for the carrier density, \( n \), and the cavity photon density, \( S \), as numerical functions of the input current density, \( J \).

\[
\frac{dn}{dt} = \frac{J}{ed} - G(n) S \frac{n}{\tau_n} \tag{1}
\]

\[
\frac{dS}{dt} = G(n) S \frac{S}{\tau_{ph}} + \beta_{sp} \frac{n}{\tau_r} \tag{2}
\]

\[
G(n) = \Gamma g_0 (n - n_0) \tag{3}
\]

\[
\frac{1}{\tau_n} = A + Bn + Cn^2 \tag{4}
\]

\[
\frac{1}{\tau_{ph}} = \frac{c}{n_r} \left( \alpha_i + \frac{1}{2L} \ln R^2 \right) \tag{5}
\]

Here \( G(n) \) is the amplification rate of the SLD, \( \Gamma \) is the optical confinement factor, and \( g_0 \) is the differential gain coefficient; \( n_0 \) is the threshold carrier density and \( n_0 \) is the carrier density at transparency; \( \tau_n \) is the total carrier lifetime, \( \tau_{ph} \) is the lifetime of photons in the optical cavity and \( \tau_r \) is the radiative lifetime (\( B = n/\tau_r \)); \( A, B, \) and \( C \) are the Shockley-Read-Hall, radiative and Auger coefficients, respectively; \( n_i \) is the effective index of refraction of the waveguide stack, \( \alpha_i \) is the waveguide loss coefficient, and \( L \) is the length of the gain region (i.e. the length of the waveguide); and \( \beta_{sp} \) is the fraction of spontaneously emitted light into the waveguide modes.

Our model was created by solving for \( n(J) \) and \( S(J) \) and output power, \( P(J) \), as
follows. Equations (1) and (2) were set to zero for the steady state, then (2) was solved for S and substituted into (1) to achieve the following:

\[ 0 = \frac{J}{ed} - G(n) \frac{\beta_{sp} n}{\tau_r} \left( \frac{1}{\tau_{ph-sld} - G(n)} \right) \frac{n}{\tau_n} \]  

\[ S(n) = \frac{\beta_{sp} n}{\tau_r} \left( \frac{1}{\tau_{ph-sld} - G(n)} \right) \]  

Here \( \tau_{ph-sld} \) is the SLD cavity photon lifetime, which is distinct from the laser cavity photon lifetime, \( \tau_{ph} \), due to differences in reflectivity of the optical facets. We then numerically solved Eq. (6) for \( n(J) \) and used our answers there to solve for \( S(J) \) in Eq. (7). Once we have solved for \( S(J) \) we can easily solve for \( P(J) \) using Eq. (8) below.

\[ P = \frac{S_d h v}{\tau_p} \]  

However, prior to solving Eqs. (6) and (7) for \( n(J) \) and \( S(J) \), respectively, we need the amplification factor, \( G(n) \). We assume that \( G(n) \) is going to be the same for laser diodes and SLDs, and so we used the following relationship for laser diodes:

\[ G(n)_{laser} = \frac{n - n_0}{\tau_{ph}(n_{th} - n_0)} \]  

Above threshold this means that \( G(n) = 1/\tau_{ph} \). By comparing Eqs. (3) and (9) we see that

\[ \Gamma g_0 = \frac{1}{\tau_{ph-laser} (n_{th} - n)} \]  

We can calculate \( \tau_{ph-laser} \) from Eq. (5) by calculating the waveguide loss, which we will discuss below, and the laser diode facet reflection, which is easily calculated from the effective index and the Fresnel equations. \( \tau_{ph-sld} \) can similarly be calculated using the same waveguide loss and assuming ideal effective reflection\(^\text{19}\) of around \( 3 \times 10^{-5} \). \( n_{th} \) is
straightforward to calculate:

\[
\eta_{th} = \frac{\tau_n J_{th}}{eL}
\]

(11)

Here \(e\) is the electron charge, and \(J_{th}\) is the threshold current density. We used \(J_{th} = 300\ \text{A/cm}^2\), a representative low current threshold from laser devices measured which corresponds to \(n_0=1.21\times10^{-19}\ \text{cm}^{-3}\). \(\tau_n\) is calculated from Eq. (4). For the A, B and C coefficients we used values from the literature: \(A=(1.3\times10^{-6}\ \text{s})^{-1}\), \(B=5\times10^{11}\ \text{cm}^3/\text{s}\) and \(C=2\times10^{28}\ \text{cm}^6/\text{s}\).\textsuperscript{20,21} We were unable to estimate \(n_0\), the transparency density, and so we treated it as a fit parameter. For the simulations presented here we used \(n_0=0.88n_{th}\).

In order to calculate the waveguide loss straight laser diode waveguides were fabricated from the epitaxial heterostructure of varying lengths. For each laser diode the differential quantum efficiency above \(J_{th}\) was found from the slope of power vs. current:

\[
\eta_d = \frac{e}{h\nu} \frac{dP}{dl}
\]

(12)

Here \(h\) is Planck's constant and \(I\) is the current. We are able to write:

\[
\frac{1}{\eta_d} = \frac{\alpha_i L}{\eta_i \ln \left( \frac{1}{R} \right)} + \frac{1}{\eta_i}
\]

(13)

Here \(\eta_i\) is the fraction of current reaching the active region. A plot of \(1/\eta_d\) vs. diode length, \(L\), gives us \(\eta_i\) from the intercept and \(\alpha_i\) from the slope. Such a plot is shown in Fig. 3, and due to the scatter in the graph give us a range of values for \(\alpha_i\), with our best estimate being \(5\text{cm}^{-1}\).

The final value needed to calculate \(n(J)\) and \(S(J)\) from Eqs. (6) and (7) is \(\beta_{sp}\) which we estimated to be on the order of \(10^{-4}\) from geometrical considerations.
Figure 3. Inverse (external) differential quantum efficiency versus waveguide length (triangular points) for straight waveguide laser diodes with structure as shown in Fig. 1. The solid lines are calculated using Eq. 13 for two different values of waveguide loss $\alpha_i$. 
CHAPTER III
RESULTS AND DISCUSSION

The angled waveguide devices fabricated in this study clearly exhibit superluminescence. In laser diodes the gain clamps after the device begins to lase, whereas in a superluminescent diode it continues to grow; this means that the exponential amplification of spontaneous emission has the potential to grow superlinearly if the gain grows fast enough. This is illustrated later in our theoretical simulations. Figure 4 is a plot of output power versus current density (L-J curve) showing the range of behaviors observed by the edge emitting, angled waveguide devices we studied. Chip 1 shows the expected superlinear growth in output power with increasing current, which is clear evidence of superluminescent output. Where laser diodes have a narrow spectral emission, superluminescent diodes have a broadband emission spectrum because they rely on amplified spontaneous emission rather than stimulated emission with a feedback characteristic of a laser. Figure 5 shows that the spectra output of Chip 1 is broad, with a 1/e full width of 230 nm (83 meV) at low current densities, which is consistent with the typical width of several $k_B T_{\text{room}}$ ($\approx 25$ meV) of a thermalized population of carriers recombining through spontaneous emission. With increasing gain the superluminescent output is expected to become spectrally narrower due to the wavelength dependence of the gain coefficient, leading wavelengths near the center of the emission spectrum to experience greater gain than emission in the wings. Figure 5 shows clear spectral narrowing of the output with increasing current.
Figure 4. Range of behaviors for light out versus current density for angled waveguide structures. Chip 1 shows superlinear growth characteristic of superluminescence. Chips 2 and 3 show lasing and low output superluminescence, respectively, likely due to facet imperfections and damage.

Figure 5. Spectrally resolved output for chip 1. Spectral narrowing is shown with increasing injection current, which is characteristic of amplified spontaneous emission due to a nonuniform gain spectrum.
Finally, superluminescence might be expected to lead to a narrowing in the angular output of the edge emission. Figure 6 shows that the angular distribution of Chip 1's emission from the end of the waveguide along its slow axis becomes narrower towards the forward direction; with the angular full width at half maximum decreasing from 32.5° to 17.5°. This behavior is expected as amplified spontaneous emission along the waveguide modes grows and dominates spontaneous emission in all directions, and is further evidence of superluminescence in this diode.

**Figure 6.** Full width at half maximum of the waveguide output along the slow axis as a function of current density for chip 1 (points). The decreasing angular width with increased current is an indication of increased amplified spontaneous emission.
Chip 2 also shows evidence of superluminescence. However, its superlinear growth in Fig. 4 was weak. It shows slight spectral narrowing in Fig. 7 while also showing a blue shift of its emission, which is indicative of band filling. The low output is most likely due to the device having increased waveguide loss, which was not uncommon as shown in Fig. 4, higher contact resistance or increased nonradiative recombination from damaged facets or sidewalls.

Figure 7. Spectrally resolved output of Chip 2. Spectral narrowing is evident with increasing current density, indicative of amplification of spontaneous emission, but is accompanied by a blue shift, indicative of band filling.

Chip 3 exhibited lasing rather than superluminescence. In Fig. 4 it shows threshold-like behavior, while in Fig. 8 it shows a narrow emission spectrum (1meV for all modes with less than 0.1 meV for the individual modes) which is characteristic of a laser. Examination of Chip 3’s facets shows significant damage at one facet which could have led to increased feedback into the waveguide, lowering the threshold. Chips 2 and 3
highlight the challenge that we experienced in obtaining reliably smooth optical facets from the softer antimonide materials when compared to wider gap superconductors.

Figure 8. Spectrally resolved output of chip 3. Each narrow peak is less than 0.1 meV is evidence of lasing on different cavity modes.

Figure 9 characterizes the efficiency of Chip 1, the device that exhibited the strongest superluminescence. Plotted are the wallplug efficiency,

$$\frac{P_{\text{out}} - I \cdot V}{I \cdot V}$$

quantum efficiency,

$$\frac{P_{\text{out}} - I \cdot V}{E_{\text{photon}}}$$

and differential quantum efficiency, $\eta_d$ defined above. It is important to note that $P_{\text{out}}$ only counts the photons emitted from one facet of the device, not emitted in all directions. The wallplug efficiency begins at 10%, drops sharply at first, and then levels off while the quantum efficiency and the differential quantum efficiency increase sharply with increasing current as the superluminescent output grows superlinearly. At high current densities all three efficiencies approach a few tenths of a percent. The differential quantum efficiency approaches a half a percent at its peak, which is a factor of 10 to 50 times lower than that of the straight waveguide lasers measured. The lower efficiency results from greater
cavity losses due to reduced facet reflection as well as greater nonradiative (Auger) scattering at the higher carrier densities the angled waveguide devices operate at. As Chip

![Figure 9](image_url)

**Figure 9.** Plot of wallplug, quantum and differential quantum efficiencies as functions of current density for chip 1. All efficiencies were calculated using “useful” external emission, emission out of one facet. Emission out of the opposite facet as well as spontaneous emission out of the waveguide were not included.

I's output showed a weak dependence on duty cycle as we increased it from 1 to 5 percent the rollover in differential and quantum efficiencies at high current densities might be explained by heating. The rollover could also be explained due to reduced carrier confinement, particularly of holes.²²
Our theoretical simulation of superluminescence is able to qualitatively reproduce the observed features of superluminescence for the L-J curve of Chip 1. Figure 10 shows a comparison of our simulated output using the theory discussed above with the L-J curve for Chip 1 at a 1% duty cycle. Our simulation shows that superlinear growth in output is expected to occur as the active region transparency is crossed (at about 220 A/cm$^2$ in this case) and then bend upward as the gain grows and the current density approaches the lasing threshold, which occurs in angled waveguide devices when the amplification rate $G(n)$ equals the cavity lifetime of a photon in the angled waveguide ($\tau_{ph-sld}$). If the current density becomes too close to the threshold the output will become unstable and collapse to lasing, as in Chip 3’s output.

**Fig. 10.** Comparison between the measured superluminescent output for chip 1 and the simulated output according to the theory above, showing good qualitative agreement. The simulation shows superlinear growth in output occurs after the active region becomes transparent (at 220 A/cm$^2$), then bends upwards as the gain increases and the lasing threshold is approached.

Figure 11 shows the corresponding simulated carrier density to the simulated
output in Fig. 10 compared with the threshold carrier density for a straight waveguide diode with an identical heterostructure. Figure 11 shows that the carrier density for a superluminescent diode doesn't clamp like a laser diode, but instead keeps increasing with current density. Losses due to nonradiative (Auger) recombination will become problematic as the superluminescent output and carrier density become very high.

![Graph showing carrier density vs current density](image)

**Figure 11.** Simulated carrier density in the superluminescent device corresponding to the simulated output from Fig. 10. The red line shows the threshold carrier density for an equivalent straight waveguide laser diode. The comparison emphasizes that carrier concentration does not clamp in a superluminescent diode, but instead continues to increase with current density.

To point the way to future improvements in superluminescent devices we theoretically examined the sensitivity of the simulated output to three engineerable parameters: facet reflection $R$, fraction of spontaneous emission into the waveguide mode $\beta_{sp}$, and the Auger nonradiative scattering coefficient $C$. The results of this are shown in
Fig. 12. Decreasing R by a factor of 10 reduces the feedback into the cavity, raising the lasing threshold and making the device output less efficient with increased cavity loss. However, this also means that higher current densities can be achieved without the device lasing, leading to a broader gain spectrum and less spectral narrowing. Reducing the facet reflection can be achieved by antireflection coating the optical facets in addition to angling them.

By engineering the Auger coefficient to be ten times lower the device output and quantum efficiency improve about five times, which is expected given the high current densities these devices operate at, without significantly changing the threshold. It should be noted that the Auger coefficient is already greatly suppressed in these quantum wells in comparison to bulk layers, which significantly improves the output of these quantum well devices.

Finally, by increasing $\beta_{sp}$ by a factor of ten the output of the superluminescent diode increases by about a factor of ten without changing the threshold significantly. Since $\beta_{sp}$ in our simulations was already very low, $10^{-4}$, an increase of ten times seems reasonable. $\beta_{sp}$ could potentially be increased by engineering the photonic modes of the waveguide by fabricating a photonic crystal waveguide.
Figure. 12. Simulations comparing the improvements to base parameters for varying the Auger coefficient, C, fraction of spontaneous emission into the waveguide mode, $\beta_{sp}$, and facet reflection, R.
CHAPTER IV
CONCLUSIONS

We have observed superluminescent output in angled waveguide, GaInAsSb/AlGaAsSb strained quantum well heterostructures emitting at 2.4 µms. The superluminescence is evidenced by superlinear growth in output power as well as spectral and angular narrowing with increased current. Output powers up to 1 mW into an F/1 solid angle were observed at room temperature and quasi-cw conditions from end facets of area only 50 x 304 µm², compared to 300 µW upper hemisphere for comparable room temperature, cascaded surface emitting LEDs with 1mm diameter mesas. Simulations suggest significant improvements in output could come from engineering the photonic modes around the waveguide to suppress spontaneous emission out of the waveguide and additional bandgap engineering to suppress Auger scattering.
APPENDIX
CLEAVING METHODS

The devices used in the study were grown and fabricated onto quarter wafers and then cleaved into individual SLDs. The cleaving process is very important to the quality of the SLDs as their output is sensitive to the quality of their two optical facets. We investigated three methods of cleaving to discover the best way to increase our yield of high quality optical facets.

The initial method that we used was cleaving chips by hand. A small scribe was created on one side of the wafer using a diamond stylus, and then pulled apart using a pair of forceps on either side of the scribe. This method was inconsistent in producing quality facets due to the scale of SLDs being cleaved, between 0.8-2.7 mm in length, meaning that the cleave was sensitive to uneven or misapplied force via the forceps. In addition, scribes that are too small or shallow require more force when pulling to break them apart, making damage more likely.

Poor yield when cleaving by hand led us to investigate other methods of cleaving. Later chips, including Chips 1-3 above, were cleaved by the company Custom Nanotech, which used a Loomis LSD-100 machine to do the cleaving. Once again a small scribe is made on one side of the wafer, and the chip is then positioned over the point of a triangular wedge. A rubber wheel is rolled down the wafer, bending the wafer over the wedge causing the wafer to break along the scribe. Cleaving by machine proved to be both more consistent, and produce a generally higher quality of chips. Fig. 13 shows a graph of 17 laser diodes comparing the LI curves of those cleaved by hand, and those cleaved by Custom Nanotech. Although the lengths of each chip varies, which will affect the lasing threshold, in general the chips cleaved by Custom Nanotech had lower lasing
thresholds, which we decided would be correlated with higher facet quality in laser diodes.

![Laser Diodes comparison](image)

**Figure 13.** IV plots of 17 laser diodes of varying lengths cleaved by us (using the by hand method) and by Custon Nanotech.

The last method explored is a method created by Jon Olesburg. It is essentially similar to how the LSD-100 cleaves; a scribe is created on the wafer and then the wafer is placed onto block with an incline on one end, as shown in Fig. 14. The wafer is then rocked over the edge of the incline using a test tube slide with the scribe positioned on the edge. This bends the wafer, causing it to break apart along the scribe. The Olesburg method was found to be inferior to using a machine to cleave our chips as cleaves tended to be influenced greatly by the orientation of the wafer during cleaving. While with the previous two methods, once the wafer started breaking the break tended to split along the
crystalline axis with the Olesburg method it instead tended to split along the incline's edge instead. This leads to a stair-stepping effect in the optical facet of the cleaved chip that is undesirable.

**Figure 14.** Picture of the block used in the Olesburg cleaving method. Wafers are placed over the incline on the right end of the block, with the scribe oriented parallel and on top of the line where the flat top of the block meets the incline on the right.
REFERENCES


