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This program is dedicated to developing a low-cost full duplex module coupled to single-mode fiber. This module allows both transmit and receive over a single optical fiber. using an InGaAsP/InP photodector at the receiver end, and a single-mode InGaAsP/InP 1300 nm VCSEL as the transmission source. The key new techonology in this module is the single-mode 1300 nm VCSEL, which should greatly reduce packaging and manufacturing costs compared to edge-emitting lasers. Although 1300nm room-temperature VCSELs do not exist today, the recent success of 1550nm VCSELs, as demonstrated by OCI and the Unversity of California at Santa Barbara, suggest that 1300 nm VCSELs will work also. In the first two quarters of thisprogram, OCI has investigated several different 1300 nm designs, which we discuss in the body of this report.

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Final Report for

"Vertical-Cavity Laser-Based Duplex Modules for Distributed Information Systems"

Abstract

This program is dedicated to developing a low-cost full duplex module coupled to single-mode fiber. This module allows both transmit and receive over a single optical fiber, using an InGaAs/InP photodetector at the receiver end, and a single-mode InGaAsP/InP 1300 nm VCSEL as the transmission source. The key new technology in this module is the single-mode 1300 nm VCSEL, which should greatly reduce packaging and manufacturing costs compared to edge-emitting lasers. Although 1300 nm room-temperature VCSELs do not exist today, the recent succes of 1550 nm VCSELs, as demonstrated by OCI and the University of California at Santa Barbara, suggests that 1300 nm VCSELs will work also. In the first two quarters of this program, OCI has investigated several different 1300 nm designs, which we discuss in the body of this report.

I. Backgound: Wafer-Fused Long-wavelength VCSELs

Over the last 2 years, progress in long-wavelength (1300nm/1550 nm) VCSELs has improved dramatically. Two years ago, all long-wavelength VCSELs operated pulsed only, and output power was generally so low as to never be reported in the literature. Today, 1550 nm VCSELs have demonstrated 0.5 mW room temperature continuous wave CW power and approximately 0.25 milliwatts of single-transverse-mode power. It appears for the fist time that the 1 mW benchmark for telecommunications may be achieved in the not too distant future. The dramatic improvements in 1550 nm lasers have been enabled by the introduction of GaAs/AlGaAs wafer-fused mirrors, coupled to InP/InGaAsP active regions. Wafer fusion is a technique whereby semiconductors of different atomic lattice spacing can be atomically joined by applying mechanical pressure and heat. Figure 1.1 illustrates the wafer-fused long-wavelength VCSEL epitaxial structure. The GaAs/AlGaAs mirrors have allowed, for the first time, sufficiently high reflectivity for room-temperature CW lasing.

Figure 1.2 sumnmarizes the results obtained by Optical Concepts during BMDO program DASG60-94-0022, which was devoted to fabricating 1550 nm VCSELs for a WDM system. As described in that program, the OCI structure employs an electrcally pumped 980 nm VCSEL, integrated wafer scale with a 1550 nm VCSEL wafer, generating high efficiency electrically pumped 1550 nm operation. The results of Fig. 2 show pumping by two different types of 980 nm VCSEL.

A more traditional approach, which employs direct electrical pumping of 1550 nm VCSELs, has generated the results shown in Fig. 1.3 [1]. Figure 1.3 represents work done by the University of California at Santa Barbara (UCSB), using the double-fused structure originally pioneered by the university. Threshold current on the order of 1 mA has been obtained with this structure. Although output power shown in Fig. 1.3 is rather limited, theory indicates power could be much higher with some design modifications.

All of the work described in Figures 1.1-1.3 has been done with 1550 nm VCSELs. For near term commercial applications, 1300 nm is a more desirable wavelength, because most of the world's existing fiber infrastructure is optimized for low dispersion at 1300 nm. Since 1300 nm VCSELs will employ a similar technology to 1550 nm VCSELs, 1300 nm VCSELs have a high probability of success. Such 1300 nm VCSELs form the backbone of this program. This program is devoted to manufacturing a full duplex module, which allows two-way communication over a single optical fiber. Two-way communcation requires coupling both in and out of a single-mode optical fiber (for transmit and receive), while simultaneously achieving spatial separation of the two beams. While this presents some optical design challenges, by far the most challenging part of this program is development of single-transverse-mode 1300 nm VCSELs operating continuously at room temperature. The risk in achieving this end has been greatly reduced by the success of 1550 nm VCSELs described above, but the 1300 nm design nevertheless presents some challenges of its own. We consider these in detail, as we examine two approaches to achieving 1300 nm single-transverse-mode VCSELs in Sections II. and III. In section IV, we summarize the advantages and disadvantages of each approach, and make some recommendations.

II. Electrically pumped designs: 1300 nm

As described in Section I, and in the reports associated with BMDO contract DASG60-94-0022, our approach to 1550 nm VCSELs has been to optically pump them with 980 nm VCSELs. This allows the long-wavelength cavity to be free of loss-producing dopants, and also eliminates resistive heating in the device. It has become increasingly apparent, however, that at 1300 nm, a direct electrically pumped device may be of comparable perfomance to an optically pumped device. One reason for this is the experimental fact of room-temperature CW 1550 nm VCSELs operating by direct electrical pumping (Fig. 1.3). Another reason is that the optical losses in GaAs mirrors designed for 1300 nm are lower than at 1550 nm. Thus, if 1550 nm lasers work well, one might expect 1300 nm lasers to work better. However, offsetting the reduced optical loss at 1300 nm is the increased temperature sensitivity at 1300 nm as compared to 1550 nm. This sensitivity arises because the electrons in InGaAsP quantum wells have weaker confinement than InGaAs wells designed for 1550 nm emission. A number of alternative material combinations can be employed, however to reduce temperature sensitivity. Given these factors, OCI has concluded that direct electrical pumping at 1300 nm demands serious consideration for this program.

A. Designing for low intracavity loss and voltage.

Figure 2.1 shows the structure of the electrically pumped 1300 nm device introduced in our original phase II proposal. As described in the introduction, this device employs wafer-fused GaAs/AlGaAs mirrors on both sides of the cavity, providing the required high reflectivity. Confinement of electrons and photons is accomplished by lateral oxidation of an AlGaAs layer, a technique which is now widely recognized to produce the best lasers at 850 nm and 980 nm [2]. Lateral oxidation is accomplished by etching a post into the actve region, exposing a high-aluminum content AlGaAs layer just above the active region. Subsequently exposing the sample to 425°C in a steam atmosphere converts the AlGaAs to aluminum gallium oxide (AlGaO), for a certain distance in from the edge of the post. Lateral oxidation creates refractive index-guiding with low optical loss, and provides confinement of current as well.

Also shown in Fig. 2.1 is a"tunnel junction" inside the cavity to convert electrons to holes. The original motivation for the tunnel junction was that p-dopants in the cavity introduce optical loss, and that a tunnel junction allows p-dopants to be minimized by creating a region where injected electrons (n-type carriers) can be converted to holes (p-type carriers). With a tunnel junction it is possible to satisfy the requirement for both electrons and holes in the device, *without* requiring both p and n mirrors in the device. Employing a tunnel junction should presumably lead to lower loss and higher efficiency.

This value of a tunnel junction, however, has become increasingly less clear in the last several months. As a result, our current design shown in Fig. 2.2 does *not* employ a tunnel junction for the following reason. The tunnel junction, which is a highly doped reverse biased p-n junction, introduces additional resistance and heating in the device. It is difficult to estimate the ultimately achievable additional voltage drop, but we can examine experimental voltages in the literature. Reference [3] indicates a resistance of

2.2 ohms for a tunnel juntion area of 15,000 μm^2. If we scale this down to a VCSEL size of 10 X10 μm square, we obtain a resistance of 330 ohms, or an additional 3.3 volts for a typical operating current of 10 mA. It is worth asking if we drop the p-doping level in a standard p-mirror so the introduced loss is adequately small, is the increased voltage comparable to or less than that of a tunnel junction? It appears the added voltage is indeed smaller than 3.3 volts. As we discuss below, dropping the p-doping from 10^{18} to $5 \cdot 10^{17}$ for the first 10 mirror periods is adequate to drop the loss in the p-mirror to acceptable values. Using a "Poisson solver" program developed at UCSB, we conclude that the additional voltage introduced is less than 1 volt. It appears a lightly doped p-mirror is a more sensible option than a tunnel junction.

We can quantify the loss of p-type mirrors for 1300 nm operation by making use of some information available in the literature. The loss in p-type GaAs at 1300 nm is approximately proportional to the doping at moderate doping levels, and equal to about 15 cm^{-1} per 10^{18} cm^{-3} doping concentration [4]. This value compares to about 30 cm^{-1} per 10^{18} cm^{-3} at 1550 nm and 10 cm^{-1} per 10^{18} cm^{-3} concentration at 980 nm. It is especially significant that the loss at 1300 nm is not much worse than the loss at 980 nm. If we use a doping concentration of 5 X 10^{17} instead of the 10^{18} typically used in 980 nm VCSELs, our p-mirror losses become comparable to those observed in 980 nm VCSELs. This lower doping scheme is illustrated in Fig. 2.2, which represents our new design. As Fig. 2.2 shows, the reduced doping only exists over the first 10 periods of the p-mirror. Most of the optical field is contained in this portion of the mirror, and the doping can be increased further away from the active region without introducing substantial additional loss.

Appendix G of reference [5] calculates the percent of power lost per reflection from a distributed GaAs/AlGaAs mirror, for different values of distributed mirror loss. Although the calculation is done for a 980 nm mirror, and not a 1300 nm mirror, the dependence on wavlength is not strong. Assuming 10 cm^{-1} loss in the mirror, we deduce from [5] that the loss is approximately 0.08% per reflection. We can add this loss to several other losses in the cavity to generate the following estimate of cavity loss per roundtrip A:

A_p=loss in p-mirror=0.08%

A_n=loss in n-mirror=0.08%

A_a=loss in active region and cladding=0.2%

A_r=residual loss measured from optical pumping=0.2%

A_{tot}= total roundtrip losses=0.56%

In the above estimate, we can reduce some of the losses further by reducing doping, but this leads to increases in voltage and reductions in speed. This tradeoff has not yet been explored in detail, and is best done experimentally. One of the losses above, referred to as residual loss A_r, has been measured expermentally, but its origin is currently unknown. It may be related to the fusing process, and may eventually be eliminated, but it has consistently been observed by OCI in optically pumped structures, and by UCSB in electrically pumped structures [6].

In the absence of resistive heating, the total internal loss in the structure above is related to the output power according to the equation:

$$P_{out} \sim (I-I_{th}) \bullet \eta_i \bullet T/(T+A_{tot})$$

where T is the fractional transmission of the output mirror, and η_i is the internal injection efficiency, typically around 0.8. The threshold current is obtained by knowledge of the quantum well gain vs. current curves, which is not published, but should be comparable to that obtained at 1550 nm. Electrically pumped 1550 nm VCSELs with $T+A_{tot}$=1% fabricated by UCSB have recently exhibited room-tmperature CW operation with threshold of 1-2 mA. Given our loss value for A_{tot} =0.56%, this suggests that with T=0.42%, we should be able also to achieve low-threshold, room temperature CW operation at 1300 nm. The 0.42% output transmission would also lead to 33% external differential efficiency if heating were not present.

Unfortunately, heating in 1300 nm VCSELs is unavoidable. VCSELs at 1550 nm by UCSB typically operate at 20-30 °C above room temperature because of resistive heating, which degrades power and makes operation at 70 or 80 °C virtually impossible with 1300 nm InP/InGaAsP active regions. For this region, alternative active regions are discussed in the next section.

B. Active regions

At least 2 candidates exist for 1300 nm active regions. The most established is InP/InGaAsP, but it is known to have poor temperature performance. The reason is shown in Fig. 2.3. The "conduction band offset" or energetic barrier which confines electrons is less than 100 meV, leading to excessive carrier leakage at higher temperatures. An alternative material system is provided by AlInGaAs/InP, which Fig. 2.4 shows provides 100-200 meV confinement, depending on the strain in the quantum well [7]. This material has produced 1300 nm in-plane lasers with operation beyond 100 °C. It is therefore a natural choice to use this material in VCSELs.

Another material system known to produce high temperature perfrmance is the InAsP/InGaP/InP system [8]. This has also exhibited lasing beyond 100 °C, and a more careful study comparing this to the AlInGaAs/InP system needs to be performed. At any rate, it appears that one of these two material systems will be required for operation up to 80 °C.

III. Optically pumped designs: 1300 nm

As described in our 1550 nm work in an earlier BMDO contract, one of the advantages of the "vertically integrated optical pump" approach is that optical pumping introduces very little heating compared to electrical pumping. In addition, the required drive power is lower, since intracavity losses in the absence of dopants can be very low. It is likely that an optically pumped 1300 nm VCSEL will operate CW up to 80 °C. This presumes that the pump laser is insensitive to temperature in this range. Fortunately, both 980 nm and 850 nm VCSELs for pumping are extremely robust vs. temperature, with 850 nm VCSELs having worked up to 200 °C. For all practical purposes, we can assume that a well-designed pump laser will operate virtually independent of temperature up to 80 °C.

In this section we present 2 different active region designs for optical pumping. These are based on the AlInGaAs/InP and InGaAsP/InP systems. Figure 3.1 shows the InP/InGaAsP design, which is intended for a 980 nm pump wavelength. The pump light is absorbed by 1.1 μm bandgap wavelength barriers, and the carriers diffuse into the quantum wells, where they re-emit at 1300 nm. The epitaxial growth also includes a superlattice of alternating 1.1Q and InP, for adjustment of the cavity mode to the desired location after growth.

Figure 3.2 shows a design using the higher temperature InP/AlInGaAs material system. This particular design is intended for 850 nm pumping. One advantage of 850 nm pumping is we can go to a 1.0Q material in the absorber region, leading to even better carrier confinement, while obtaining reasonable absorption efficiency. Both the structures of Fig. 3.1 and 3.2 should absorb more than 70% of the light in one pass. One could, however, grade the absorber region in the case of 850 nm pumping, which may improve device speed. One disadvantage of 850 nm pumping is that 850 nm VCSELs are currently not as efficient as 980 nm VCSELs. The structure of Fig. 3.2 also has a superlattice for mode adjustment, and care has been taken to replace InP with AlInAs wherever possible, because InP absorbs 850 nm light in undesired places.

A number of features are apparent from both the designs of Figs. 3.1 and 3.2. First, the quantum wells are widely spaced, to create a thick absorber region. As a result, they could be placed on different peaks of the optical standing wave. In the electrically pumped device, all quantum wells must be on one standing wave peak, for current injection reasons. This ultimately limits the number of quantum wells, which in turn may limit the temperature performance of the device. Also, spacing the quantum wells widely relaxes the strain limit somewhat, so it is possible to stack up a large number of compressively strained wells without introducing defects.

IV. Summary: Pros and Cons of Optical vs. Electrical approaches.

In this report, we have presented a number of different designs for 1300 nm VCSELs. All of these designs rely on wafer-fused GaAs/AlGaAs mirrors, which have been proven by 1550 nm CW VCSELs. At 1550 nm, CW operation has been achieved by direct electrical pumping, and also by optical pumping with a pump VCSEL at a shorter wavelength.

In comparing the 2 approaches for 1300 nm development, the advantage of direct electrical pumping is its simplicity, since only one VCSEL is required, and optical pumping requires 2 VCSELs to generate 1300 nm radiation. The disadvantages are resistive heating, and the need for loss-producing dopants in optical cavity. In addition, because the quantum well number is limited by the need to place all wells on one standing wave, the temperature performance of the directly electrically pumped device may be also limited. The temperature performance may also be limited by the need to operate at higher gain per well to overcome dopant-induced losses inside the cavity. It appears the optically pumped device may have better temperature performance.

Another issue not discussed in this report is that of obtaining single-transverse-mode operation. The optically pumped approach has demonstrated 0.25 mW of single-mode power, while the highest power direct electrically pumped devices have been multi-mode. Single-mode is extremely important for longer distance single-mode fiber applications. The optically pumped approach provides a simple solution to the single-mode problem. Making the pump laser diameter smaller than the 1300 nm laser diameter can guarantee single-mode operation. Obtaining single-mode in direct electrically pumped devices is more complicated, and remains to be demonstrated for high output powers.

As is evident fom this discussion, a number of complex issues drive 1300 nm development. Given the success of both direct pumping and optical pumping at 1550 nm, and because of reduced free carrier loss at 1300 compared to 1550 nm, both optical and electrical approaches should be pursued for 1300 nm. This research should be coupled with investigating different active region materials for high temperature performance.

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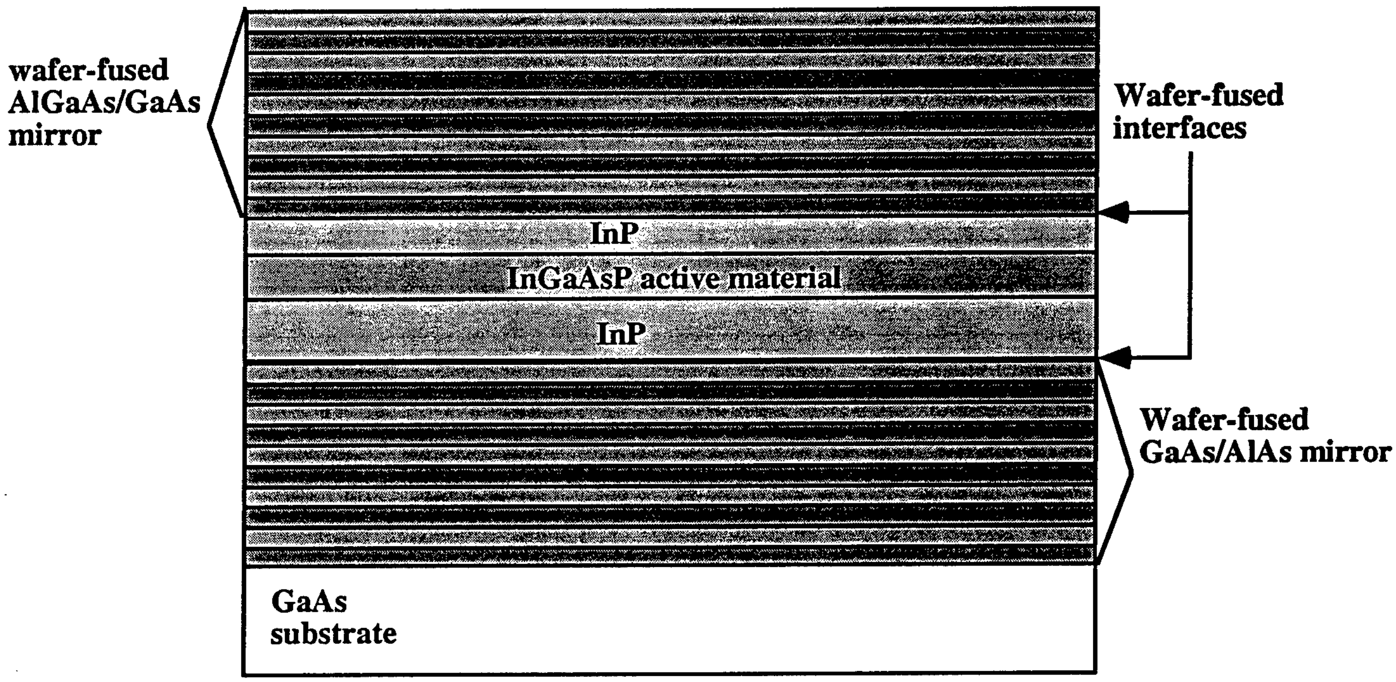

Figure 1.1:"Double-fused" 1550 nm VCSEL.

16 μm diameter Long-wavelength VCSELs with 2 quantum-well active regions, pumped by top and bottom-emitters

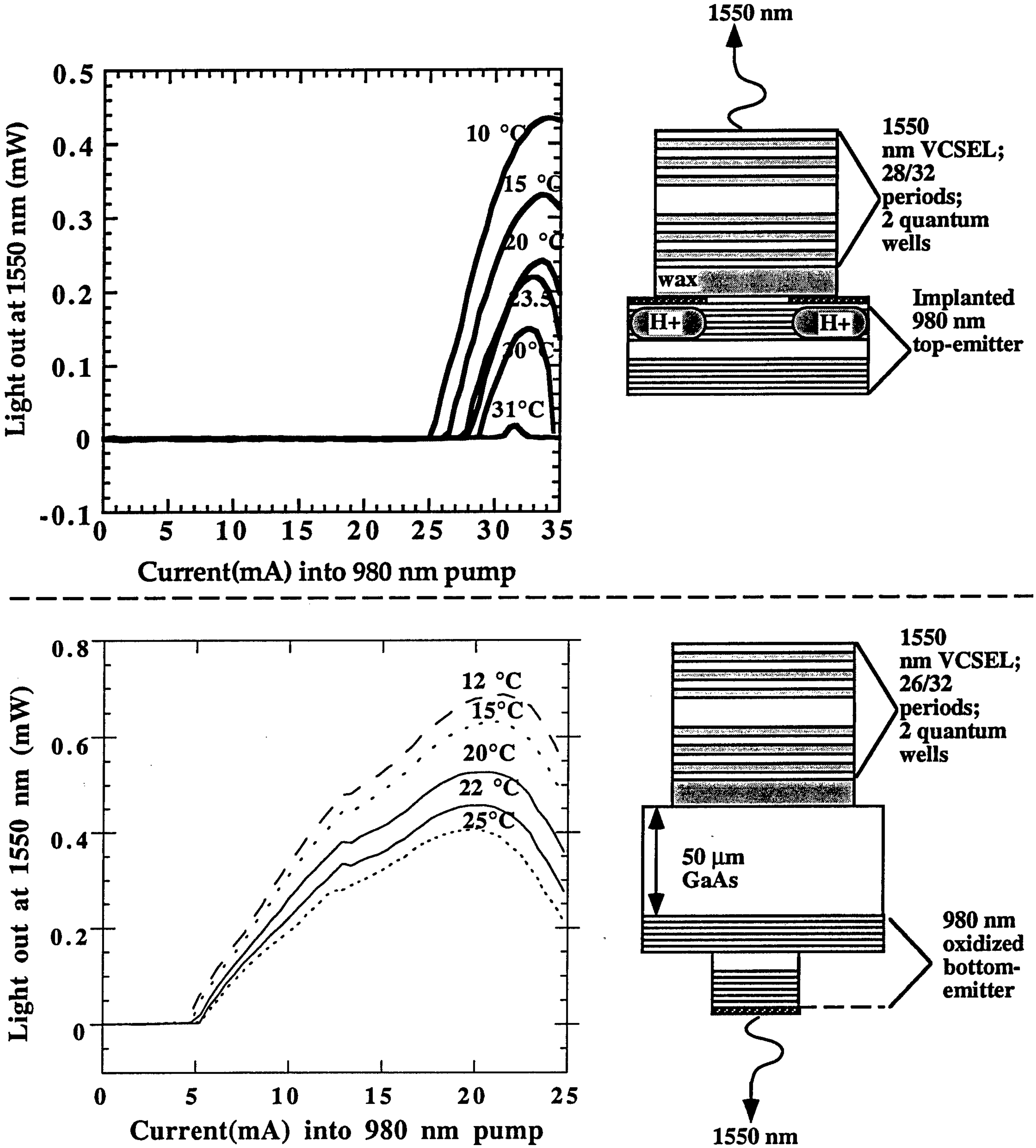

Figure 1.2: Performance of 1550 nm laser with two different 980 nm pump lasers.

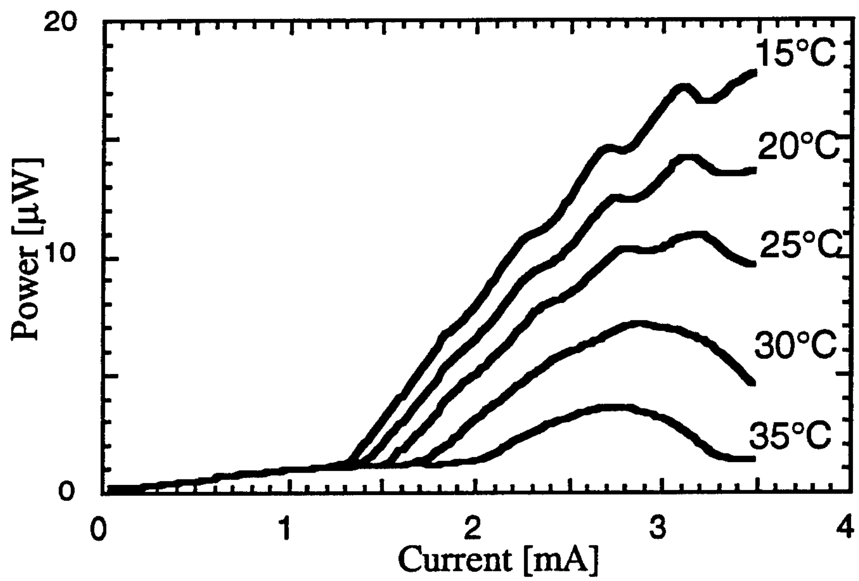

Figure 1.3- CW L-I vs Temperature for direct electrically pumped double-fused device.

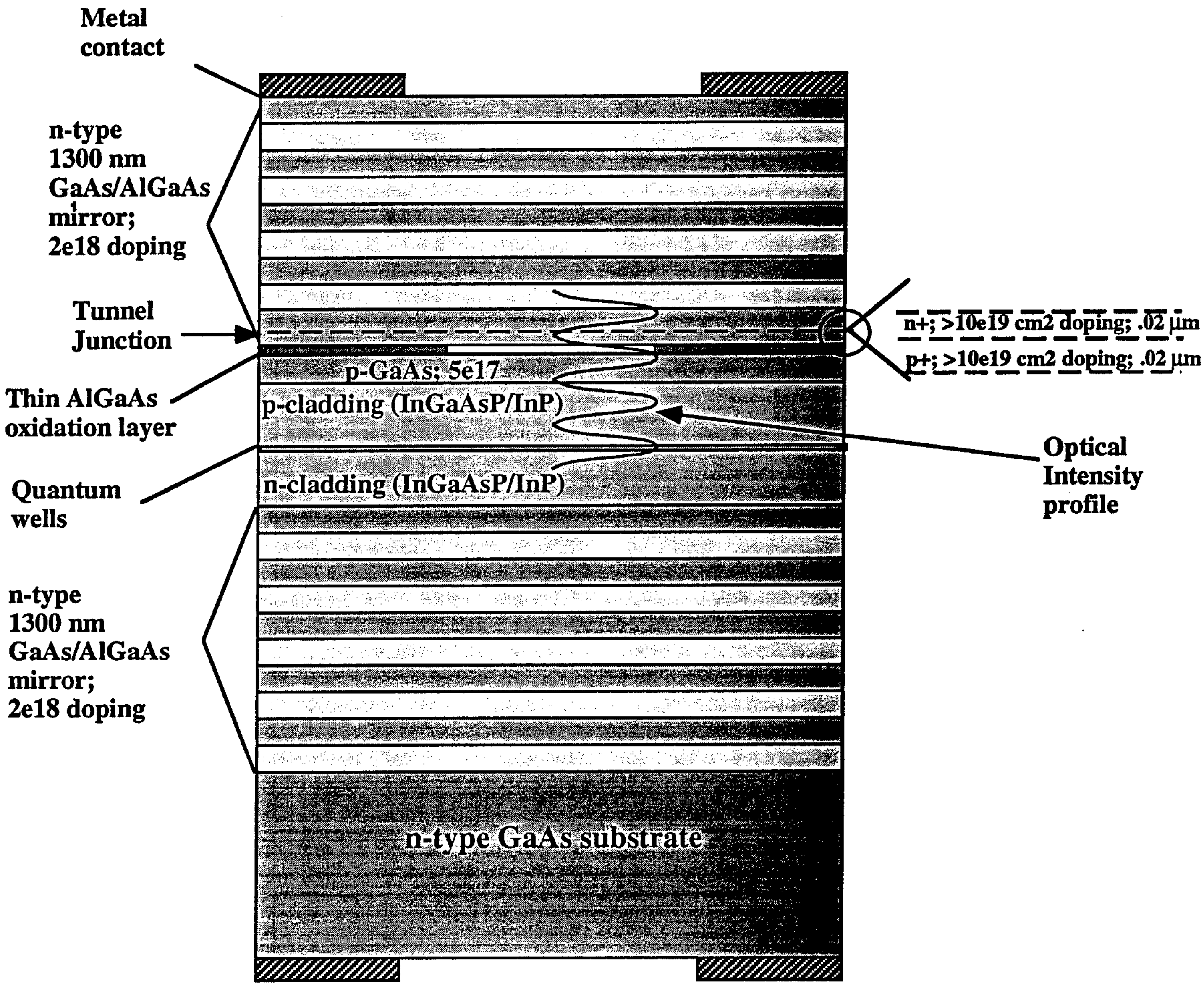

Figure 2.1: Oxide-constricted Tunnel junction VCSEL with current driven through both mirrors.

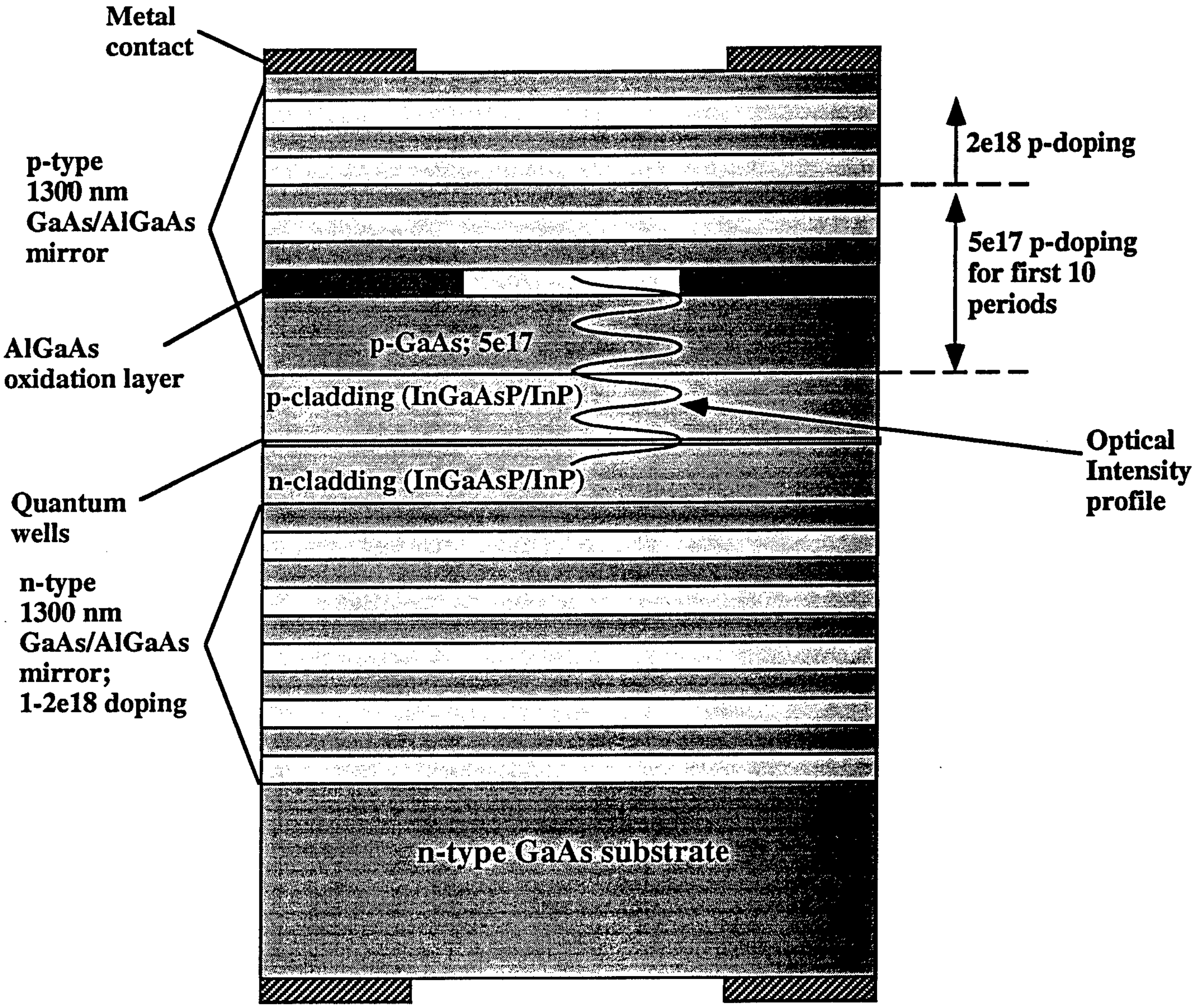

Figure 2.2: Oxide-constricted Tunnel junction VCSEL with current driven through both mirrors.

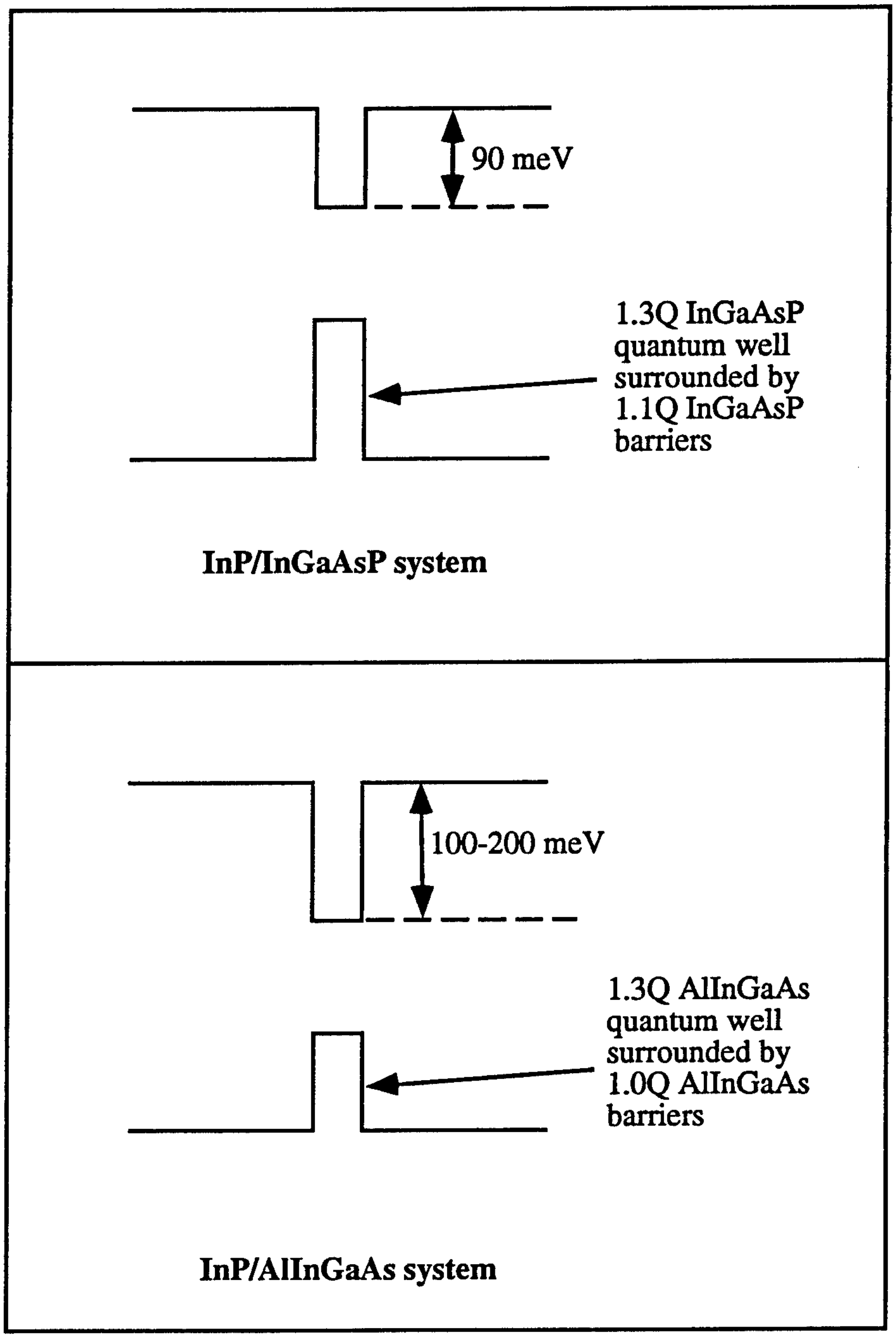

Figure 2.3: Electrom confinement in two material systems

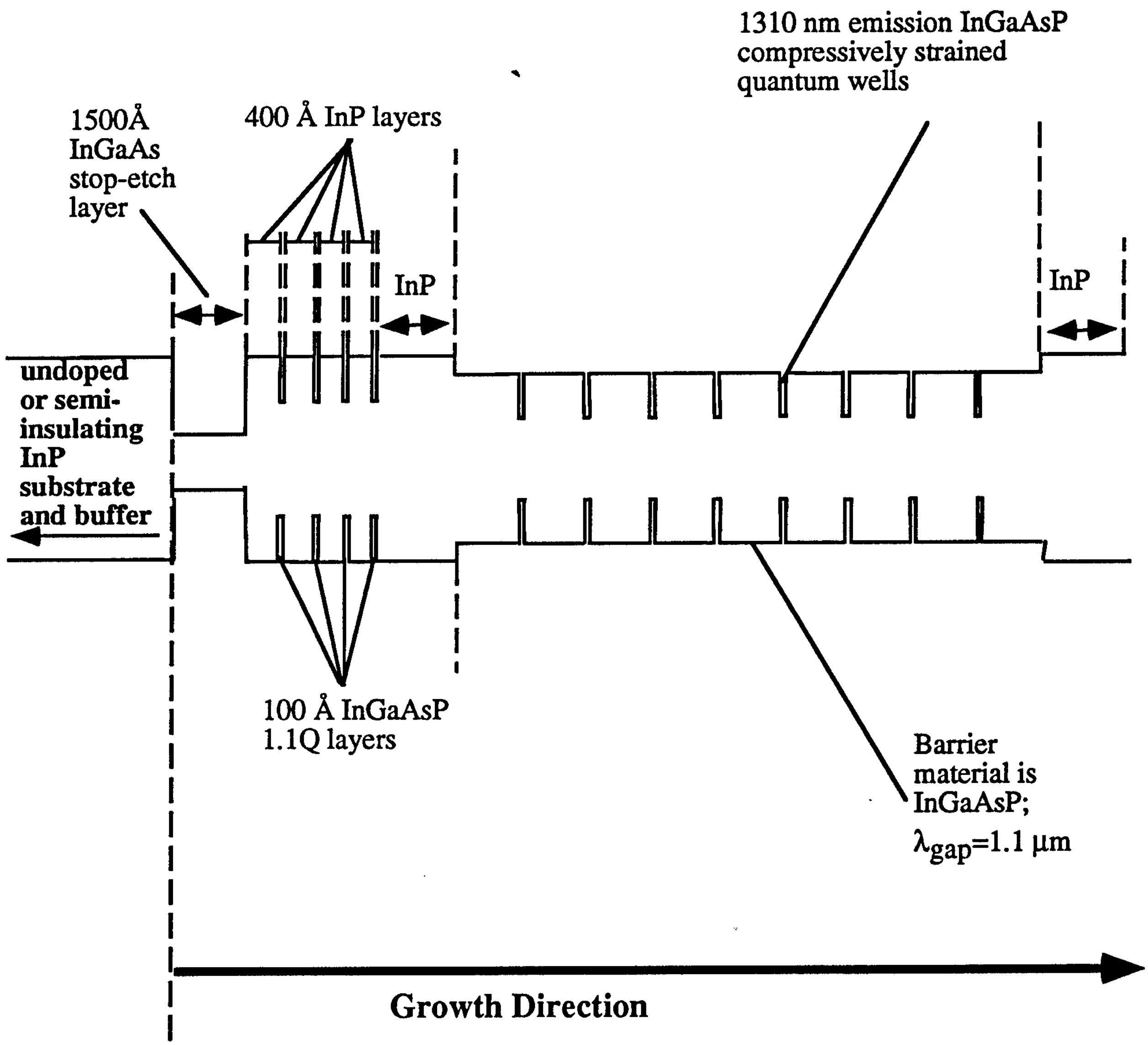

Figure 3.1: Epitaxial design for optically pumped 1300 nm VCSEL. Pump wavelength is 980 nm.

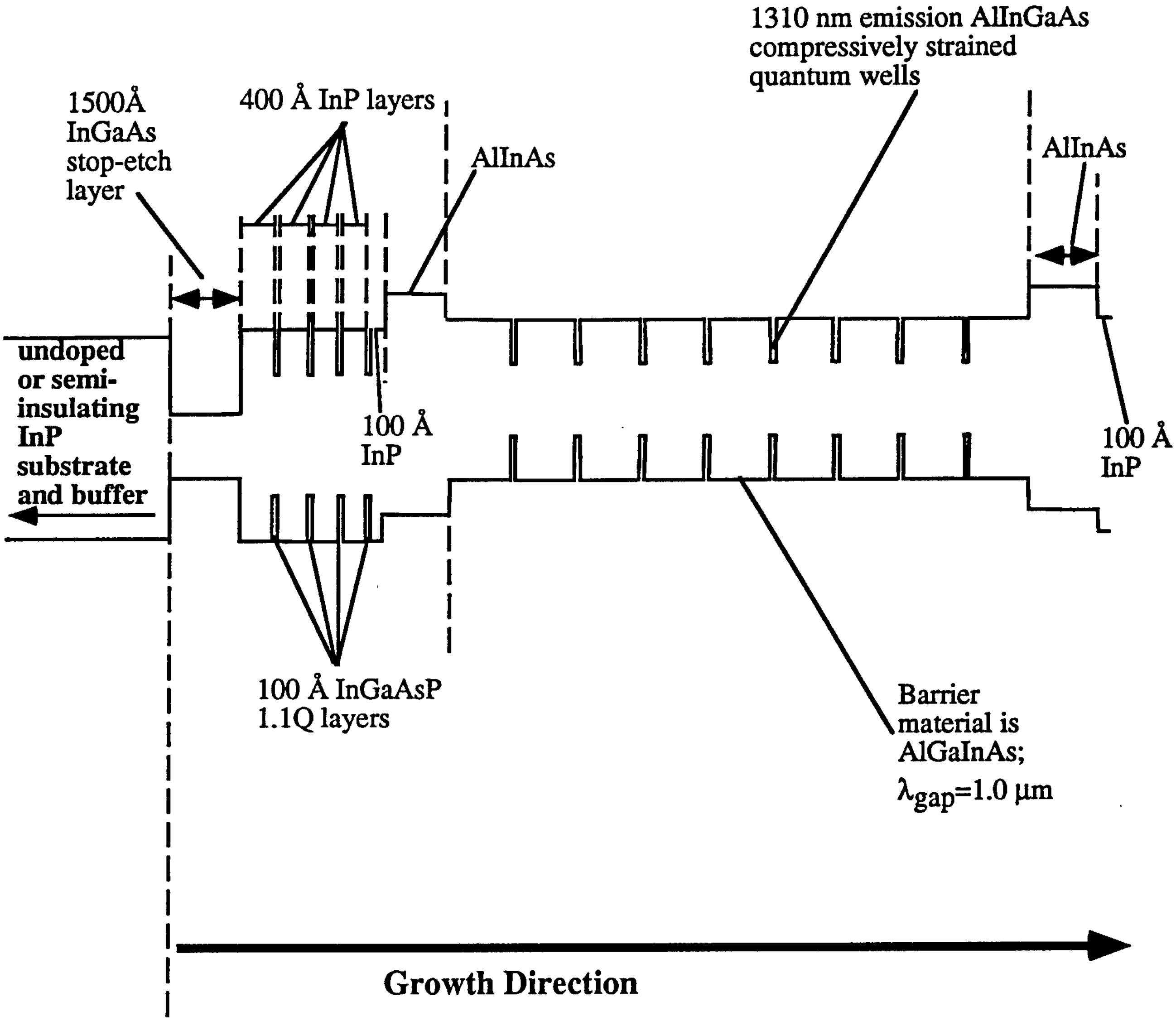

Figure 3.2: Epitaxial design for optically pumped 1300 nm VCSEL. The structure is pumped by an 850 nm VCSEL.