Long Wavelength Vertical Cavity Lasers

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Abstract

The need for low cost, high speed telecommunication sources demands the maturation of long wavelength vertical cavity lasers (VCLs). Both long haul fiber optic systems and gigabit ethernet links are potential markets for 1.3 and 1.55 micron VCLs. This past year has seen much progress to this end, but the emerging technology has yet to be determined. This paper overviews critical issues in long wavelength VCL design, and discusses the most recent technological advances in the field.

I. Introduction

The emergence of a high speed, low threshold, long wavelength vertical cavity surface emitting laser (LW-VCSEL) source is much anticipated. VCSELs operating at 1.3 and 1.55 µm wavelength have long been heralded as the ultimate low cost solution for optical sources for gigabit ethernet links and fiber to the home (FTTH), offering both efficient fiber coupling and on wafer testing. Despite the widespread acceptance of GaAs based VCSELs by industry, the development of their long wavelength counterparts has been hampered by the temperature performance of long wavelength systems. In order for long wavelength VCSELs to maintain their cost advantage over uncooled distributed feedback lasers (DFB), VCSELs must operate reliably over a wide temperature range. Commercial standards require operating ranges from -40°C to 85°C for telecom, and between 0°C and 70°C for datacom applications. The difficulty in achieving suitable thermal behavior in long wavelength systems is manifested in low characteristic temperatures, and attributed to the high Auger recombination and inter-valence band absorption characteristic of low energy gap materials. An additional obstacle is the problem of finding a lattice matched mirror system capable of achieving the high reflectivities necessary for VCSEL design. In this paper, we will first review the possible materials systems that can be used for both laser active regions and mirror systems. The second section will focus on design issues relevant to attaining a thermally stable long wavelength VCSEL source, and finally we will discuss the recent technological advances in the field.

II. Mirror System

Many different mirror systems have been proposed and demonstrated for long-wavelength VCLs. The optical, thermal, and electrical properties of each system must be addressed. They can be classified into three main categories: epitaxially-grown (either lattice matched or pseudomorphic), dielectric-deposited, and wafer-fused. Epitaxially-grown mirrors have the obvious advantage that they are directly integrated with the device much like standard GaAs based VCLs. This allows for easy manufacturability and device processing. The majority of the work on long wavelength epitaxial mirrors has been done in the InGaAsP/InP system. Unfortunately, the relatively small index contrast between InP and InGaAsP necessitates growth of a large number of mirror periods before reaching acceptable reflectivities. Figure 1 shows a typical plot of reflectivity (at 1.55µm) of three different mirror systems versus the number of periods in the mirror. The need for long growths with good control over growth rates is even more pronounced when operating at 1.3 µm where the composition choice for the InGaAsP layer is even further constrained. The small index difference also results in large penetration depth into the mirrors, increasing diffractive and absorptive losses. Furthermore, the thermal conductivity of InGaAsP material is very low due to alloy scattering of phonons from quaternary material. This results in a thick mirror (>10µm) with a very low thermal conductivity. Heating in such a device is very pronounced and limits the maximum operating temperature.

There have recently been some promising results in antimonide-based mirrors lattice matched to InP\textsuperscript{1}. The
index contrast in Sb based mirrors is quite high, although this system, too, suffers from poor thermal conductivity characteristic of ternary and quaternary materials. Recently, an optically pumped room temperature continuous wave operation of a 1.48 µm VCL was reported using one fused GaAs/AlGaAs mirror and one AlGaAsSb/AlAsSb mirror with an index contrast of 0.54\(^2\). Despite the initial results using this system, considerable effort must still be put forth in the areas of growth, dislocation control, and development of effective dopant grading schemes for low resistance mirrors.

GaAs/AlAs mirrors provide a high index contrast as well as the uniformity and reproducibility concomitant with epitaxial growth. Unfortunately, inter-valence band absorption in p-doped GaAs becomes more pronounced at longer wavelengths, limiting the maximum reflectivity of the mirrors. This absorption is significantly worse at 1.55 µm than at 1.3 µm, but still allows for very high maximum reflectivities.

III. Active region material and design

Due to high Auger coefficients and smaller conduction band discontinuities, high temperature InP-based active regions have proven more difficult to achieve than those based on GaAs. Fortunately, much groundwork has been laid for high temperature designs through progress in InP based edge emitters. These lasers employ strained quantum wells to reduce the effects of Auger recombination. Strain limits the number of QWs that can be grown without inducing an unacceptably high density of misfit dislocations. In order to incorporate many wells for the high gain requirements of VCLs, strain compensation techniques have been developed to reduce the net strain in the active region. Thus far, the best reported high temperature results employ strain compensated InGaAsP/InGaAsP active regions.\(^5,6\)

In order to provide stronger electron confinement and prevent carrier overflow out of the MQW region at elevated temperatures, other material systems have been investigated. A considerable amount of work has been done in the AlGaInAs system lattice matched to InP. Theory compares this system favorably to the more traditional GaAsP system, predicting slightly higher material gain and maximum critical temperatures. The conduction band offset is considerably higher in the (Al)GaInAs/Al(Ga)InAs (\(\Delta E_c = 0.72 \Delta E_g\)) compared with the InGaAsP/InGaAsP system (\(\Delta E_c = 0.4 \Delta E_g\)), leading to increased hole transport in the active layer and enhanced differential gain in edge-emitting lasers.\(^7\) AlGaInAs active regions have been used to demonstrate cw lasing in a double fused oxide implanted VCL design operating up to 40ºC.\(^8\)

Another attractive material system for active region design is GaInNAs lattice matched to GaAs. The extremely large bandgap bowing of the GaAsN system makes it possible to decrease the bandgap energy of the As rich ternary from 1.42 eV to 0 eV (semi-metal) simply by increasing the N content. However, there is a miscibility gap in this system that limits the amount of N that can be incorporated. Also, it has been reported that the valence band lineup in the GaAs-GaInNAs is considered to be a staggered (type II) line-up.\(^9\) By increasing the Indium content and minimizing the N content, demonstration of type-I heterostructures with emission wavelengths as long as 1.3 µm have been successful. More research into the growth of this material system is necessary to demonstrate
efficient emission at longer wavelengths. Continuous-wave room-temperature photo-pumped laser oscillation has been demonstrated in vertical cavity laser designs employing single or multiple GaInNAs quantum wells, with lasing wavelengths as long as 1.256 \( \mu \text{m} \)\(^{10}\). Electrically-injected devices have achieved pulsed operation at room temperature.

Work has also been done on InGaAs quantum dots\(^{12}\), and in InGaP/InAsP systems to produce long wavelength active regions. Another interesting approach has been the development of InGaAs ternary substrates to produce extremely high temperature operating in-plane lasers\(^{11}\), although no VCLs have been demonstrated to date.

IV. Device Design

In addition to the choices of materials for both active region and mirrors, there are numerous other design issues for the optimized performance of a long wavelength VCSEL. Only recently have many different research groups achieved room temperature continuous wave operation. Table 1 summarizes some of the recent technological advances in the field, ranging from all epitaxial structures to single and double fused structures, to quantum dot VCSELs. Aside from the choice of material system for both active region and mirror system, perhaps the most important attributes of the device design are the method of current constriction, the ability to tune the cavity, and the ability to scale devices down to small dimensions. In the next section, we will describe a particular VCSEL design that we have employed to achieve state of the art high-temperature performance, and relate the observed device characteristics to important design choices.

V. State of the art performance

The highest performance long wavelength VCSEL has consistently been achieved through wafer fusing. Using the best performing electrically pumped device as an example, we will highlight the state of the art performance as well as focus on the areas that need to be further addressed to commercialize LW-VCLs.

The device structure we employ consists of two Al(Ga)As/GaAs mirrors grown on GaAs substrates by molecular beam epitaxy (MBE) fused to an InGaAsP/InP active region grown on an InP substrate by metal organic chemical vapor deposition (MOCVD). A schematic of the device is shown in Fig. 2. Details of the fusion conditions are reported elsewhere\(^{13}\). The top p-mirror consists of 25.5 quarter wave periods with a single 40nm Al\(_{0.98}\)Ga\(_{0.02}\)As layer for selective lateral oxidation placed 145 nm from the GaAs/InP fused junction. The interfaces are parabolically graded with a pulsed doping of 3x10\(^{18}\)/cm\(^{3}\). Prior to fusion, a 30nm GaAs layer was regrown with a Be doping of 8x10\(^{18}\)/cm\(^{3}\). The bottom mirror is an undoped 30 period GaAs/AlAs quarter wave stack.

![Figure 2. Schematic of a double fused VCSEL using an InGaAsP/InGaAsP MQW active region and two wafer fused GaAs/AlAs DBRs.](image)

<table>
<thead>
<tr>
<th>Active region</th>
<th>Mirror system</th>
<th>(\lambda) ((\mu\text{m}))</th>
<th>Performance</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAsP:InP</td>
<td>Double fused Al(Ga)As/GaAs</td>
<td>1.55</td>
<td>74 °C, 1 mW at 15°C, (I_\text{th}= 0.8\text{mA}, V_\text{th} = 2.1\text{V}) oxide aperture</td>
<td>UCSB</td>
</tr>
<tr>
<td></td>
<td>Metamorphic Al(Ga)As/GaAs InGaAsP/InP</td>
<td>1.55</td>
<td>45 °C, (J_\text{th}= 3k\text{A/cm}(^2), V_\text{th} = &lt;3\text{V}) H(^{+}) implantation, cavity tuned</td>
<td>Alcatel</td>
</tr>
<tr>
<td>Si/Al(_{2})O(_3) Si/SiO(_2)</td>
<td>1.3</td>
<td>36 °C, (To = 50\ \text{K}, I_\text{p}= 2.4\text{mA}) Buried heterostructure</td>
<td>Furukawa</td>
<td></td>
</tr>
<tr>
<td>SiO(_2)/TiO(_2)+ InGaAsP/InP Fused AlGaAs/AlAs+ InGaAsP/InP</td>
<td>1.55</td>
<td>27 °C, 7 (\mu\text{W at RT, } J_\text{th}= 1.8\text{kA/cm}(^2), V_\text{th} = 2.1\text{V}) cavity tuned</td>
<td>NTT</td>
<td></td>
</tr>
<tr>
<td>AlGaInAs:InP</td>
<td>Fused Al(Ga)As/GaAs ZnSe/MgF</td>
<td>1.3</td>
<td>40 °C, 0.5 mW at RT, (I_\text{th}= 0.8\text{mA}, V_\text{th} = 2.1\text{V}) O implantation</td>
<td>Cornell</td>
</tr>
<tr>
<td>GaInNAs:GaAs</td>
<td>AlGaAs/GaAs SiO(_2)/TiO(_2)</td>
<td>1.25</td>
<td>RT cw photo-pumped Electrically pulsed at shorter wavelengths</td>
<td>Hitachi</td>
</tr>
<tr>
<td>InGaAs quantum dots</td>
<td>MgF/ZnSe AlGaAs/GaAs</td>
<td>1.15</td>
<td>(J_\text{th} = 640 \text{A/cm}(^2)</td>
<td>UT Austin</td>
</tr>
</tbody>
</table>
The active region incorporates two In$_{0.9}$Ga$_{0.1}$P barrier layers on either side of the multiple quantum well region. The MQW region consists of six 7 nm 1%-strained quantum wells (QWs) with seven 7 nm thick barriers. The emission wavelength of the barriers is 1180nm. On either side of the active region is a 300nm InP cladding to form a $3/2\lambda$. The InGaP barriers serve both to compensate the compressive strain in the QWs and increase the confinement energy of the electrons in the active region by 30meV relative to InP.

The room temperature (RT) photoluminescence peak of the active region is at 1542 nm and the lasing mode is at 1515 nm. Figure 3 shows the high temperature L-I curves of a device with a 7 µm oxide opening. This is the first demonstration of a device operating cw up to 74°C. The threshold current at RT is 1 mA, and the threshold voltage is 3 V. The high temperature performance of this device cannot be attributed to the misalignment of the gain peak and optical mode at RT, as the gain-offset increases with temperature. The gain peak and mode wavelength shifts with temperature are 0.54 and 0.11 nm/K respectively$^{14}$. The zero gain offset is calculated to be at -38°C and the optimum temperature for low threshold operation is expected at -108°C when the mode wavelength is 30 nm longer than the gain peak wavelength.

In summary, there are three major design factors that have contributed to the improved performance of these devices over those previously fabricated. The use of carbon doping enables 90%Al(Ga)As/GaAs mirrors to be used in the top p-mirror as opposed to the Be doped 67%Al(Ga)As/GaAs mirrors formerly used, reducing the loss. The low operating voltage of the device contributes to reduced device heating. Finally, the introduction of an In$_{0.9}$Ga$_{0.1}$P barrier layer to the active region acts both as a strain compensation mechanism for compressively strained QWs, and to increase the confinement energy of the electrons in the active region, reducing carrier leakage at higher temperatures. The InGaP barriers also act to reduce inter-valence band absorption in the active region, allowing the device to operate in a regime less sensitive to temperature. Further improvements in device performance...
can be expected by better alignment of the gain peak and cavity mode at room temperature.

VI. Critical Issues to resolve

Despite the great success of LW VCLS, there are many problems yet to be overcome. Critical for run to run reliability is the ability to tune the cavity mode. Although this is difficult in a double fused structure, successful tuning has been demonstrated by a number of groups using both all epitaxial structures\(^ {17}\) and single fused structures\(^ {18}\).

Current constriction has always been a problem in long wavelength VCLS. One advantage to using the GaAs-based mirror system is the ability to use high Al content layers for selective lateral oxidation. Only recently have successful techniques for oxide apertures in InP based systems been demonstrated, specifically, using AlAs/AlInAs superlattice layers\(^ {19}\). Although oxidation can occur at reasonable temperatures (~500°C), the oxidation rate is very slow, requiring times on the order of 30 to 120 minutes for an oxidation depth of 5 to 18 µm. Another demonstrated technique for current constriction is ion implantation\(^ {8}\). Although the resultant current confinement is good, there are oftentimes problems with poor optical guiding in these devices, as well as a difficulty with scaling down to small dimensions.

VI. Summary

There has been great progress in the field of long wavelength VCLS. Figure 6 shows a roadmap of progress made since 1993. To date, the high temperature performance has been limited by a number of factors, difficulty with cavity tuning, current spreading, and joule heating among the most prominent. The ultimate design would allow for a monolithically grown device, preferably on a GaAs substrate to take advantage of the low cost, large diameter bulk crystal as well as the superior mirror systems available. The prospect for 1.3µm VCSELs grown on GaAs using InGaAsN active layers is good, but it remains questionable whether this system is physically capable of reaching longer wavelengths. This will become important if tunability over the entire 1.3µm to 1.55µm range is required in the future. Although the optically pumped structures have shown improved performance, to maintain cost and performance advantages in the future, an electrically pumped long wavelength VCSEL source is the ultimate goal. To this end, the best reported LW-VCSELs have been achieved through wafer fusion. Double fused, electrically pumped VCLs have demonstrated record high output

![Figure 6. Progress in long wavelength VCSELs.](image-url)
powers and operating temperatures, and utilize a versatile technology that can be used to achieve lasers throughout the telecommunications frequency band.


6this work.


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