NEW PbSnTe HETEROJUNCTION LASER DIODE STRUCTURES WITH IMPROVED PERFORMANCE*

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INTRODUCTION

In this article, we will summarize several of our recent advances in the state-of-the-art of lead tin telluride double heterojunction laser diodes, advances which make significant strides in increasing the operating temperatures of these devices and in controlling the modal quality and tunability of their output. CW operation to 120°K and pulsed operation to 166°K with single, lowest order transverse mode emission to in excess of four times threshold at 80°K have been achieved in buried stripe lasers fabricated by liquid phase epitaxy in the lattice-matched system, lead-tin telluride-lead telluride selenide [1,2]. At the same time, liquid phase epitaxy has been used to produce PbSnTe distributed feedback lasers with much broader continuous single mode tuning ranges than are available from Fabry-Perot lasers [3].

The physics and philosophy behind these advances is as important as the structures and performance of the specific devices embodying the advances, particularly since structures are continually being evolved and the performance continues to be improved. There is art in any science, but as we will demonstrate, there is a tremendous amount of science to be applied to Pb-salt tunable diode lasers, and where this is done, their performance can be predicted, tailored, and reproducibly controlled. Most importantly, their performance can be dramatically enhanced.

HIGH TEMPERATURE OPERATION

Achieving higher temperature operation of laser diodes requires both that the threshold current density be reduced at higher temperatures, and that the total threshold current be reduced. The former goal can be achieved by increasing the internal radiative efficiency of the lasing semiconductor, and by using a double heterojunction geometry to increase the efficiency with which stimulated recombination of the electrically injected carriers occurs. The latter goal requires development of a viable stripe geometry device achieving good lateral current confinement.

The double heterostructure was introduced to PbSnTe in the early 1970's [4,5] but the performance of the early devices was no better than that of diffused lasers. As we shall discuss first, this was due to the large degree of lattice mismatch inherent in these early devices which used PbTe substrates and confinement layers.

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Elimination of Lattice Mismatch

a. Role of Lattice Mismatch

Heterostructure devices make elegant use of semiconductor epi-layers with different energy gaps to achieve specific objectives, and laser diodes are an excellent example of such devices. Nonetheless, if these layers do not have nearly identical lattice paramerers, a, an excessive number of defects will exist at the heterojunctions and in the bulk of the layers near them, and the desired performance will be degraded by these defects.

The surface morphology of mismatched epi-layers will also, in general, be much poorer than that of lattice matched layers. While this effect has not been quantified, it clearly has an important influence on the modal properties of the structures. The effect of mismatch created defects can be quantified in terms of an interface recombination velocity, s_v. This is in addition to the bulk lifetime, τ, which also can be affected by the mismatch. In the active region of a laser diode, which consists of a thin bulk layer of width d bounded by two heterojunctions, any excess minority carriers will see an effective lifetime which is lower than τ and decreases with increasing s_v and decreasing d, [6,7]

$$\tau_{eff}^{-1} \simeq \tau^{-1} + 2s_v/d$$

By measuring τ_{eff} on many devices with different d, one can measure τ and s_v [7,8]. By also doing this measurement on samples with different amounts of mismatch, $\Delta a/a$, the dependence of s_v on mismatch can be found. In PbSnTe/PbTe, we find [9]

$$s_v = 2.9\text{x}10^7\ \Delta a/a \text{ cm/sec}$$

In a laser diode, the threshold current density is directly proportional to d/τ_{eff}, or in the limit of d going to zero, to $2s_v$ [10].

In traditional PbSnTe/PbTe DH laser diodes the mismatch can be very large and s_v can easily exceed 10^5 cm/sec. In a typical device, $\tau = 4$ nsec, $d = 1$ µm, and $s_v = 10^5$ cm/sec, so $\tau_{eff} = 0.8$ nsec and the threshold is five times higher than it would be if $s_v = 0$. Moreover, recent calculations have shown that the radiative lifetime should exceed 100 nsec [10] so the bulk lifetime, τ, is much lower than should be achievable with, in part, elimination of the mismatch.

b. Lattice Matched Systems

Except for the AlGaAs/GaAs combination, and to a lesser extent AlGaSb/GaSb, there are no lattice-matched binary/ternary combinations. In the III-V's, where it is to date only practical to grow binary substrates, it has thus been necessary to go to quaternary compounds such as InGaAsP to find a lattice-matched heteroepitaxy system. (InP is used as the substrate in this case.) In the IV-VI's we can grow bulk ternary substrates and it is possible to form lattice-matched heteroepitaxy systems from the ternaries. One such combination, which was first suggested by Walpole et al. [11], is PbSnTe and PbTeSe. Lead telluride selenide has the wider bandgap of this combination. This system can be used to cover the same bandgap range as PbSnTe. Another system covering a similar range is PbSSe (wider gap) and PbSnTe. A system covering the 4-6 µm range would be PbSTe (wider gap) and PbSSe. In all of these systems, the energy gap difference, and therefore the effectiveness of the heterostructure, decreases to zero as the compositions used approach the common binary, i.e. PbTe, PbSe, and PbS, respectively, in the three systems discussed. This is true in any lattice-matched system, of course, but is worth remembering, because it is important for short wavelength lasers.

c. Performance of Lattice-Matched Structures

Lead telluride selenide was chosen as the substrate material by Walpole et al. because of its wider bandgap, but it is difficult to work with (etch, polish, cleave, etc.), however, and perhaps for this reason, they saw little or no improvement in thresholds of their devices [12]. By using PbSnTe substrates we have overcome the problems of substrate preparation and end mirror cleaving, and have seen the anticipated threshold reductions in lattice-matched lasers[1].

The basic lattice-matched heterostructure begins with a p-type PbSnTe substrate upon which a p-type PbTeSe lower confinement layer, a 0.5-1.5 μm thick PbSnTe active layer, and an n-type PbTeSe upper confinement layer are grown. As with conventional lasers, ohmic contacts are then applied to both sides of the wafer, it is cut into bars with a wire saw, and individual lasers are cleaved from the bars. The 80°K threshold of these lasers is twenty times lower than that of comparable PbSnTe/PbTe lasers ($\lambda \simeq 10$ μm) and pulsed operation has been achieved to 166°K [1]. In addition to these dramatic operating improvements, it is also found that the surface morphology, i.e. uniformity and smoothness, of the heterostructures, is much better than that of mismatched structures. In fact it typically equals that of the original substrate. Furthermore, the mode structure of even these broad area Fabry-Perot lasers is, qualitatively, cleaner than that of earlier structures.

Reduction of Total Current - Stripe Geometries

To optimize high temperature CW operation, a viable stripe geometry providing lateral current confinement is required. As will be discussed further below, it is also desirable for the structure to provide modest (as opposed to strong) lateral optical confinement to help achieve single mode output.

Two stripe techniques which have been used on Pb-salt lasers are the diffused stripe homojunction [13] and the selectively grown molecular beam epitaxy (MBE) mesa heterojunction stripe [14]. The first structure provides no optical confinement, while the latter provides too much. The latter also suffers because the thickness of the epi-layers tends to vary across the width of the stripe, and most importantly, the lasers often have very high excess currents and thus much higher threshold current densities than wide area lasers.

We initially investigated insulator-defined stripe contact and then etched mesa DH lasers. The former was unsuccessful because there is too much lateral current spreading through the low sheet resistance epi-layers and thus insufficient current confinement to yield any significant reduction in total threshold current. Interestingly, however, such lasers did show cleaner mode structure than broad area contact lasers. The etched mesa lasers showed excess junction leakage (discernable as a temperature invariant threshold at very low temperature [10]), which appeared to be occurring at the exposed junctions along the mesa walls. Anodization was partially successful in reducing this leakage but the technique is not yet controllable enough to yield consistently repeatable results. The etched mesa has the inherent disadvantages of very strong lateral optical confinement and a very narrow top contact, too, so in light of the leakage problem, it seems most reasonable to abandon it at this time in favor of more generally attractive structures.

The buried mesa has recently received a great deal of attention from the III-V community because it offers strong carrier confinement and modest optical confinement in a relatively simple and easily controlled structure [15]. We have recently been successful in fabricating buried mesa DH lasers in the PbSnTe/PbTeSe system [2]. These first devices have low total threshold currents, 60-70 mA at 80°K, and emit over one hundred microwatts of power in a single, lowest order transverse mode at 80°K ($\simeq$ 9 μm). They have been operated CW to 120°K while mounted in a simple pressure contact test jig (from which they could be demounted). Modal properties of the devices will be discussed somewhat later.

The buried mesa lasers are fabricated by first growing a p-type PbTeSe layer and a PbSnTe active layer on a PbSnTe substrate. The wafer is then removed from the liquid phase epitaxy (LPE) system and photoresist stripes are patterned on the surface using standard photolithographic techniques. Mesas are next etched into the surface through the active layer and into the first epi-layer using the photoresist stripes as a mask. Then the surface is cleaned and the wafer is returned to the epitaxy system, where a final n-type (undoped) PbTeSe layer is grown over the entire surface of the wafer. Contacts are then applied to both sides of the wafer, the individual stripes are separated with a wire saw, and lasers are cleaved from the bars [2].

The present buried mesa lasers rely upon the fact that the current density across the PbTeSe-PbSnTe diode heterojunction in the stripe mesa should be much larger than that at the PbTeSe homojunction covering the rest of the device. Thus even though the area of the homojunction is 50 times as large as the heterojunction, most of the current should go through the stripe, i.e., the active region. In practice this was only partly successful, and the threshold indicated there was only partial current confinement. The reason for this is not yet fully understood, but it is perhaps due to too low a doping level in the upper n-type layer resulting in too large a sheet resistance in that layer. It may also be simply that what is needed is a structure wherein a truly blocking region is provided on either side of the mesa stripe. Such a structure will require the growth of additional layers and is currently under consideration.

Further Reduction in High Temperature Threshold

To achieve high temperature (> 100°K) operation of Pb-salt lasers, not only must the low temperature threshold current density and total current be decreased as has been discussed, but the rate of increase in threshold with increasing temperature must also be reduced. This is an obvious statement but it is worth making because the high temperature behavior of Pb-salt lasers is dominated by a factor which has been ignored in the present discussion thus far, and which is often neglected, i.e. the active layer doping level. The active layer must be very heavily doped in Pb-salt lasers [4c], on the order of 10^{18} cm^{-3}, because the high temperature threshold is directly proportional to the minority carrier density necessary to achieve population inversion in the active region [10], and this density decreases with increased doping levels [4c]. As the doping level is increased, however, at some point the minority carrier lifetime must surely decrease, and the free carrier absorption losses must increase; both effects will work to increase the threshold. The optimum active region doping level is, in fact, unknown, and this is perhaps one of the most important questions remaining to be answered. It should be given immediate attention. At the same time the control of doping levels and of dopants in the grown epi-layers must also be studied much more. It is not sufficient to know what the optimum doping level is because one must also be able to produce layers having the required doping profile.

As regards the buried mesa diodes mentioned above, the active region doping level was relatively low, and the rate of increase of their threshold with temperature was considerably more rapid than has been seen in broad area devices with more heavily doped active regions, and there is clearly room for improvement.

SINGLE MODE OUTPUT

A laser cavity like that found in a diode laser can have three types of families of modes: normal transverse modes, modes related to the portion of the cavity normal to the junction plane; lateral transverse modes related to the cavity in the junction plane but perpendicular to the direction of propagation; and longitudinal or axial modes arising from the long dimension of cavity in the junction plane. The normal transverse modes are controlled in the double heterojunction laser by making the active region sufficiently thin. The lateral transverse modes can be controlled by using a suitable stripe structure. The longitudinal modes are determined primarily by the spacing of the end mirrors in a Fabry-Perot laser, or the grating period in a distributed feedback laser. We will assume the active region can readily be made sufficiently thin so that the laser operates only in the lowest order normal lateral mode, and we will then look first at controlling the transverse lateral modes, and then the longitudinal modes.

Control of Transverse Modes

Mode control in the plane of the junction transverse to the direction of propagation can be achieved by providing a refractive index step in the plane either by passive, built-in means or by active, induced means. In the latter, there is transverse guiding or confinement only in the presence of an excitation current, i.e. gain guiding. The resulting index step is hard to control, however, and varies with the operating conditions.* A built-in index step is

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* In an oxide defined stripe contact laser, gain guiding would be the primary transverse confinement mechanism.

more desirable and in fact should be large enough to dominate over any gain induced step that may potentially exist.

On the other hand, there is a distinct advantage in keeping the index step as small as possible. The smaller the index step, and thus, the weaker the guiding, the wider the guide can be and still support only the lowest order mode. If the index step is large, as is the case in an etched mesa structure, the stripe must be extremely narrow to ensure operation only in the lowest order transverse mode. In addition to being easier to fabricate, a wider laser will have a much higher output power than a very narrow one.

The transverse index step is greatly reduced in the buried mesa laser structure described earlier and those lasers do indeed operate in the lowest-order transverse mode up to four times threshold [2]. This has been confirmed by near and far field measurements of the emission, which showed one symmetrically shaped emission peak. Above four times threshold evidence of a second, higher order transverse mode family is seen although the emission remains substantially single mode to six times threshold.

The present buried mesa lasers have active regions 1.5 μm thick, and mesas 5 μm wide. If the active region is reduced to 0.5 μm thick, still wider mesas can be used. Nonetheless, the transverse index step is still larger than necessary to dominate over gain guiding and even wider stripes could be used if the guiding was weaker. A possible solution may be the incorporation of an additional, smaller index step within the buried mesa, possibly in the spirit of the channeled substrate planar (CSP) geometry lasers [16]. With such a combination our calculations indicate that stripe widths of 25 to 30 microns are practical. Fabricating such a device will require additional development of the LPE growth technology, however, and other solutions are also being explored.

Control of Longitudinal Modes

a. Role of Transverse and Lateral Modes

The importance of transverse mode control to the achievement of single mode operation in laser diodes has only recently been understood, but it is now generally accepted that a device that is constrained to operate only in one transverse mode (typically this is the lowest order mode) will oscillate over a broad range of drive currents in only one (longitudinal) mode. We can easily obtain lowest order normal transverse mode operation of a DH laser but unless a suitable stripe is used, there will be many lateral transverse modes, and there is a family of longitudinal (Fabry-Perot) modes associated with each transverse mode. Thus, while in a homogeneously broadened laser like a diode laser, one longitudinal mode in each family will dominate when operating well above threshold; there will still be many modes in the output because there are many transverse modes. Eliminating all but one transverse mode eliminates all but one family of Fabry-Perot modes, and leads to single mode output. Consequently, the key to obtaining a single longitudinal mode output, i.e. truly single mode output, lies in achieving operation in only the lowest order transverse mode.

b. Distributed Feedback

As was just discussed, one longitudinal mode in each transverse mode family will dominate and that mode is the one nearest the peak of the gain curve. As the junction temperature of the laser is changed, i.e., as it is tuned, the gain curve shifts and thus the preferred longitudinal mode may change and mode hopping may occur. This hopping will be frequent in the case of a Fabry-Perot (FP) laser where the longitudinal modes are closely spaced.* The spacing of the cavity modes can be increased, and thus the incidence of mode hopping decreased, by shortening the laser, but this also increases the threshold (which varies as 1/L) and is thus a clear compromise solution.

Another solution is to replace the Fabry-Perot end-mirror cavity by a distributed cavity formed by making a weak periodic variation in refractive index within the active region in the direction of the propagation of the light. Such a distributed feedback (DFB) cavity also has a family of closely spaced modes but the modes away from the two nearest the Bragg frequency of the periodic variation or "grating" have much higher thresholds and there is strong discrimination against them. Thus, a DFB laser will lase in a single mode, the near-Bragg mode nearest the gain peak, over a much wider tuning range than an FP laser will before mode hopping occurs. On the other hand, the DFB laser will only lase at those temperatures for which the gain curve overlaps the Bragg frequency, whereas there are always modes that overlap the gain curve in an FP laser.

We have successfully fabricated PbSnTe DFB lasers by liquid phase epitaxy and observed unusually clean, single mode emission spectra continuously tunable over a range in excess of 20 cm^{-1} (0.33 μm) centered about 780 cm^{-1} (12.8 μm) at an average rate of 1.2 $cm^{-1}/°K$ from 9°K to 26°K.

The DFB lasers were produced by LPE growth of PbSnTe (1.5 μm thick) and PbTe (0.5 μm) layers directly on a 0.79 μm period corrugation ion milled into a PbTe substrate, and had a 25 μm wide insulator defined stripe contact extending over 400 μm of their overall length of 710 μm. Fabry-Perot modes were thus eliminated by providing an unpumped absorbing region on one end of the device; the end of the absorbing region was also saw-cut at an angle of approximately 30° to the stripe axis to further reduce FP reflections.

These DFB lasers are unique in that they are fabricated by liquid phase epitaxy and in that the feedback corrugation is placed within the active region of the device and is produced before, rather than after, the growth of the active layer. The tuning rate and range, and the cleanliness of the mode spectrum and the degree of single mode operation of these devices are superior to previously reported PbSnTe DFB lasers [17]. The full operating range of these devices is in fact still unknown because they were already operating at the lowest temperature and even broader tuning ranges may be possible.

These DFB lasers had moderate threshold 3.6 kA/cm^2 (pulsed). While the

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*The mode spacing is λ^2/nL, where λ is the lasing wavelength, L the cavity length, and n the index of refraction.

output power vs. current relationship is not completely free of kinks, substantially single mode operation can be obtained over the entire operating range and to over 10 times threshold. Weaker modes can at times be seen in the spectrum, however, which indicates that the transverse modes are not adequately suppressed by the stripe contact.

While these DFB lasers clearly demonstrate the merit of this structure, they were not fabricated in the lattice matched system described earlier nor was the mesa stripe employed and thus there remains much room for improvement. On the other hand, the technology for fabricating micron period corrugations and the stripe mesa technology are both sufficiently new that it is felt that the immediate emphasis should be placed on fully developing those technologies, after which their combination to produce optimal DFB lasers will be relatively straightforward.

CONCLUSIONS AND FUTURE PRIORITIES

The recent developments described above demonstrate the value of using sophisticated device geometries to improve the performance of Pb-salt laser diodes. It should be clear, furthermore, that only through the use of heterostructures and stripe geometry devices with built-in index steps can the goals of high temperature CW operation and single mode, low noise emission be reproducibly achieved. To fabricate such structures requires the use of epitaxial techniques and of more complex processing sequences than are commonly used with Pb-salt devices at present, but the gains to be realized are tremendous.

With each new solution to yesterday's problems, and with each device refinement, device performance is improved but new limitations are encountered which, if overcome, promise still better performance. With Pb-salt lasers, the most important immediate goal remains the perfection of the stripe geometry, single mode device in a lattice-matched system. While nothing has been said in this presentation about the impact of this on emission noise, it is expected that such devices will have much lower noise, and determining if this is indeed the case will be the next question to answer. Beyond that the most important basic issues before us appear to be controlling and optimizing doping profiles in devices; determining and minimizing the role of defects and impurities in limiting the internal radiative recombination efficiency; understanding the limitations on laser output power at high pumping levels; and understanding sources of, and solutions for, noise in the output of these lasers.

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