Quantum Well Lasers in Telecommunications

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Quantum well (QW) lasers are semiconductor lasers that use the special two-dimensional physical properties of very thin semiconductor layers in their light emitting regions to enhance their performance. The superior performance of the QW laser has made it the laser of choice for future lightwave communications systems. This paper deals historically with the concept of the QW laser by first looking in depth at its major antecedent, the bulk active diode laser. It then turns to the specific properties and advantages of the QW laser in modern optical communications systems, and studies the fabrication of QW lasers. Finally, the paper briefly explores future directions in QW laser research.

Introduction

Continued improvements to the semiconductor laser have been key to AT&T's progress in developing higher performance, lower cost lightwave transmission systems such as those described elsewhere in this issue. Progress on semiconductor lasers has not abated, and the QW laser, because of its superior performance, is expected to become the laser of choice for lightwave communication systems.

The QW laser was developed by Robert W. Dingle and C. H. Henry of AT&T Bell Laboratories in 1975.[1,2] Only in the last few years has it become a practical reality at the important lightwave transmission wavelengths of 1.3μm and 1.5μm. This is because of advances in the growth of uniform, thin (0.001 micrometer [μm] to 0.01μm) layers of $In_{1-x}Ga_xAs_yP_{1-y}$ on InP, and to a greater understanding of the electrical and optical properties of the QW laser and its requisite materials.[3]

The Bulk Active Diode Laser

To understand the basic concept and properties of the QW laser, it is useful to begin by considering the properties of its predecessor, what is usually called a "bulk active" diode laser.

Figure 1 shows a bulk active, single wavelength, distributed feedback (DFB) diode laser chip of the type used in today's lightwave systems. Small enough to fit comfortably inside the small letter "o," it appears as a dark speck of dust to the human eye. But viewed at high magnification, it incorporates considerable amounts of optical, electrical, and material physics, chemistry, and engineering.

Electrically, the bulk or uniform composition active laser behaves like a p-n junction diode. Typical laser chip dimensions are 250μm length, 500μm width, and 100μm height; however, all significant optical and electrical activity takes place in the small, centrally located stripe region whose typical dimensions are 250μm length, 1μm width, and 0.1μm height. This is called the *active* region, where recombining electrical carriers produces a region of optical gain.

The remainder of the laser's composite of materials mechanically, electrically, and optically supports the active region. The active material differs in composition from the surrounding material because it has a lower electronic bandgap energy and a higher refractive index. In addition, it is located at the diode's p-n junction. The active region's lower bandgap allows it to confine carriers injected across the p-n junction; this provides optical gain at a wavelength corresponding to its bandgap energy. At the same time, the higher refractive index causes the active

Panel 1. Acronyms in This Paper	
AsH_3	arsine
ASK	amplitude shift keyed
CW	continuous wave
DC	direct current
DFB	distributed feedback
dG/dn	differential optical gain per unit injected carrier
EDFA	Er-doped fiber amplifier
H_2	hydrogen
MO-CVD	metalorganic chemical vapor deposition
MQW	multiple quantum well
PH_3	phosphine
QW	quantum well laser
SEL	surface emitting laser
TE	transverse electric
TEM	transmission electron microscope
TM	transverse magnetic

region to form the core of an optical waveguide that confines emitted light.

Optical feedback is provided by the crystal's optically flat cleaved edges that act as mirrors. When optical gain is high enough to overcome the optical losses in the waveguide and mirrors, laser oscillations occur. The electrical current at which this occurs is called the *laser threshold current*: at injected currents higher than threshold, electrical current is converted into laser light. The typical 1.5µm communications laser achieves threshold at a current of about 10 milliamperes (mA), and can convert injected current to optical power above threshold at a 0.15 watts per ampere (W/A) efficiency rate.

Much of the evolutionary effort in diode laser technology has focused on fabricating the active region of light emitting material. For the laser to have a low threshold current and well-behaved laser characteristics, the active region must be as thin as possible to minimize the current needed for optical gain. Because of the limitations of past epitaxial growth techniques, the lasers in currently installed lightwave systems have active regions ~0.1µm thick. In this thickness regime, the active is thick enough—and the scattering times of the injected carriers are short enough—so the carriers do not effectively feel the bandgap difference of the "walls" that confine them to the active.

From an electronic energy standpoint, the active material behaves (i.e., has the same properties) as though it were infinitely large, with a continuum of energy levels in the conduction and valence bands, and the parabolic density of states depicted in Figure 2a. This is the "bulk active" regime. It has two distinguishing characteristics:

- Equal gain for either transverse electric (TE) or transverse magnetic (TM) polarizations of light in the waveguide.
- The presence of many injected carriers—at energies near the conduction and valence band edges—that do not contribute to the laser because the low density of states at these energies does not allow enough gain to permit lasing. These non-contributing states must be "filled" before lasing can occur between the higher energy states. This results in the need for higher injected current to achieve threshold.

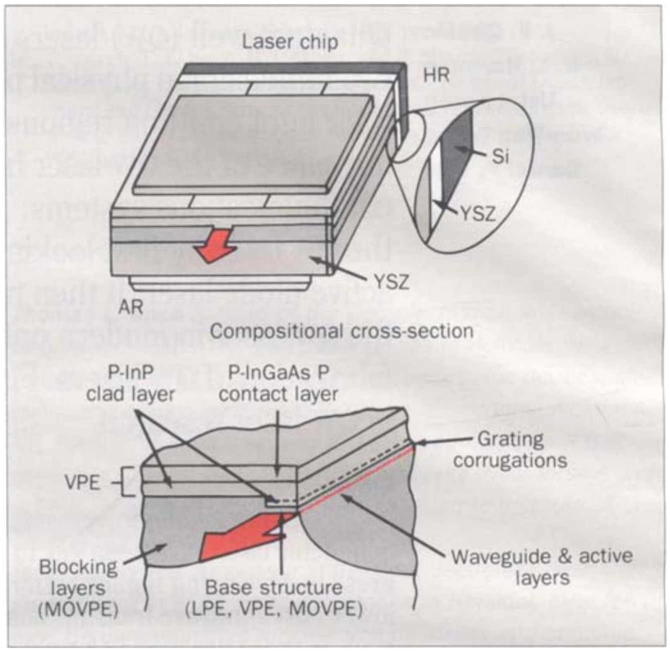

Figure 1. Schematic cross section of a single-wavelength $In_{1-x}Ga_xAs_yP_{1-y}/InP$ DFB laser diode. The "base structure" section corresponds to the active region of the laser.

The Quantum Well Diode Laser

At an active thickness of ~0.03µm—a region accessible with today's vapor phase or molecular beam epitaxial growth techniques—a remarkable change in

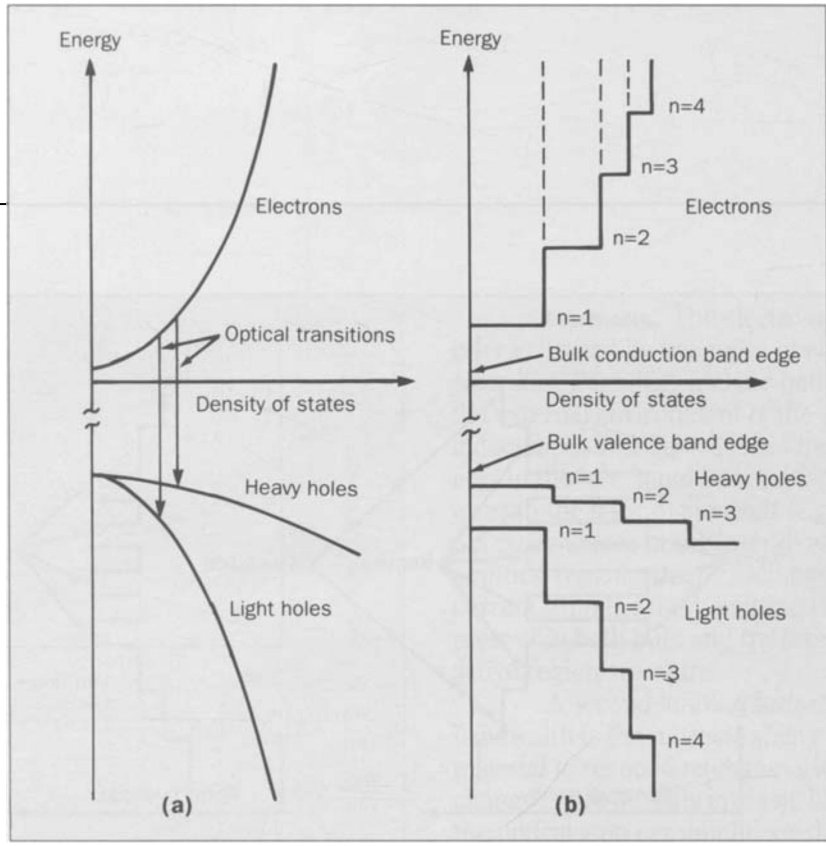

Figure 2. Density of states functions for (a) bulk active material and (b) quantum well material. Representative optical transitions are shown on the bulk case. With the quantum well, they are omitted for clarity.

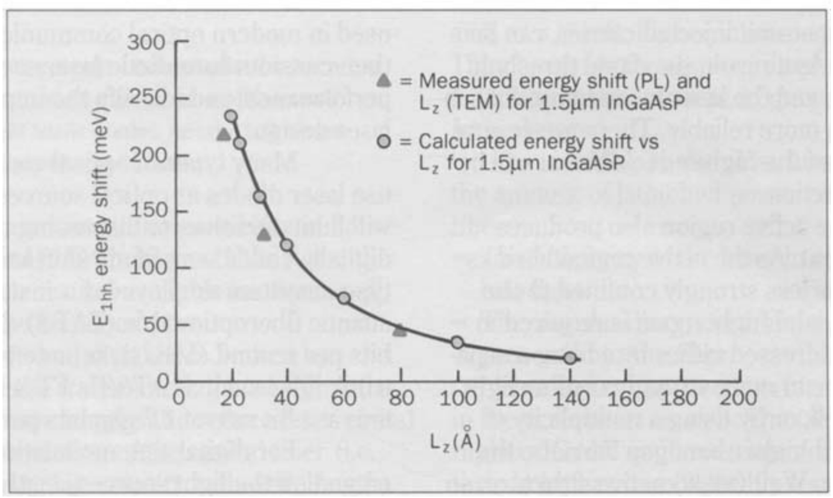

Figure 3. Theoretical energy shift of band edge luminescence from quantum well material as a function of well thickness.

material behavior occurs. Below this thickness, the carriers experience the effects of the confining bandgap "walls" or barriers above and below the active region. As a result, the energy levels in the conduction and valence bands break into discrete sub-bands (see Figure 2b), with stepped rather than parabolic density of states. Each step is associated with a different confined quantum state of the carriers (e.g., electrons, light holes, and heavy holes) in the thin active layer "well." Another consequence of this confinement—because the light and heavy hole valence bands are split—is the broken symmetry between TE and TM optical behavior. The heavy hole is primarily TE polarized, the light hole is primarily TM. The active region is described as a "quantum well" because of the quantum mechanical nature of the energy splitting in the active region "well." Figure 3 illustrates the effect of well confinement by showing the shift in transition energy of the lowest electron-hole recombination as a function of well thickness.

One effect of splitting the energies of the injected carriers and breaking the TE-TM symmetry is that injected current into the diode can be used more efficiently. Instead of pumping energy into unneeded carrier energy states (e.g., those near the band edges or that amplify the wrong polarization), only the desired states are pumped. In laser parlance, the "dG/dN," or

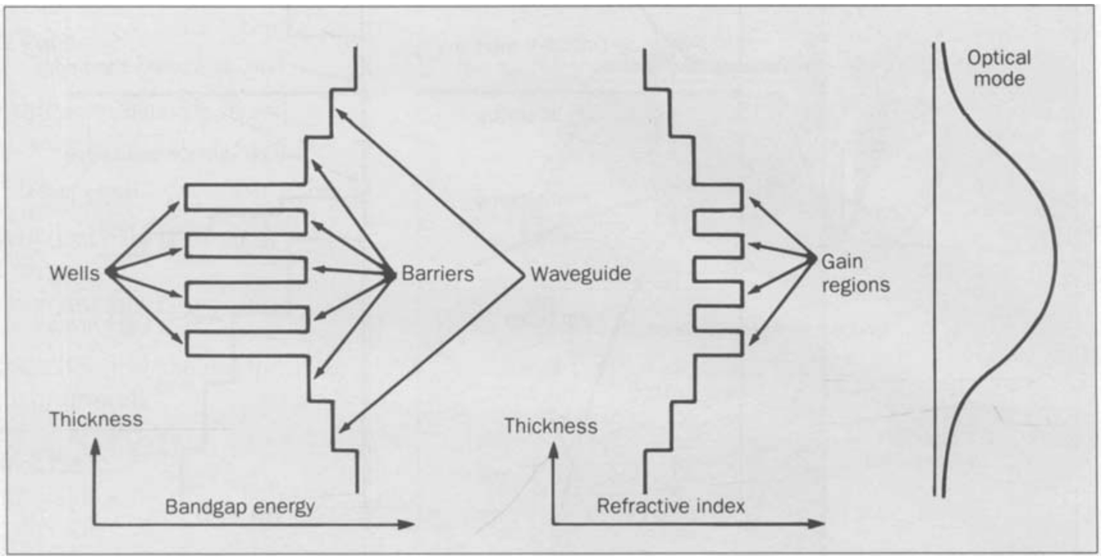

Figure 4. Schematic of a multi-quantum well (MQW) active layer structure. The vertical direction corresponds to thickness of the active region, and the horizontal shows the profile of material bandgap energy and refractive index. The structure allows for higher overlap of the optical field and gain region, and is often accompanied by additional waveguide layers.

differential optical gain per unit injected carrier, can be significantly increased. As a result, the diode threshold current can be lowered, and the laser made to oscillate in the desired polarization more reliably. There are several other beneficial effects of the higher dG/dN that will be discussed in the next section.

But thinning the active region also produces lower optical confinement. As the active region shrinks below 0.1μm, the light is less strongly confined to the quantum well structure, and higher gain is required to lase. This difficulty is addressed either by adding a separate waveguide structure to more strongly confine light around the quantum well, or by using a multiplicity of lower bandgap wells and higher bandgap barriers, the so called Multi-Quantum Well (MQW) active structure, so the optical overlap is increased (see Figure 4).

To summarize, a QW laser resembles a bulk laser in most respects. But the QW laser has a thin enough active region to show the effects of quantum confinement in its narrowest dimension. The consequences of this thinness are higher differential gain per injected carrier, and polarization selectivity. In the next section, we will discuss some benefits of these effects to communication laser performance, and present data illustrating the diferences between QW and bulk lasers.

Advantages of Quantum Well Lasers

To understand the superiority of a QW laser to a bulk active laser, we must first consider how lasers are used in modern optical communication systems. We can then consider how diode laser sources can limit system performance, and identify the improvements in a QW laser design.

Many types of optical communication systems use laser diodes as optical sources. For simplicity, we will limit ourselves to discussing the most common type: digitally coded, amplitude shift keyed (ASK). This is the type of system employed, for instance, in the first transatlantic fiberoptic cable (TAT-8) at a bit rate of 280 megabits per second (MB/s), or in terrestrial high capacity trunk lines such as AT&T's FT-series G lightwave system at a bit rate of 1.7 gigabits per second (GB/s).

For digital ASK, modulation is handled by turning on and off the light source (i.e., the laser chip) with digitally encoded drive current pulses. The digital information could include voice, video, or computer data. The resulting pulses of laser light are coupled to an optical fiber, and propagate long distances (tens to hundreds of kilometers) along the fiber before detection and decoding by an optical receiver. This method of optical communication is limited by three features of the transmitting laser.

- The bit rate (in pulses per second) at which information is transmitted is limited by the electo-optic bandwidth of the transmitting laser, i.e., its ability to transform short current pulses into short light pulses.
- The distance the signal may be transmitted through the fiber is limited by the launched power from the transmitting laser and the attenuation of the optical

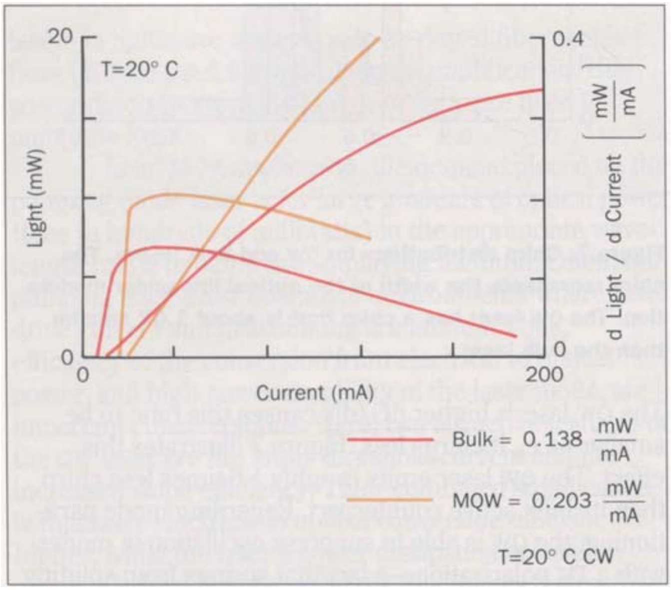

Figure 5. Comparison light-current characteristics for a QW and bulk laser. The light-current curves as well as their slopes are shown. The QW laser shows nearly 1.4 times higher slope efficiency than the bulk laser.

fiber (omitting for the moment the possibility of optical signal amplification). At the highest data rates, the pulsed electrical drive current available is often small, and thus may limit the launched power.

- The product of bit rate and distance is limited by the spectral width of the transmitted optical signal (i.e., the range of optical wavelengths the source laser emits) and the chromatic dispersion of the optical fiber (i.e., the variation in propagation velocity with wavelength). This limitation stems from the problem of having transmitted pulses smear and overlap during propagation through the fiber. Both the width of the individual laser lines (e.g., because of laser wavelength shift or "chirp" caused by the drive current pulses) and the tendency for the laser to oscillate, even briefly, on lines other than the desired one (often called "mode partitioning") are potential problems that limit system performance.

As mentioned above, system performance is often limited by source laser electro-optic bandwidth, launched power, and chirp. QW lasers offer improved performance in all these respects. We first consider the improvement in electro-optic bandwidth.

Bandwidth. The electro-optic bandwidth of a laser is limited by two types of effects. The first effect is *parasitics*. Parasitics include both limitations caused by the external environment of the diode laser (e.g., the inductances and capacitances from the wires that connect to the laser) and internal frequency-limiting structures in the laser diode itself (e.g., the presence of internal capacitances in the laser diode, unrelated to the light emitting region, which shunt away high frequency current from the light emitting region). Parasitics are present in both bulk and QW lasers, regardless of the active region structure.

A second limiting factor to laser electro-optic bandwidth is the intrinsic ability of the laser active material to respond to changes in drive current with changes in light. This intrinsic limitation is related to the optical gain per unit injected carrier, or dG/dN. QW lasers have, as we noted earlier, higher dG/dN values and, as a result, higher intrinsic frequency response. They have, for the same emitted optical power, roughly 1.7 times larger intrinsic frequency response than bulk active lasers.[4]

Launched Power. Two laser chip features affect the amount of launched power coupled to the optical fiber:

- The efficiency of the laser in converting current into light.
- The angular divergence of the beam of light presented to the fiber.

QW lasers offer improved performance over bulk lasers in these respects as well. The QW laser, because of its higher dG/dN and lower injected carrier density at threshold, has demonstrably less internal losses in its optical cavity. This results in a higher conversion efficiency from injected current to optical power, and a higher slope of the light versus current characteristic (i.e., "slope efficiency"). Figure 5 shows comparison light-current (LI) characteristics for a QW and bulk laser. Note that the slope of the QW laser LI is 1.4 times higher than the bulk laser LI.

QW lasers—again, by virtue of the higher dG/dN—can also be made to exhibit narrower beam angular divergences for better coupling into optical fiber. The higher dG/dN value allows the laser designer to slightly relax the tight coupling normally required between the active region (typically 0.01 to 0.1μm in thickness) and the optical waveguide mode (typically

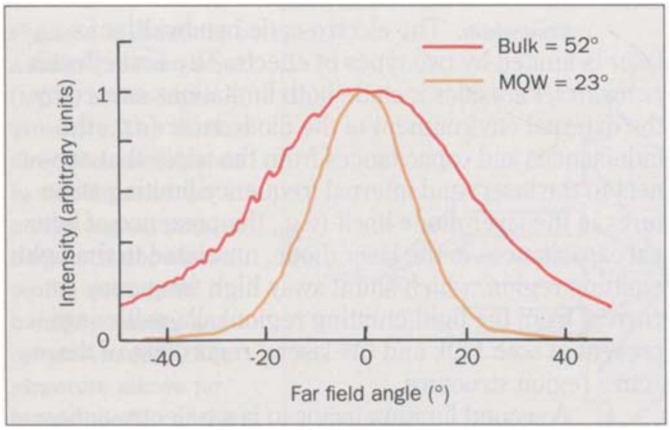

Figure 6. Representative perpendicular far-field profiles for QW and bulk lasers. The QW laser has 2 times smaller beam divergence.

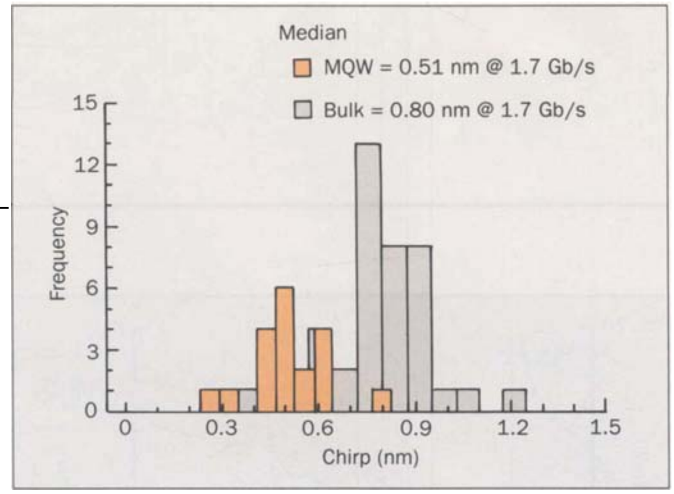

Figure 7. Chirp distributions for QW and bulk lasers. The chirp represents the width of the optical line under modulation. The QW laser has a chirp that is about 1.6X smaller than the bulk laser.

0.5μm). This looser coupling permits a spatially expanded optical mode and, because of the wave nature of light, a narrower angular divergence for the emitted beam. Figure 6 shows typical far-field patterns in the perpendicular direction—the direction in which the active region is thinnest—for a QW and a bulk laser. The QW laser here offers a nearly 50 percent reduction in far field angular width.

One other improvement a QW laser can offer—also by virtue of its higher dG/dN—is reduced threshold current for lasing. But a designer might choose to sacrifice the lower threshold current for the sake of some other property of the device, because threshold current is not directly related to communication system performance.

As mentioned earlier, it is important that the pulsed ASK laser source be highly monochromatic so the output pulses will spread minimally in time as they pass through the wavelength dispersive fiber. As a result, it is particularly important for the QW to reduce wavelength laser chirping (i.e., the shift in time of the laser wavelength caused by the drive current pulses), and to reduce the laser's tendency to oscillate briefly in other lines (mode partitioning). The QW can improve on both aspects when compared to bulk active lasers.

Chirping. The chirping aspect of laser operation is related to the ratio between the change of refractive index and change of gain of the laser medium. Both changes are caused by the modulating current pulse. The QW laser's higher dG/dN causes this ratio to be smaller—i.e., it chirps less. Figure 7 illustrates this effect. The QW laser emits roughly 1.6 times less chirp than its bulk active counterpart. Regarding mode partitioning, the QW is able to suppress oscillation in modes with a TM polarization—a fact that springs from splitting the light and heavy hole states. And because of its looser optical coupling, the QW can achieve tighter control over emission in higher order optical waveguide modes.

Figure 8 illustrates the QW's ability to suppress emission in TM modes. Note that the optical gain of a QW laser is contrasted with a bulk laser. Observe, too, that the TE polarization (i.e., electric field parallel to the wide dimension of the active layer) is dominant, and that the TM polarization (magnetic field parallel to the wide dimension of the active layer) is strongly suppressed and shifted in wavelength. In the bulk active case, the TE and TM polarization gain peaks are at the same wavelength, and there is no gain difference between them.

The same mechanism that allows the QW laser to exhibit lower chirp under modulation also allows it to show narrower linewidths in continuous-wave (CW or DC) operation on a single cavity mode. This effect makes the QW laser attractive as a compact optical source for systems needing clean, narrow optical lines. Such systems would include externally phase-modulated coherent detection systems.

QW Laser Benefits To Other Lightwave Applications

QW lasers have uses and benefits in addition to those as transmission sources in digital ASK systems. One example is their use in analog amplitude modulated systems, which experience most of the benefits outlined above for digital ASK systems.

Another, newly emerging, use of semiconductor lasers in lightwave systems is in Er doped fiber amplifiers (EDFAs) used for optical signal amplification. High power diode lasers at 1.48μm or 0.98μm are used to pump the EDFA.

In an EDFA application, the demand placed on the pumping diode laser is for large amounts of optical power (tens to hundreds of milliwatts) in the appropriate wavelength range to pump the amplifying medium. Often, the pumping laser must operate in environments where laser drive current and heat sinking are limited. Thus, efficiency of the conversion from electrical to optical power, and high power capability of the laser diode, are important considerations. Here, two attractive features of the QW laser are the lower threshold current and the increased slope efficiency. Their combined significance is that laser electrical to optical conversion efficiency is higher, while the laser's power dissipation is smaller.

A third feature of the QW that makes it attractive in this context is the low internal loss: almost 3 times lower than in a bulk active laser. The low loss in the QW structure means the laser chip can have a longer cavity length than it would in the bulk active case. This allows the injected current and the dissipated heat to be spread over more surface area. The result is a lower series resistance that increases the conversion efficiency even more, and a lower thermal impedance that reduces laser temperature and allows higher optical power output. These features of the QW laser have been used, for example, to fabricate high power laser/traveling wave amplifier combinations.[5]

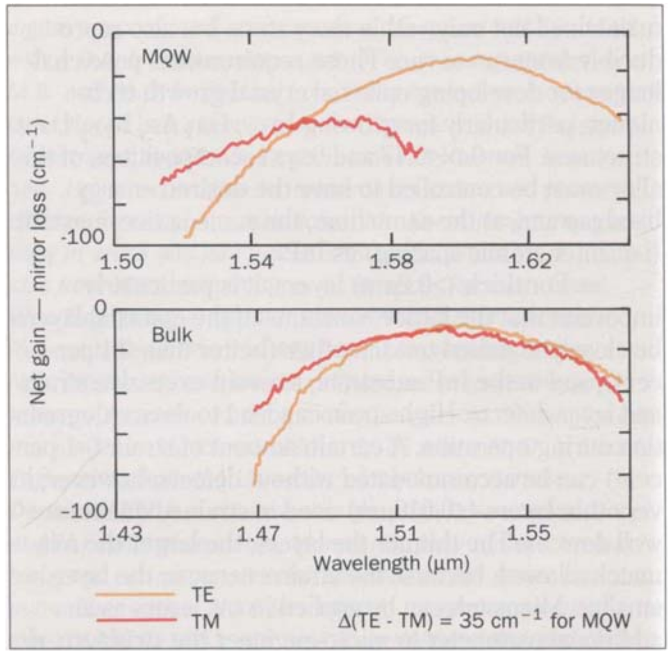

Figure 8. Gain spectra for QW and bulk active lasers. The QW laser exhibits a splitting of the TE and TM mode gain peaks and a suppression of the TM mode by about 35 cm^{-1}. The bulk laser shows virtually identical gain spectra for both TE and TM polarizations.

Quantum Well Laser Design Considerations

To achieve the optimum QW laser characteristics for a given application requires improved growth and process techniques, and careful design of the quantum well structure. Because of the relationship between laser wavelength and active thickness, the active thickness must be tightly controlled by the crystal growth process to produce lasers with the proper emission wavelength. Control is required over the QW crystal growth process down to a few atomic layers. High temperature processing of the quantum well structure during laser fabrication also must be limited because, at high temperatures, the individual atoms forming the wells and barriers can interdiffuse and change the QW structure's properties in undesirable and unpredictable ways. Careful design of the QW structure is necessary because the stepped density of states in the quantum well limits the maximum optical gain in the well within a given sub-band. This causes the QW optical gain to saturate more quickly with injected carrier density than it does in a bulk active laser. The result is that a poorly designed QW laser can be overly temperature sensitive, operating with low threshold current at room temperature but unable to operate at temperatures much above it. This effect can be compensated for by adding more wells, or by increasing optical confinement to the well structure, thus reducing the threshold gain per well. But there will be some cost in terms of the other desirable QW properties.

Fabricating Quantum Well Lasers

Quantum well structures require layer thicknesses as small as 0.02μm (8 monolayers) and interfaces as abrupt as one monolayer. Moreover, in manufacturing where multiple large diameter single crystal InP substrates are used, the layer thicknesses, interface abruptness, and material composition uniformity must be maintained not only within the wafers, but also reproducibly from run to run. These requirements pose challenges for developing epitaxial crystal growth techniques, particularly for growing $In_{1-x}Ga_xAs_yP_{1-y}$ laser structures. For $0 \le x \le 0.47$ and $0 \le y \le 1$, compositions of this alloy must be controlled to have the desired energy bandgap and, at the same time, the same lattice constant (i.e., inter-atomic spacing) as InP.

For thick (≥0.2μm) layers, it is particularly important that the lattice constants of the epitaxial layers be closely matched to each other (better than 0.1 percent), and to the InP substrate, to avoid excessive strain and layer defects. High strain can lead to device degradation during operation. A certain amount of strain (~1 percent) can be accommodated without defects, however, in very thin layers (≤0.015μm) used in strained quantum well devices. The thinner the layers, the larger the mismatch allowed, because the strain energy in the layer is smaller. Mismatch can be applied in QW lasers as an additional parameter to micro-engineer the structure of the well sub-bands and improve the laser characteristics.

There are several possible techniques for epitaxial growth of diode laser structures; they have been described in a previous issue of the *AT&T Technical Journal*.[6,7] However, for preparing $In_{1-x}Ga_xAs_yP_{1-y}/InP$ QW structures, metalorganic chemical vapor deposition (MO-CVD) appears to be particularly suitable for manufacturing. Liquid phase epitaxy (i.e., growing layers from a liquid melt) lacks the thickness control required for very thin layers. Molecular beam epitaxy (a vacuum technique using atomic beams (e.g., Ga and In) and molecular beams (e.g., As_4 and a P_4) evaporated at high temperatures from solid elemental sources) lacks the precise and reproducible control of As_4 and P_4 flux ratio needed to grow lattice matched $In_{1-x}Ga_xAs_yP_{1-y}$.

In MO-CVD, the growth of epitaxial layers occurs by the pyrolysis of vapor-phase mixtures of metalorganic compounds such as trimethylgallium and trimethylindium, and hydrides such as arsine (AsH_3) and phosphine (PH_3) in a flowing hydrogen (H_2) atmosphere. The substrate is held at 630° C. Precise, reproducible control of the various gas flows, and thus of the deposited material, is achieved by electronic mass flow controllers. In growing QW structures, the different gas streams are switched in and out of the growth chamber by using electronically controlled 2-way mechanical valves. The entire process, gas flows, switching, and substrate temperature is typically supervised by a real-time computer process control system.

Future Directions

An interesting area of current research is surface emitting lasers (SELs) that use high-optical-gain QW stacks sandwiched between epitaxial multilayer reflectors to form a diode laser that emits light normal to the surface of the crystal, rather than from a cleaved edge.[8] SELs suffer from the short optical path between the reflectors. This short path makes extremely high demands on the QW's optical gain. Consequently, today's SEL is low power and temperature sensitive. However, further research and development could make it a practical laser device.

The success of QW lasers naturally prompts questions about active regions that are "small" in two or three dimensions. Both these possibilities ("quantum wires" and "quantum dots") are being examined theoretically, and offer possible performance improvements.[9] Regarding quantum dots, the spectra and energy levels are discrete and similar to those of isolated atoms in gases or rare earth ions in insulating crystals. Rigorous investigations of these types of materials await new breakthroughs in crystal growth and processing techniques.

A final possibility is that materials such as silicon, that do not normally emit light because of unfavorable energy band structures, can be coaxed into making efficient light emitters through quantum confinement effects provided by quantum wells, wires, or dots.[10] A consequence is that materials other than III-V's may become important for lasers in the future.

Acknowledgment

We wish to acknowledge the help of L. J. P. Ketelsen, V. R. McCrary, and S. J. Wang of AT&T Bell Laboratories for providing the data and figures for this article.

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(Manuscript received July 24, 1991)

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