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Although an ultimate goal of this work is to achieve long term reliable laser operation of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures (QWH's), or similar III-V QWH's, grown on Si, this has proven to be a formidable enough problem that to the best of our knowledge no one has exceeded the results we reported in 1987 and 1988. This problem is of such dimensions that it may not be solved for as much as 10 years, or even more All we know so far is that continuous (cw) 300 K $Al_xGa_{1-x}As$-GaAs QWH lasers can be grown on Si,

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III-V SEMICONDUCTOR QUANTUM WELL LASERS AND RELATED OPTOELECTRONIC DEVICES ON SILICON

REPORT NO. 1

N. Holonyak, Jr./K. C. Hsieh/G. E. Stillman
June, 1989

U.S. ARMY RESEARCH OFFICE
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I. INTRODUCTION

Although an ultimate goal of this work is to achieve long term reliable laser operation of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures (QWH's), or similar III-V QWH's, grown on Si, this has proven to be a formidable enough problem that to the best of our knowledge no one has exceeded the results we reported in 1987 and 1988.[1-6] This problem is of such dimensions that it may not be solved for as much as 10 years, or even more All we know so far is that continuous (cw) 300 K $Al_xGa_{1-x}As$-GaAs QWH lasers can be grown on Si,[1-5] and that, indeed, the heat sinking of an $Al_xGa_{1-x}As$-GaAs QWH laser on Si is better than a similar laser on a GaAs substrate.[6] Nevertheless, the problem of growing better versions of these devices (i.e., long-lived high performance cw 300 K lasers on Si) has run into the fundamental issue of the large GaAs-Si lattice and thermal expansion mismatch, and hence the built-in difficulty in reducing the defects guaranteed by mismatch. Accordingly, as much as we have worked further on the problem of $Al_xGa_{1-x}As$-GaAs QWH lasers on Si, we have worked as hard on other QWH laser problems, as well as on impurity-induced layer disordering (or layer intermixing, IILD) and its application in laser devices. We briefly describe this work below and append the titles and abstracts of the papers we have published on laser studies and IILD.

II. QUANTUM WELL HETEROSTRUCTURES ON Si

As in our previous work,[1-6] we are employing metalorganic chemical vapor deposition (MOCVD) to grow $Al_xGa_{1-x}As$-GaAs QWH's on GaAs-on-Si "substrates" grown at Texas Instruments (H. Shichijo and co-workers) by molecular beam epitaxy (MBE). The only change in our work is that the MOCVD $Al_xGa_{1-x}As$-GaAs

QWH's on the TI MBE GaAs-on-Si are being grown in the University of Illinois Emcore GS 3000 DFM reactor instead of the Burnham-built reactors (Xerox) of our earlier work.[1-6] A wide variety of $Al_xGa_{1-x}As$-GaAs QWH's have been grown, mainly with various modifications of buffer layers to attempt to reduce mismatch dislocations. For example, many of these buffer layers, including superlattice layers, have had incorporated in them major amounts of the large atom In in an attempt to pin dislocations or to put lower gap "softer" layers in the buffer region to "absorb" mismatch. To render a layer harder, we switch to $In_{1-x}Ga_xP$, which matches GaAs at $x \approx 0.51$.

Although we have been successful in growing $Al_xGa_{1-x}As$-GaAs QWH's on GaAs-on-Si that have exhibited cw 300 K photopumped laser operation, as well as pulsed and in some cases cw 300 K diode laser operation, we have not duplicated or exceeded the results of Refs. 3-6. Some of our results are shown in Table I. The problems with mismatch defects are still severe, and more is required than just improved buffer and matching layers, which, incidentally, are not sufficient to stop inherent IILD effects. These are accelerated by dislocations and Si autodiffusion (see Ref. 7 and the abstract appended to this report). Since the final device sizes we require are small, it is unnecessary to grow defect-free layers over extended regions--rather over small regions. Consequently, we are attempting to modify the TI GaAs-on-Si into a mosaic of small islands, with the regions between islands disordered (by laser melting) and thus converted into a sink for defects. We are able to grow QWH's and superlattices on these modified GaAs-on-Si "substrates" and find a considerable difference in the MOCVD $Al_xGa_{1-x}As$-GaAs grown on the islands compared to the disorder stripes. A manuscript is in preparation to describe this work, which is being pursued further to construct QWH lasers on Si.

III. IMPURITY-INDUCED LAYER DISORDERING

For a considerable period we have been studying the fundamental problem of impurity-induced layer disordering (IILD) of thin layer III-V heterostructures (QWH's and superlattices, SL's), and have been applying IILD to the IC-style construction of sophisticated single and multiple-stripe buried heterostructure QWH lasers. Some of our recent IILD work is described in Refs. 8-14. Of special interest, we have introduced a convenient method of effecting IILD by depositing SiO_2 directly on the high gap Al-bearing confining layers of $Al_xGa_{1-x}As$-GaAs QWH's and using Al-reduction of the SiO_2 to act as a source of Si and oxygen, thus yielding Si-O IILD.[11] Silicon acts as an active disordering impurity and the oxygen raises the resistivity of the disordered region,[10,11,14] which is desired. Not only is Si-O IILD important for use on $Al_xGa_{1-x}As$-GaAs QWH's but also on this basic structure modified with a pseudomorphic $In_xGa_{1-x}As$ QW at its center to form longer wavelength (~ 1 μm) lasers,[10,14] lasers free of absorption assuming they are grown on GaAs substrates. If the problem of high performance QWH laser growth on Si is solved, then Si-O IILD could become (beyond its present importance) important also as an IC-technology to form various laser configurations and arrays on Si, including longer wavelength QWH lasers employing $In_xGa_{1-x}As$ pseudomorphic QW's.

IV. PHONON-ASSISTED LASER OPERATION

We have known for a long time (10+ years) that photopumped phonon-assisted laser operation of "properly prepared" QWH's (i.e., cleaved rectangles free of contact layers and substrates) can be observed. This has been questioned from its first observation up to the present in spite of the fact that Kolbas and co-workers (Applied Physics Letters 53, 2266 (1989)) have repeated and confirmed on MBE crystals our experiments and results of 10+ years on MOCVD QWH crystals. In recent work we have established more fundamentally the conditions (independent of the form of QWH crystals, MOCVD or MBE) under which photopumped cleaved $Al_xGa_{1-x}As$-GaAs QWH rectangles exhibit phonon-assisted laser operation. This work is described in Refs. 15-19. We have shown that the form of sample heat sinking, high-Q heat sinking versus ordinary low-Q heat sinking, permits a direct comparison to be made between phonon-assisted laser operation and laser operation turned-on also on confined-particle transitions. In other words, cavity boundary conditions are also at issue (cavity Q), as is described in some detail in Refs. 15-19. It is, of course, important in these experiments to employ photopumping since each 2.41 eV photon (Ar^+ laser pump) is the source of $(2.41-1.5)/0.036 \sim 25$ phonons. In addition, a QWH that collects electron-hole pairs and confines carriers and phonons in a compact region is important in these experiments, which, incidentally, we are continuing not because of their practicality for diodes, as such, but because of the importance in knowing how electrons and holes and stimulated photon and phonon emission operate in a QWH.

V. OTHER LASER STUDIES

Besides the work described above, we have maintained our interest in laser problems in general, two further examples being short wavelength (visible spectrum) laser operation (Ref. 13) and QWH laser operation in an external grating cavity (Ref. 20).

In the case of visible-spectrum lasers we employ $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ QWH crystals grown at H-P (M. G. Craford and co-workers, H-P Optoelectronics). Although it is possible in principle to match the growth of $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ to GaAs substrates, in practice this is not a simple procedure, and strain effects aggravate the usual problem with defects. Nevertheless, we view this work as important for shorter wavelength sources that have general merit and specific interest for writing and reading information at higher densities.

Some of the QWH $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ laser devices described here (e.g., Ref. 10) inherently exhibit low loss and bandfill over a large range, thus making them ideal for use as wide band tunable sources in an external grating cavity. Some number of years ago we introduced this area of work (QWH lasers operated as tunable sources in external grating cavities) and extended the tuning range from $\Delta E \sim kT$ (ordinary double heterojunction lasers) to $\Delta E \sim 4kT \approx 100$ meV (QWH lasers). We have now extended this (Ref. 20) to $\Delta E \sim 6kT$ (~ 150 meV, $\Delta\lambda \sim 1000$ Å), which is a remarkable tuning range and not necessarily a limit. This work takes on considerable practical importance if we can extend it (quite likely) to multiple-stripe higher power sources.

Finally, we mention that in this period of work we have had issued a U.S. patent listed at Ref. 21.

VI. CONTRIBUTORS

The principal investigators contributing to various parts of the work reported here are:

1) N. Holonyak, Jr.
2) K. C. Hsieh

(This report has been prepared by N. Holonyak, Jr.) The graduate students either receiving direct project support or otherwise contributing to various portions of the work reported here are:

1) J. M. Dallesasse, Ph.D. Student
2) D. C. Hall, Ph. D. Student
3) F. Kish, Ph.D. Student
4) J. S. Major, Jr., Ph. D. Student (Intel Fellowship, 1989-1990)
5) D. W. Nam, Ph. D. Student (Kodak Fellowship)
6) M. A. Plano, Ph.D. Student (Stillman advisor)
7) W. E. Plano, Ph.D. Student
8) A. R. Sugg
9) E. J. Vesely, Ph. D. Student (NSF Fellowship)

Note that some of the graduate students making contibutions to this work (Refs. 1-20) have received support from other projects or have received fellowship support. Another contributor, L. J. Guido, completed his Ph.D.

work in late 1988, now has a post-doctoral appointment (same project), and in August 1989 will join Yale University. Of the students listed above Dallesasse, Hall, Major, Nam, Plano, (Stillman advisee) and Plano are past their doctoral preliminary examinations. We mention that the National Science Foundation Engineering Research Center has supported much of our MOCVD crystal growth (EMCORE reactor) and our NSF MRL has supported our TEM and SIMS analyses, which are spread throughout much of the work reported here.

Finally, we mention that in May 1989 N. Holonyak, Jr. received the Sigma Xi Monie A. Ferst Award and in June 1989 the IEEE Edison Medal.

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TABLE I

$Al_xGa_{1-x}As$-GaAs Quantum Well Heterostructure Laser Structures Grown by MOCVD on TI MBE GaAs-on-Si "Substrates."

Crystal Number	T_g (°C)	Growth Temperature	Buffer Layers operation	Photopumped laser	Diodes	Comments
BP256	815	AlGaAs-GaAs SL		pulsed	undoped	no QW
BP257	760-815-760		AlGaAs-GaAs SL	pulsed	undoped poor emitter	QW intact but
BP259	790	AlGaAs-GaAs SL		pulsed	undoped	smeared QW
BP265	775	AlGaAs-GaAs SL		cw	undoped fairly stable	QW intact, cw,
BP287	775	AlGaAs-GaAs SL	stable	cw	undoped substrate	Zn-diffused
BP338	775	AlGaAs-GaAs SL		---	pulsed	High resistance
BP341	775	AlGaAs-GaAs SL		---	cw $\lesssim$ 10 min	$R_s \sim$ 15-20Ω
BP346	775	AlGaAs-GaAs SL		---	cw $\lesssim$ 10 min	$R_s \sim$ 15-20Ω
BP365	750	AlGaAs-GaAs SL		pulsed lase (DNL)	did not emitter	Poor light
BP373	760	AlGaAs-GaAs SL		---	cw < 10 min	$R_s \sim$ 10-15 Ω
BP383	760	AlGaAs-GaAs SL		cw	cw < 10 min 30 min anneal @ 760 before growth	$R_s \sim$ 10-15 Ω
BP426	760	InGaAsP	cw stable	DNL	Doping too low poor I-V's in InGaAsP	
BP723	760	InGaAs-GaAsSLs		pulsed rapidly	pulsed, died low R_s (~ 5 Ω)	High threshold
BP761	760	InGaAsP	pulsed	pulsed, died rapidly	High threshold low R_s (~ 5 Ω)	
BP762	760	None	did not lase (DNL)	DNL	InGaAs QW	
BP763	760	3 InGaAs wells		DNL	DNL	InGaAs QW
BP770	760	2 InGaAs wells		pulsed	pulsed, died low R_s (~ 5 Ω)	High threshold

Ref. 5

Effects of microcracking on $Al_xGa_{1-x}As$-GaAs quantum well lasers grown on Si

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Data are presented demonstrating continuous (cw) 300 K operation of *p-n* $Al_xGa_{1-x}As$-GaAs quantum well heterostructure lasers grown on Si and fabricated with naturally occurring microcracks running parallel to or perpendicular to the laser stripe. Operation for over 17 h is demonstrated for a diode with a parallel microcrack inside the active region. Diodes with microcracks perpendicular to the laser stripe exhibit relatively "square" light output versus current (*L-I*) characteristics and spectral behavior indicating internal reflections involving coupled multiple (internal) cavities. The lasers have operated (cw, 300 K) as long as 16 h.

Since the earlier successful fabrication of III-V semiconductor lasers grown on Si substrates,[1,2] there has been continued interest in improving the performance of these devices beyond simply pulsed 300 K operation.[3,4] We have recently achieved continuous-wave (cw) room-temperature operation of $Al_xGa_{1-x}As$-GaAs lasers grown on Si, initially in photopumped operation[5,6] and also as *p-n* laser diodes.[7,8] To date, $Al_xGa_{1-x}As$-GaAs laser diodes grown on Si have been operated cw room-temperature for over 10 h.[9] Other workers have also reported cw room-temperature operation of $Al_xGa_{1-x}As$-GaAs lasers grown on Si but apparently not for times beyond 4 min.[10,11] Clearly major problems face the GaAs-Si system: $Al_xGa_{1-x}As$-GaAs lasers grown on Si are mismatched 4% in lattice size relative to Si and exhibit a ~250% difference in thermal expansion. At the III-V crystal growth temperature the large lattice mismatch relative to Si is accommodated by a high density of dislocations. When the system is cooled to room temperature, the large difference in thermal expansion results in highly strained epitaxial III-V layers. Although the III-V epitaxial crystal quality, measured in terms of dislocation density, improves further from the GaAs-Si interface, the strain in the epitaxial layers increases as the layer thickness increases. Above a certain thickness microcracks form in the epitaxial layer and to some extent relieve the strain. It is the effect of these microcracks on the performance of the laser diodes grown on Si that is at issue in this letter. We show that the microcracking occurring in $Al_xGa_{1-x}As$-GaAs lasers grown on Si can have a dominant effect on the spectral characteristics of these devices. Also, the microcracking is shown to have no particularly deleterious effect on the laser devices in terms of threshold or operating lifetime and, in fact, may offer some benefit by providing strain relief.

The crystal growth and device fabrication used in this study have been described previously[5-8] and will be reviewed only briefly. First a 2 μm GaAs *n*-type ($n_{Si} \sim 10^{18}$ cm^{-3}) buffer layer is grown directly on the n^+-Si substrate using molecular beam epitaxy (MBE). The wafer is then transferred to a metalorganic chemical vapor deposition (MOCVD) growth system in which an $Al_xGa_{1-x}As$-GaAs *p-n* single quantum well (QW) separate confinement laser structure is grown. The total thickness of the III-V epitaxial layers (MBE + MOCVD) is ~5 μm. Laser diodes are fabricated by defining 10-μm-wide oxide stripe openings to contact the *p* side (epitaxial layer side). The *p*-side metallization consists of 250 Å of Cr followed by 1000 Å of Au. The *n* side is contacted, via the n^+-Si substrate, using a 500 Å alloyed Al metallization on the Si followed by 250 Å of Cr and 1000 Å of Au. Typical pulsed thresholds of these devices are 90–110 mA for 350-μm-long cavities. For cw operation the laser diodes are mounted on a copper block either in a "junction-up" or "junction-down" configuration. It has been shown that cw operation in the "junction-up" configuration is aided in part by the higher thermal conductivity of the Si substrate.[9]

We have previously found that when the total III-V epitaxial layer thickness is ~10 μm, cracking and severe warping occur in the epitaxial layers.[5] For a total thickness of ~5 μm only a few microcracks are observed in the top-surface III-V epitaxial layer after crystal growth. However, when the wafer is cleaved into smaller pieces to process into laser diodes, the flexing of the Si substrate together with the built-in strain in the epitaxial material can introduce a high density of microcracks in the final III-V laser structure. These microcracks run in the ⟨110⟩ directions and are typically spaced ~20–500 μm apart in areas of the crystal in which the microcracks are densest. Therefore, there is a significant probability for some of these microcracks to be either parallel to the laser stripe (near or even within it), or be perpendicular to the laser stripe. For example, Fig. 1 shows a photograph of a microcrack running along the inside of an oxide stripe opening, and thus *in* the laser active region. The quantum well heterostructure laser of Fig. 1 is shown after metallization, and, even through the 250 Å of Cr and 1000 Å of

Thermal behavior and stability of room-temperature continuous $Al_xGa_{1-x}As$-GaAs quantum well heterostructure lasers grown on Si

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Data are presented on the thermal characteristics of *p-n* $Al_xGa_{1-x}As$-GaAs quantum well heterostructure (QWH) diode lasers grown on Si substrates. Continuous 300-K operation for over 10 h is demonstrated for lasers mounted with the junction side away from the heat sink ("junction-up") and the heat dissipated through the Si substrate. "Junction-up" diodes that are grown on Si substrates have measured thermal impedances that are 38% lower than those grown on GaAs substrates, with further reductions possible. Thermal impedance data on "junction-down" diodes are presented for comparison. Measured values are consistent with calculated values for these structures. Low sensitivity of the lasing threshold current to temperature is also observed, as is typical for QWH lasers, with T_0 values as high as 338 °C.

I. INTRODUCTION

The growth of III-V semiconductors on Si is currently receiving much attention because Si substrates are cheaper, sturdier, and have better thermal properties than III-V semiconductor substrates and because III-V devices are capable of light emission and higher speed. Now III-V semiconductor devices potentially can be merged with more highly developed Si integrated circuit technology. Despite the large crystal lattice mismatch (4%) and the difference in the thermal expansion coefficients of GaAs and Si, which result in high defect densities in the epitaxial GaAs, recent progress in the study of $Al_xGa_{1-x}As$-GaAs heterostructures and quantum well heterostructures (QWHs) grown on Si substrates indicates considerable promise for this hybrid technology.

Device-quality GaAs must have reasonably low defect densities, particularly for injection devices, as it has been shown that the formation and propagation of dislocation networks depends primarily upon carrier recombination rather than upon current flow.[1] Perhaps the most demanding test of the GaAs-on-Si material is that of continous (cw) 300-K laser operation of a III-V QWH grown on a GaAs-on-Si substrate. Continuous 300-K laser operation, the most severe test, was first achieved (though not reliably) for a photopumped multiple well $Al_xGa_{1-x}As$-GaAs quantum well heterostructure laser grown on GaAs-on-Si.[2] By simplifying the structure to a single GaAs quantum well, Nam *et al.* reduced the number of active region interfaces threaded by dislocations, thus making lower threshold and more reliable (cw, 300 K) photopumped laser operation possible.[3] By utilizing such a single-well structure with *p* and *n* doping, Deppe *et al.* (spring, 1987) realized the first room-temperature cw *p-n* diode $Al_xGa_{1-x}As$-GaAs QWH lasers grown on GaAs-on-Si.[4,5] Operation for over 4 h has been demonstrated.[6] Another laboratory later reported presumably cw room-temperature operation[7]; a further report indicated ~5-min operation.[8] These developments, along with earlier reports of pulsed laser operation,[9–12] suggest that practical high level $Al_xGa_{1-x}As$-GaAs diodes grown on Si substrates can indeed be realized.

In the present work we describe further progress in the cw 300-K operation of $Al_xGa_{1-x}As$-GaAs QWH lasers grown on Si, including the important demonstration that cw 300-K laser operation is possible with the diode heat sunk from the side of the Si substrate ("junction-up") and *not* with the III-V semiconductor active layers mounted, as usual, downward on the heat sink ("junction-down"). In the "junction-up" configuration over 10 h of cw 300-K laser operation is demonstrated. This is potentially very important if III-V optoelectronics is to be successfully integrated with Si technology, where integrated circuit (IC) style processing may necessitate that most lasers fabricated on an integrated optoelectronic "chip" will have the junction region (the active region) turned upward and not downward on a heat sink. This increases the importance of the issue of thermal impedance, which is a measure of how well the heat generated in a laser diode is dissipated. The stability of the laser diodes of the present work, and of Refs. 5 and 6, makes it possible to perform more extensive characterization measurements on these diodes. In this paper the thermal characteristics of these diodes are examined. Measurements and calculations of thermal impedance are presented for GaAs-on-Si and GaAs-on-GaAs lasers mounted both junction-up and, for comparison, junction-down. We show that the thermal impedance of junction-up lasers is reduced by the higher conductivity Si substrates. Also presented are measurements showing the temperature sensitivity of the lasing threshold current for the QWH GaAs-on-Si diodes.

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Ref. 7

DISLOCATION-ACCELERATED IMPURITY-INDUCED LAYER DISORDERING OF $Al_xGa_{1-x}As$-GaAs QUANTUM WELL HETEROSTRUCTURES GROWN ON GaAs-ON-Si

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Data are presented showing that dislocations and Si autodiffusion promote accelerated layer disordering of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures grown on GaAs-on-Si "substrates" via metalorganic chemical vapor deposition. The accelerated impurity-induced layer disordering is more extreme at higher temperatures ($> 800°C$) and virtually non-existent at lower temperatures ($\lesssim 775°C$).

Role of Native Defects in Al-Ga Interchange and Layer Disordering in $Al_xGa_{1-x}As$ Quantum Well Heterostructures

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ABSTRACT: Data are presented demonstrating the effects of growth parameters (Fermi-level and V/III ratio) and annealing conditions (surface encapsulants and As_4 pressure) on Al-Ga interdiffusion in MOCVD grown $Al_xGa_{1-x}As$-GaAs QWHs.

1. INTRODUCTION

As suggested by Laidig et al (1981), impurity-induced layer disordering (IILD) has important consequences for fabrication of thin layer $Al_xGa_{1-x}As$-GaAs buried heterostructure devices. In order to realize fully the potential of IILD it is necessary to better understand the Al-Ga interchange mechanism. In the experiments described here $Al_xGa_{1-x}As$-GaAs superlattices (SLs) and single-well quantum well heterostructures (QWHs) grown by metalorganic chemical vapor deposition (MOCVD) are used to study Al-Ga interdiffusion. Photoluminescence (PL), transmission electron microscopy (TEM), and secondary ion mass spectroscopy (SIMS) data show that the crystal surface condition (surface encapsulant and As_4 pressure) strongly influences Al-Ga interdiffusion. For a clearly defined Al-Ga interdiffusion regime we have measured the activation energy for Al-Ga interchange (E_{Al-Ga}), thereby labeling this regime. By employing three single-well QWHs that differ only in the QW location, we further demonstrate that Al-Ga interchange is enhanced by re-equilibration of depth-dependent native defect concentrations involving the crystal surface. In contrast PL and TEM measurements of annealed $Al_xGa_{1-x}As$-GaAs SLs show that Al-Ga interdiffusion is relatively depth-independent. Finally, we have investigated the effect of crystal growth parameters (Fermi-level and V/III gas ratio) on the Al-Ga interchange mechanism.

2. EXPERIMENTAL RESULTS

2.1 Activation Energy

To the extent that the activation energy varies with growth parameters and experimentally determined annealing-conditions values of E_{Al-Ga} can ultimately be used to label interdiffusion regimes. Consequently, the magnitude of E_{Al-Ga} will provide insight to the atomic mechanisms responsible for Al-Ga interchange. A review of available Al-Ga interdiffusion data

Ref.9

Depth-dependent native-defect-induced layer disordering in $Al_xGa_{1-x}As$-GaAs quantum well heterostructures

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Photoluminescence measurements on annealed single-well $Al_xGa_{1-x}As$-GaAs quantum well heterostructures demonstrate that layer disordering caused by native defects is strongly depth dependent. The depth-dependent layer disordering, as well as the corresponding depth-dependent net carrier concentration, is a consequence of the re-equilibration of the V_{Ga}^- vacancy and the As_{Ga}^+ antisite native defect concentrations via the crystal surface.

Previously we have shown that for $Al_xGa_{1-x}As$-GaAs quantum well heterostructures (QWHs) layer disordering by means of native defects is strongly influenced by the anneal ambient and surface encapsulant conditions (e.g., As overpressure, SiO_2 crystal cap, Si_3N_4 crystal cap).[1] With the proper choice of encapsulant mask and annealing conditions this form of layer disordering can be made selective and, for example, can be used to construct a buried QWH laser.[2] These observations suggest that the extent of layer disordering should be proportional to the nonequilibrium, depth-dependent native defect concentration. In contrast, depth-dependent layer disordering has not been observed in $Al_xGa_{1-x}As$-GaAs superlattices, i.e., in structures that contain a "distributed heterointerface or distributed heterosurface." In the present work we demonstrate by direct measurement that for single-well $Al_xGa_{1-x}As$-GaAs heterostructures, with different well depths, native defect layer disordering is strongly depth dependent. The data show that the extent of layer disordering is determined by the proximity of the QW to the crystal surface, i.e., to the defect source.

The four QWH samples used in this work are grown via metalorganic chemical vapor deposition (MOCVD) in an Emcore GS 3000-DFM reactor. As shown in the scanning electron microscope (SEM) cross sections of Fig. 1, the QWHs are identical except for the location of the quantum well in each crystal, which is approximately (1) 0.7, (2) 1.4, and (3) 2.1 μm below the surface (downward arrows in SEM images). The low alloy composition $Al_xGa_{1-x}As$ QW($x \sim 0.04$, $L_z \sim 100$ Å) is confined on top and on bottom by a total of ~2.8 μm of nominally "undoped" $Al_{x'}Ga_{1-x'}As$($x' \sim 0.45$). Actually, because of the significant alloy composition and prevalence of carbon (C) in MOCVD $Al_xGa_{1-x}As$ growth, the doping concentration is $n_c \sim 2 \times 10^{17}$ cm^{-3} (Ref. 3). For QWH-4 the confining layer thickness is reduced to ~1.8 μm, and the QW is ~0.9 μm below the surface. In all cases the QWHs are grown on Si-doped GaAs substrates ($n_{Si} \sim 2 \times 10^{18}$ cm^{-3}).

The photoluminescence (PL) data shown in Fig. 1 are typical of spectra observed on QWH-1 through QWH-3 after an 825 °C (12 h) sample anneal. The curve labeled "as-grown" in Fig. 1 is for QWH-1 but is representative of all three as-grown samples. Each as-grown QWH is measured (PL) at nine different positions before annealing, and again after annealing to determine the shift to higher energy of the $n = 1$ electron-to-heavy hole ($e \rightarrow hh$) confined-particle transition. The increase in energy of the $n = 1$ transition is a measure of the Al-Ga interdiffusion at the QW-confining layer interface.[4-7] All samples have been annealed at 825 °C for 12 h and also for 25 h in an evacuated (10^{-6} Torr) and sealed quartz ampoule. The anneal ambient is As-rich (As overpressure of ~2 atm) because of excess As added to the ampoule. A summary of the PL data for QWH-1 through QWH-3 is given in Table 1. For a given QW depth (e.g., ~0.7 μm in QWH-1) the upward shift in energy (ΔE) increases with anneal time (12–25 h) by a factor of ~2.5. In addition, for a fixed anneal schedule (e.g., 825 °C, 25 h) ΔE increases ~4-fold as the QW depth below the crystal surface decreases from ~1.4 μm (QWH-2) to ~0.7 μm (QWH-1). These trends clearly demonstrate that the extent of Al-Ga intermixing at the QW is strongly depth dependent, and is a consequence of re-equilibration of native defect concentrations at the crystal surface.

Further insight into the defect diffusion and layer disordering is gained by examining via capacitance-voltage (C-V) profiling the depth-dependent net carrier concentration. The net (p-type) carrier concentration profiles for QWH-3

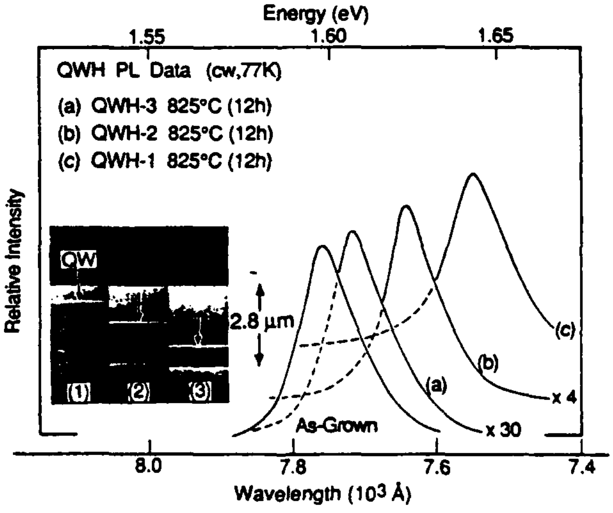

FIG. 1. Photoluminescence data (cw, 77 K) for QWH-1 through QWH-3 after an 825 °C (12 h) anneal. The extent of QW Al-Ga intermixing, as measured by the shift to higher energy in the PL spectra, increases with a decrease in QW depth from 2.1 to 0.7 μm (SEM cross sections at the left).

Ref. 10

Low-threshold disorder-defined buried heterostructure strained-layer $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well lasers ($\lambda \sim 910$ nm)

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The stability of strained-layer $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ single quantum well heterostructures against thermal processing is examined using transmission and scanning electron microscopy. A self-aligned impurity-induced layer disordering process employing Si-O diffusion is used to produce buried heterostructure stripe geometry lasers with a pseudomorphic $In_xGa_{1-x}As$ quantum well active region. The 2-μm-wide stripe laser diodes exhibit high efficiency ($\eta \sim 41\%$/facet), low threshold ($I_{th} = 7$ mA), and high output power ($P_{out} > 20$ mW/facet).

The insertion of a strained-layer $In_xGa_{1-x}As$ quantum well into a lattice-matched $Al_yGa_{1-y}As$-GaAs quantum well heterostructure (QWH) crystal, e.g., sandwiched in a GaAs layer, leads to the possibility of creating longer wavelength lasers ($\lambda > 870$ nm) in a convenient heterostructure system. Longer wavelengths than are typical of $Al_xGa_{1-x}As$-GaAs QWHs provide the capability of pumping directly Yb-sensitized Er:glass lasers, propagation of optical signals through the transparent GaAs substrate, and laser emission at longer wavelengths ($\lambda > 870$ nm) for optical fiber communications. Since the initial observation of continuous (cw) room-temperature (300 K) stimulated emission in strained-layer QWH crystals,[1,2] including in GaAs-$In_xGa_{1-x}As$ QWH's, considerable improvement has been achieved in both crystal quality[3] and device performance. To date there have been several reports of long-wavelength ($\lambda \sim 1\,\mu$m) $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ QWH laser diode operation, including the case of high-power cw strained-layer arrays.[4,5] These advances raise a number of important issues concerning laser diode performance, including the possibility of increased carrier confinement (because of larger band discontinuities), the question of strain effects in the QW active region, and stability of the strained-layer QW against high-temperature processing (thermal annealing). Specifically the ability of pseudomorphic QW active regions to withstand high-temperature annealing suggests that impurity-induced layer disordering (IILD) can be used for fabrication of buried heterostructure laser devices,[6,7] particularly since it is already known that the column III components Ga, Al, and In will interchange by IILD.[8] In this letter we describe low threshold buried heterostructure $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ QW lasers fabricated via a self-aligned Si-O diffusion and layer disordering (Si-O IILD) procedure.[9] We show also that pseudomorphic $In_xGa_{1-x}As$ QWs are stable against both native defect-enhanced layer disordering[10] and dislocation generation over extended thermal annealing schedules.

The QWH laser crystals used in these experiments have been grown by low-pressure metalorganic chemical vapor deposition (MOCVD).[11] The growth temperature is held at 800 °C except for the $In_{0.15}Ga_{0.85}As$ QW, which is grown at 630 °C to avoid desorption of In from the crystal surface.[5] The epitaxial layers are grown on a Si-doped GaAs substrate beginning with (1) a GaAs buffer layer, followed by (2) an n-type (Se doping) $Al_{0.8}Ga_{0.2}As$ lower confining layer ($\sim 1.25\,\mu$m), (3) a nominally undoped QW active region, (4) a p-type (Mg doping) $Al_{0.8}Ga_{0.2}As$ upper confining layer ($\sim 1.00\,\mu$m), and (5) a p-type (Mg + Zn doping) GaAs contact layer (~ 1500 Å). The active region itself consists of an $Al_{0.35}Ga_{0.65}As$ waveguide layer ($\sim 0.5\,\mu$m) that sandwiches a GaAs well (~ 690 Å) with an $In_{0.15}Ga_{0.85}As$ QW (~ 150 Å) in its center.

The laser diode fabrication process begins with the chemical vapor deposition (CVD) of a Si_3N_4 layer (~ 1000 Å) that is patterned with photoresist into 2 μm stripes. The Si_3N_4 and photoresist serve as a mask for wet chemical etching (H_2SO_4-H_2O_2-H_2O) through the GaAs contact layer (between stripes) down to the high-gap upper $Al_{0.8}Ga_{0.2}As$ confining layer. Next, a 1000 Å SiO_2 source layer is selectively deposited (e-beam) onto the exposed $Al_{0.8}Ga_{0.2}As$, with then a lift-off procedure to remove both the SiO_2 and photoresist from the stripe region. The crystal is then sealed in an evacuated quartz ampoule with excess As (~ 10 mg) and is annealed at 825 °C for 24 h. The high-temperature anneal results in chemical reduction of the SiO_2 diffusion source layer by Al at the SiO_2-$Al_{0.8}Ga_{0.2}As$ interface. The Al-reduced SiO_2 is a source of both Si and O for Si-O diffusion and layer disordering. As illustrated in the scanning electron microscope image (SEM) of Fig. 1, the waveguide region ($Al_{0.35}Ga_{0.65}As$), GaAs well, and pseudomorphic $In_{0.15}Ga_{0.85}As$ QW have been intermixed with the upper and lower ($Al_{0.8}Ga_{0.2}As$) high-gap confining layers (n) to the left and right of the buried laser stripe (p). Note, however, that the QW active region remains intact below the 2 μm Si_3N_4 masking stripe in the center of the image of Fig. 1. The lateral diffusion of Si, which is characteristic of other disordering techniques,[7] is greatly reduced by using the encapsulants and procedure outlined here. This is evident from the

Ref. 11

Disorder-defined buried-heterostructure $Al_xGa_{1-x}As$-GaAs quantum well lasers by diffusion of silicon and oxygen from Al-reduced SiO_2

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We describe a convenient method utilizing chemical reduction of SiO_2 by Al (from $Al_xGa_{1-x}As$) to generate Si and O for impurity-induced layer disordering (IILD) of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures (QWHs). Experimental data show that Si-O diffusion (from SiO_2) is an effective source of Si for Si-IILD and of O that compensates the Si donor, thus resulting in higher resistivity layer-disordered crystal. The usefulness of the Si-O IILD source for fabricating low-threshold disorder-defined buried-heterostructure $Al_xGa_{1-x}As$-GaAs QWH lasers is demonstrated.

The study of impurity-induced layer disordering (IILD)[1,2] and its use in fabricating low-threshold single-emitter quantum well heterostructure (QWH) lasers,[3] high-power multi-emitter laser arrays,[4,5] and other device structures is accelerating (see Ref. 6 for a review). The most widely used IILD fabrication process, e.g., for QWH lasers, is selective Si diffusion from an evaporated (*e*-beam) or chemical vapor deposited (CVD) surface source layer.[2] Dielectric encapsulants such as SiO_2 and Si_3N_4 are typically used to mask the Si diffusion source, and to enhance (SiO_2) or retard (Si_3N_4) layer disordering involving native defects themselves.[7,8] In the case of disorder-defined QWH lasers based on Si diffusion (Si-IILD), the free-electron concentration in the disordered region is quite large ($n > 10^{18}$ cm^{-3}), thus limiting the current confinement of stripe geometry lasers, the coupling between stripes of multiple stripe lasers, or the freedom from absorption near the disordered facet region of "window" lasers.[9] In this letter we describe an IILD fabrication process (Si-IILD by means of simply a SiO_2 layer) that, by increasing the resistivity of the disordered region, can lead to improved stripe geometry QWH laser performance.

In order to effect Si diffusion from a SiO_2 diffusant source, the crystal surface region must contain Al to chemically reduce the SiO_2. For a typical QWH laser crystal, a surface source of Al can be achieved with a thin auxiliary $Al_xGa_{1-x}As$ capping layer grown and patterned on the usual GaAs contact layer, or preferably by simply etching away the GaAs contact layer to expose the high-gap upper $Al_xGa_{1-x}As$ confining layer. In the case of an $Al_xGa_{1-x}As$-GaAs superlattice crystal, Al at shallow depth can be transported to the surface by the layer disordering process itself.[7] The Al at the crystal surface reduces the SiO_2 to form free Si and O, and presumably Al_2O_3. The Si and O released become sources for impurity diffusion and layer disordering. In the present work, the effectiveness of this form of diffusant source is investigated for an undoped $Al_xGa_{1-x}As$-GaAs superlattice (SL) crystal and a *p-n* single-well QWH laser crystal that have been grown by metalorganic chemical vapor deposition (MOCVD).[10] The *p-n* QWH laser crystal active region (undoped) contains a single GaAs quantum well ($L_z \sim 80$ Å) centered within an $Al_{x'}Ga_{1-x'}As$ ($x' \sim 0.40$) separate-confinement (or waveguide) region. The waveguide is confined further by high-gap $Al_xGa_{1-x}As$ ($x \sim 0.85$) that, for laser diode fabrication, is doped *p*-type above (~ 0.6 μm thick) the active region and *n*-type below (~ 1.1 μm thick). The 60-period $Al_{x'}Ga_{1-x'}As$-GaAs ($x' \sim 0.35$, $L_B \sim 120$ Å, $L_z \sim 120$ Å) superlattice is similarly confined on top (~ 1000 Å) and on bottom (~ 1000 Å) by high-gap $Al_xGa_{1-x}As$ ($x \sim 0.85$) that is nominally undoped. For both crystals, the high-gap upper confining layers are protected by GaAs ($\gtrsim 1000$ Å) that, for diffusion purposes, has been patterned and etched before SiO_2 (~ 1000 Å) encapsulation and annealing. This, of course, permits direct contact of the SiO_2 with $Al_xGa_{1-x}As$ and hence with Al.

Secondary-ion mass spectroscopy (SIMS) depth profiles are shown in Fig. 1 for the SL sample after Si-O diffu-

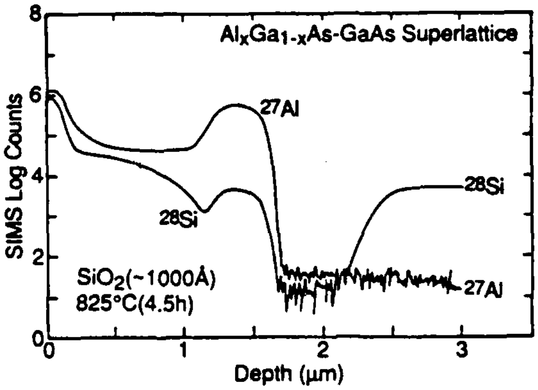

FIG. 1. Secondary-ion mass spectroscopy (SIMS) data for an $Al_{x'}Ga_{1-x'}As$-GaAs ($x' \sim 0.35$, $L_B \sim 120$ Å, $L_z \sim 120$ Å) superlattice crystal after Si-O diffusion (825 °C, 4.5 h) from an Al-reduced SiO_2 source. The high-gap $Al_xGa_{1-x}As$ ($x \sim 0.85$) layers confining the superlattice on top and on bottom are marked by the large increase in ^{27}Al signal at the surface and at ~ 1.2 μm. The Si diffusion profile (labeled ^{28}Si) extends to the bottom heterointerface of the lower confining layer.

Ref. 12

Zn disordering of a $Ga_{0.5}In_{0.5}P$-$(Al_xGa_{1-x})_{0.5}In_{0.5}P$ quantum well heterostructure grown by metalorganic chemical vapor deposition

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It is well established by now that epitaxial layers of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ and $Ga_{0.5}In_{0.5}P$ grown on (001) GaAs substrates by metalorganic chemical vapor deposition at temperatures below 700 °C show an ordered arrangement of the group III atoms on the column III sublattice, resulting in a shift of the band gap to lower energies by ≈ 90 meV. In this letter we show that an $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-$Ga_{0.5}In_{0.5}P$ quantum well heterostructure containing the ordered phase can be converted to random alloy by a relatively short sealed-tube zinc diffusion at a temperature of 600 °C, without affecting the dimensional or compositional stability of the quantum well. Complete intermixing of the quantum well with the cladding layers occurs at diffusion times longer than that required to disorder the column III ordered structure.

The $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-$Ga_{0.5}In_{0.5}P$ material system has been used successfully for the fabrication of short-wavelength semiconductor lasers emitting at wavelengths as short as $\lambda \approx 6210$ Å with an AlGaInP active layer (operating at 0 °C),[1] with the potential of providing emission at wavelengths as short as 5600 Å. These lasers are attractive for optical recording, printing, and as a replacement for most He-Ne gas lasers. However, the band-gap energy (E_g) of this material grown lattice matched on (001) GaAs substrates by metalorganic chemical vapor deposition (MOCVD) has been found to depend on the growth conditions, i.e., the growth temperature and the V/III ratio in the gas phase.[2-4] E_g is typically 50–90 meV lower than that of crystals grown by liquid phase epitaxy (LPE).[5,6] Lasers with a $Ga_{0.5}In_{0.5}P$ active region grown by MOCVD on (001) GaAs at growth temperatures <700 °C, therefore, tend to emit at $\lambda > 6600$ Å, rather than 6400 Å.[7-10]

The shift of E_g of MOCVD-grown $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ and $Ga_{0.5}In_{0.5}P$ to lower energy has been shown to result from ordering of the group III atoms on the column III sublattice.[2,10,11] Transmission electron microscopy (TEM) studies of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ and $Ga_{0.5}In_{0.5}P$ grown by MOCVD at temperatures below 700 °C reveal an anomalous diffraction pattern[2,10,11] in the [110] orientation, with additional strong extra spots halfway between the diffraction spots from the zinc blende (ZB) matrix along the $\langle 111 \rangle$ directions. No additional diffraction spots were observed in the orthogonal $[1\bar{1}0]$ orientation.

Recently, it has been shown by TEM and photoluminescence (PL)[10,11] that either a Zn diffusion from a Zn_3P_2 source or a thermal anneal under phosphorus overpressure is an effective means for randomizing the column III ordered atomic arrangement in bulk epilayers of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$, $(0<x<0.4)$. Simultaneously, a shift of E_g to higher energy by ≈ 90 meV, independent of the alloy composition, is observed.

The purpose of this letter is to demonstrate that the properties of $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-$Ga_{0.5}In_{0.5}P$ quantum well heterostructures can be altered by zinc diffusion in two very different ways, depending on the diffusion conditions: (1) a *short* Zn diffusion (<7 h at 600 °C) transforms the ordered arrangement of the group III atoms on the column III sublattice into a random alloy, with a simultaneous increase of E_g in both the diffused $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ and $Ga_{0.5}In_{0.5}P$ by ≈ 90 meV. The physical stability of the quantum well is not affected; and (2) a *much longer* Zn diffusion time (>24 h at 600 °C) is required to completely intermix the $Ga_{0.5}In_{0.5}P$ quantum well with the adjacent $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ cladding layers.

It is therefore possible to either shift the band gap E_g of the epilayers or compositionally disorder the $(Al_xGa_{1-x})_{0.5}In_{0.5}P$-$Ga_{0.5}In_{0.5}P$ quantum well heterostructure in conjunction with the shift in band gap by selecting the appropriate diffusion conditions to fabricate index-guided structures.

The heterostructure is grown epitaxially on (001) GaAs substrates, tilted 2° toward (110), by low-pressure MOCVD ($p = 100$ Torr) in a vertical cold-wall reactor. The GaAs substrates are supported on a SiC-coated graphite susceptor at a small angle ($\approx 8°$) to the vertical axis. The susceptor is induction heated. Trimethylgallium, trimethylaluminum, trimethylindium, and 20% phosphine in hydrogen are used as reactants. A 0.2-μm-thick GaAs buffer layer is grown prior to the growth of the heterostructure which consists of a 180 Å $Ga_{0.5}In_{0.5}P$ quantum well confined by two 1.1 μm $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ cladding layers ($x \approx 0.4$). The growth temperatures of the QW and the cladding layers are 650 and 680 °C, respectively. The growth rates are 1.0 μm/h for the QW and 1.6 μm/h for the cladding layers. The V/III ratio is 500 for the QW and 300 for the cladding layers. All layers are undoped, but are n type with residual electron concentration $n < 5 \times 10^{15}$ cm^{-3}, as measured by a Polaron doping profiler. The lattice mismatch $\Delta a/a$ is less than 2×10^{-3}, as determined from double-crystal x-ray diffraction measurements.

For measurement of the band-gap energy, samples are photoexcited with an Ar^+ laser (4880 Å, intensity 100 W cm^{-2}) at room temperature. The PL signal is dispersed

Ref. 13

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Impurity-induced layer disordering in $In_{0.5}(Al_xGa_{1-x})_{0.5}P$-InGaP quantum-well heterostructures: Visible-spectrum-buried heterostructure lasers

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Diffusion of Si into quantum-well heterostructures and superlattices employing the high gap III-V quaternary system $In_y(Al_xGa_{1-x})_{1-y}P$ is shown to result in impurity-induced layer disordering. Secondary ion mass spectroscopy, transmission electron microscopy, and photoluminescence data indicate that the diffusion of Si into an InAlP-InGaP superlattice grown lattice matched on GaAs ($y \simeq 0.5$) results in the intermixing of the layers, thus forming an alloy of average composition. Buried-heterostructure lasers are fabricated using Si layer disordering of $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ *p-n* quantum-well heterostructures. The disorder-defined stripe-geometry diode lasers operate pulsed at 300 K near 6400 Å. Continuous wave operation at $\lambda \sim 6255$ Å is achieved at -47 °C.

I. INTRODUCTION

One of the more interesting developments in the study of quantum-well heterostructues (QWHs) and QW lasers has been the discovery that the diffusion of impurities into a III-V heterostructure (a layered crystal) enhances intermixing of the individual layers. Impurity-induced layer disordering (IILD) has been studied extensively in the $Al_xGa_{1-x}As$-GaAs system,[1-7] where it has been used to produce buried-heterostructure semiconductor lasers and laser arrays with superior performance characteristics.[8-11] As is well known, buried-heterostructure stripe-geometry lasers outperform other stripe geometries because of superior waveguiding and current confinement,[12] which in the present case is afforded by higher gap intermixed layers. The study of IILD in $Al_xGa_{1-x}As$-GaAs and other heterosystems is of fundamental importance, and is specifically of some importance in producing high-performance semiconductor lasers, and in general for use in optoelectronics. (See Ref. 13 for a review of IILD and its applications.)

An important III-V heterosystem for use in visible-spectrum lasers and to consider as a candidate for IILD is the quaternary $In(Al_xGa_{1-x})_{1-y}P$. This quaternary, which is a modification of the high gap ternary $In_yGa_{1-y}P$,[14] is of specific interest because of its known high direct–indirect crossover,[15] as well as the fact that IILD works particularly well for the case of Al-Ga substitution. Thus far, only a few IILD experiments have been performed in this heterosystem.[16] Through the use of metalorganic chemical vapor deposition (MOCVD),[17] it is possible to produce high-quality stacked layers (quaternary or ternary layers) of different Al and Ga composition, and thus of different energy gap. By analogy with the $Al_xGa_{1-x}As$ system, this makes possible the growth of heterostructures suitable for semiconductor lasers in the visible portion of the spectrum.[18-23] For example, room-temperature continuous (cw) operation of *p-n* diode $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ QW lasers has already been demonstrated at wavelengths as short as 6395 Å.[24,25] Continuous (cw) photopumped laser operation at 300 K has been achieved at wavelengths as short as 6250 Å.[26,27] Because of the short wavelength capability of the $In_y(Al_xGa_{1-x})_{1-y}P$ system, the possibility of producing buried-heterostructure *p-n* diode QW lasers by IILD in this III-V material is of considerable interest. Previously, Zn diffusion in an $In_{0.5}(Al_xGa_{1-x})_{0.5}P$-GaAs heterostructure has been demonstrated to result in IILD, but has not been used to fabricate buried-heterostructure devices.[16] In the present work Si diffusion is demonstrated to result in the intermixing of $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ layers grown lattice matched on GaAs. Silicon-IILD is used to produce buried-heterostructure QW diode lasers.

II. LAYER DISORDERING IN THE $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ SYSTEM

A. Experimental procedure

In order to study the properties of Si IILD in the $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ system, Si diffusion has been performed into an undoped 20-period $In_{0.5}Al_{0.5}P$-$In_{0.5}Ga_{0.5}P$ superlattice (SL, $L_B \simeq 210$ Å, $L_z \simeq 200$ Å). The quaternary SL is grown by low-pressure (100-Torr) MOCVD on a (100) *n*-type GaAs substrate in an EMCORE GS3000-DFM reactor. Sources of the various crystal constituents are trimethylindium (TMIn), trimethylaluminum (TMAl), triethylgallium (TEGa), and phosphine (PH_3). The crystal growth parameters are chosen so as to minimize lattice mismatch between the In $(Al_xGa_{1-x})_{1-y}P$ layers and the GaAs substrate. The degree of lattice match is assessed by rotating crystal x-ray diffractometry on thick test layers of

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[a] Kodak Doctoral Fellow.

Ref. 14

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High-power disorder-defined coupled stripe $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure lasers

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Data are presented describing continuous (cw) room-temperature laser operation of $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure (QWH) phase-locked arrays. The ten-stripe arrays have 3 μm emitters, with emitter to emitter spacing of 4 μm, and are patterned onto the QWH crystal using a self-aligned Si-O impurity-induced layer disordering (IILD) procedure. The IILD process is devised to provide limited layer intermixing to ensure optical coupling (across ~1 μm). The coupled stripe QWH lasers exhibit narrow twin-lobed far-field patterns that show unambiguously phase locking in the highest order supermode. The cw output power of the lasers (differential quantum efficiency 52%) is shown from threshold (~75 mA) to over 280 mW (both facets, no optical coatings).

Ref. 15

Observation of phonon-assisted laser operation of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures

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Data are presented showing that the key to observing the phonon-assisted photopumped laser operation of narrow rectangular samples of $Al_xGa_{1-x}As$-GaAs quantum well heterostructures (QWHs) is the control of the edge-to-edge resonator Q across the sample. If the sample is heat sunk in metal, with metal reflectors folded upward along the edges, the resonator Q across the sample is high, and laser operation across the sample on confined-particle states (a reference) and along the sample a phonon lower in energy ($\Delta E \approx \hbar\omega_{LO}$) is observed. If the sample edges across the sample are left uncoated (weakly reflecting, low Q), laser operation is observed only along the sample (longitudinal modes) but shifted ($\Delta E \approx \hbar\omega_{LO}$) below the confined-particle states and absorption. A QWH rectangle, with proper heat sinking and control of its edge-to-edge resonator Q, can act as a hot-phonon "spectrometer" if it is fully photopumped across its width and is only partially pumped along its length.

In this letter we consider the problem of how phonon-assisted laser operation of quantum well heterostructures (QWHs) or superlattices (SLs) can be observed,[1-4] indeed, whether it can be observed. The observation by Holonyak and Kolbas almost ten years ago of hot-phonon participation in the photopumped laser operation of $Al_xGa_{1-x}As$-GaAs QWHs grown (Dupuis) by metalorganic chemical vapor deposition (MOCVD)[1-4] has in a few cases been disputed by workers employing QWHs grown by molecular beam epitaxy (MBE).[5-8] Recently Kolbas and his co-worker Lo[9] have shown that in fact phonon-assisted laser operation can be observed on MBE $Al_xGa_{1-x}As$-GaAs QWHs heat sunk and photopumped as in the original experiments on MOCVD QWHs.[4] We describe in this letter the importance of how the rectangular QWH samples are heat sunk and how, because of this (i.e., the control of the edge-to-edge cavity Q), a narrow rectangular sample can act as a hot-phonon "spectrometer."

First we remark that the usual simple method of attaching a thick-substrate QWH ($\gtrsim 100$ μm) on a cold finger with grease for low-temperature photoluminescence measurements is not a good heat sinking scheme, particularly for high level photoexcitation intended to generate a large number of (LO) phonons in the electron-hole thermalization process. It makes more sense to remove the substrate (by polishing and etching), reduce the sample thickness to 1–2 μm, cleave it into rectangular form (10–50 μm × 100–500 μm, [100] orientation), and sandwich it between sapphire on one side and metal on the other.[10] A critical matter, which we will elucidate in describing the data, is whether the metal is folded up along the four sample edges to make them more reflecting or whether the edges are left bare and thus only weakly reflecting.

The QWH for which we show data here is shown in Fig. 1. The $Al_xGa_{1-x}As$-GaAs QWH crystal is grown on (100) GaAs substrates by usual MOCVD processes[11] in an EMCORE GS 3000 DFM reactor. The transmission electron microscope (TEM) image of Fig. 1 shows only the active region, which consists of a central 325 Å GaAs well sandwiched on either side by a six-period SL with 30 Å GaAs wells and 50 Å $Al_{0.2}Ga_{0.8}As$ barriers. The active region, which serves as a waveguide for recombination radiation, is sandwiched on top and bottom by 0.5 μm $Al_{0.3}Ga_{0.7}As$ layers that have on their boundaries 0.1 μm $Al_{0.8}Ga_{0.2}As$ confining layers to prevent surface recombination losses. This choice of layer compositions and thicknesses ensures good absorption of the 5145 Å Ar laser pump signal and, of even greater importance, insures copius LO phonon generation in a narrow energy range (35–36 meV)[12] because the GaAs LO mode is much stronger ($x \lesssim 0.3$) than the AlAs mode.

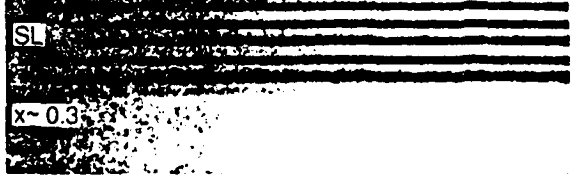

FIG. 1 Transmission electron microscope (TEM) image of the active region of an $Al_xGa_{1-x}As$-GaAs QWH designed for observation of phonon-assisted laser operation. The active region consists of two six-period superlattices (30 Å GaAs wells and 50 Å $Al_{0.2}Ga_{0.8}$ barriers) separated by a 325 Å GaAs well.

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0003-6951/89/111022-03$01.00

Ref. 16

Photopumped phonon-assisted laser operation (77 K) of $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ quantum well heterostructures

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The photopumped phonon-assisted laser operation (612 nm, 77 K) of a high-gap $In_{1-y}(Al_xGa_{1-x})_yP$ quantum well heterostructure (QWH) lattice matched to GaAs ($y \approx 0.5$) is identified using a single rectangular sample that is shifted in its heat sinking from (a) low Q when clamped onto Au (bare edges) to (b) high Q when further compressed into Au with all four edges reflecting. For the low-Q QWH sample photopumped in a spot (partially photopumped), phonon-assisted laser operation (abrupt threshold, narrow spectrum) is observed on closely spaced end-to-end laser modes $\Delta E = \hbar\omega_{LO} \approx 45$–47 meV below the lowest confined-particle transitions. For the *same* sample shifted to high Q, edge-to-edge laser operation across the sample on confined-particle transitions is "turned on" also, thus providing an unambiguous experimental reference ($\hbar\omega_{LO} \approx 45$–47 meV) for the phonon sideband.

The development of metalorganic chemical vapor deposition (MOCVD)[1,2] and molecular beam epitaxy (MBE)[3] in the last dozen years has made possible utilization of Al-Ga substitution to fabricate, among other possibilities, higher gap III-V compounds, specifically now $In_{1-y}(Al_xGa_{1-x})_yP$ heterojunctions and quantum well heterostructures (QWHs). As a result the $In_{1-y}(Al_xGa_{1-x})_yP$ quarternary lattice matched to GaAs ($y \approx 0.5$) has begun to receive increasing attention. A number of workers have reported considerable progress in producing short-wavelength $In_{1-y}(Al_xGa_{1-x})_yP$ lasers lattice matched to GaAs.[4–10] Furthermore, Raman scattering experiments[11,12] have shown that the optical phonon modes of $In_{1-y}(Al_xGa_{1-x})_yP$ consist of three distinct types: GaP-like longitudinal optical (LO) phonons ($x = 0 \rightarrow 0.4$, $\hbar\omega_{LO} \approx 48 \rightarrow 46$ meV, InP-like LO phonons ($x = 0 \rightarrow 0.4$, $\hbar\omega_{LO} \approx 45$ meV), and AlP-like LO phonons ($x = 1 \rightarrow 0.4$, $\hbar\omega_{LO} \approx 57 \rightarrow 54$ meV). Until the present work, however, phonon-assisted laser operation of a high-gap system such as $In_{1-y}(Al_xGa_{1-x})_yP$ has not been observed. In this letter we report the photopumped laser operation (phonon-assisted laser operation) of rectangular $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ QWH samples that act as small phonon "spectrometers."[13]

Photopumped phonon-assisted laser operation of $Al_xGa_{1-x}As$-GaAs QWHs grown via MOCVD is now at least ten years old[14–17] but has been confirmed only recently as observable also on QWHs grown by MBE.[18] Laser operation (rectangular samples) on phonon sidebands has typically been recognized by a set of narrowly spaced end-to-end laser modes occurring one longitudinal optical (LO) phonon ($\Delta E = \hbar\omega_{LO}$) below the lowest confined-particle transitions, and thus below the fundamental absorption.[13–18] Several researchers, unable to observe phonon-assisted laser operation of MBE QWHs, have offered arguments disputing the existence of phonon-assisted laser operation of photopumped QWHs.[19–23] The recent demonstration that control of the edge-to-edge resonator Q across a cleaved rectangular sample is essential in confirming photopumped phonon-assisted laser operation of $Al_xGa_{1-x}As$-GaAs QWHs[13] (also strained-layer $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ QWHs),[24] as well as the independent observation recently of the phonon-assisted laser operation of $Al_xGa_{1-x}As$-GaAs QWHs grown via MBE,[18] leaves no doubt concerning observation of phonon-assisted laser operation of photopumped QWHs. So far the phenomenon of phonon-assisted laser operation has been observed only in GaAs and its derivative systems ($Al_xGa_{1-x}As$ or $In_xAl_xGa_{1-x}As$).[13,14–18,24] In this letter we present data demonstrating the photopumped phonon-assisted laser operation (77 K) of $In_{1-y}(Al_xGa_{1-x})_yP$ QWHs grown lattice matched on GaAs ($y \approx 0.5$). In addition, by shifting the cavity Q of a rectangular $In_{0.5}(Al_xGa_{1-x})_{0.5}P$ QWH sample from low Q to high Q, we show that laser operation on phonon sidebands can be identified unambiguously.

For observation of phonon-assisted laser operation of QWHs (partially photopumped in a small spot) it is important that the measurements be performed on cleaved samples with the substrates removed and with the (100) QWH samples (rectangles) embedded in soft metal (In or Au) under a sapphire window.[13,24] This results not only in excellent heat sinking, but more significantly, it allows the metal (In or Au) to be folded up along the cleaved edges so as to provide high edge reflection, and thus high cavity Q across the sample (small width, 10–50 μm). In this configuration, the Q across the sample at higher energies becomes comparable to the Q along the sample at lower energies (e.g., below the fundamental absorption). Thus, both widely spaced edge-to-edge laser modes occur on the confined-particle transitions as well as narrowly spaced end-to-end laser modes one phonon (LO) below the lowest confined-particle states. When the reflective metal does not cover the sample

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Ref. 17

Gain-loss model for the dependence of the stimulated-emission transition in AlGaAs-GaAs quantum well heterostructures on photoexcitation geometry

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The gain-loss laser oscillation condition is applied to photoexcitation geometries in which phonon-assisted laser operation is observed in AlGaAs-GaAs quantum well heterostructures (QWHs). The model is found to agree with a variety of experimental conditions in which cavity size, photoexcitation spot size, and mirror reflectivity are varied. Also, it serves to indicate further how others might have failed to observe phonon-assisted laser operation in QWHs and how photoexcitation geometries can be varied to verify these results.

Since the first discussion by Holonyak and co-workers of phonon-assisted stimulated emission in AlGaAs-GaAs quantum well heterostructures (QWHs) grown by metalorganic chemical vapor deposition (MOCVD),[1–4] considerable controversy has surrounded this recombination mechanism.[5–8] Theoretical arguments based on enhanced electron-phonon interaction and increased phonon occupation number in two-dimensional semiconductors have supported the claims.[2,4,9] However, other researchers have failed to observe these same features and have suggested other possible mechanisms to account for the results of Holonyak and co-workers.[1–4] Two recent developments have helped clarify this problem. First, Lo and Kolbas[10] independently have observed laser spectra in QWHs grown by molecular beam epitaxy (MBE) that are consistent with the results of Holonyak and co-workers on MOCVD QWHs. Second, Holonyak and co-workers[11] have shown recently that the laser transition depends not only on cavity size and photoexcitation spot size but also on mirror reflectivity (the edge boundary condition). In this letter we apply the laser threshold oscillation condition to photoexcitation geometries in which phonon-assisted laser operation is observed in AlGaAs-GaAs quantum wells.

The photopumped AlGaAs-GaAs QWH lasers described by the model of interest here have the following shared features: (1) the QW active regions are not intentionally doped; (2) the QW active regions are confined by high energy gap AlGaAs confining layers, and the photoexcitation laser beam ($\gtrsim 30\,\mu$m diameter) is still higher in energy so that the large electron-hole pair population photogenerated in the confining layers is collected by the quantum wells and thermalizes to the lowest confined-carrier states emitting LO phonons before recombining; (3) the (100) QWH samples are thinned to 1–2 μm and are cleaved into rectangles (10–50 μm $\times$ 50–250 μm) so that photopumped laser oscillation can occur either along their length or width; and (4) the rectangular QWH samples are heat sunk compressed in metal under a sapphire window.[12]

Several of the many possible photoexcitation geometries are tabulated schematically in Fig. 1. The semiconductor sample is rectangular with sample length l and width w, and the circular photoexcitation beam is shown shaded with the photoexcitation dimension along the length denoted as a and across the width as b. Note that $a < l$ and $b < w$. These geometries are grouped in Fig. 1 according to the sample geometry aspect ratio, l/w, and the photoexcitation geometry aspect ratio a/b.

An example of the data that can be interpreted with the gain-loss model described here is shown in Fig. 2.[4] Two distinct sets of Fabry–Perot laser modes separated by $\hbar\omega_{\rm LO} \approx 36$ meV are observed when the rectangular sample (with high edge reflectivity)[11] is photoexcited fully across its width and only partially along its length. The closely spaced modes and the widely spaced modes represent laser oscillation along the length and across the width of the sample, respectively. The argument of Holonyak and co-workers[1–4,11] has been that the low-energy laser operation is phonon-assisted since (1) it is 36 meV (the energy of an LO

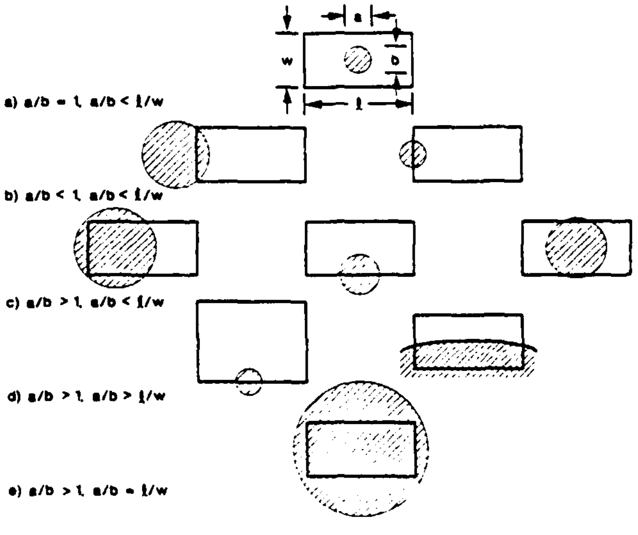

FIG. 1. Photoexcitation geometries on rectangular quantum well heterostructure (QWH) samples for various values of a/b and l/w. The photoexcitation spot is represented by the shaded circles. The sample and excitation spot configuration variables a, b, w, and l are defined in (a). Phonon-sideband laser operation is typically observed on samples excited as shown in (c).

PHONON-ASSISTED STIMULATED EMISSION IN STRAINED-LAYER $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ QUANTUM WELL HETEROSTRUCTURES

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ABSTRACT

Data are presented demonstrating phonon-assisted laser operation (77 and 300 K) of photopumped strained-layer $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ ($x \sim 0.15$) quantum well heterostructures (QWHs) grown using metalorganic chemical vapor deposition. When a cleaved rectangular sample (10-50 μm x 100-500 μm) of the QWH, with GaAs substrate removed, is imbedded in In under a sapphire window (for 77 K data), and the In is folded upward along the cleaved edges to provide high edge reflection and high cavity Q, closely spaced end-to-end laser modes (9000 Å) occur along the sample at an energy one LO phonon below the lowest confined-particle transition ($\Delta E = \hbar\omega_{LO} \approx 36$ meV), and widely spaced edge-to-edge laser modes occur across the sample on confined-particle transitions. For comparison, the experiment is repeated with rectangular QWH samples clamped on Au with a sapphire window, but with no metal folded onto

the sample edges, thus insuring low reflectivity at the cleaved edges (low Q cavity). In the low Q resonator configuration, all of the high energy modes (transitions on confined-particle states) disappear, and only the low energy phonon-assisted laser modes are evident. This comparison (high-Q versus low-Q photoexcitation), as well as the abrupt turn-on of laser operation in a narrow spectral range one phonon ($\Delta E = \hbar\omega_{LO} \approx 36$ meV) below the lowest confined-particle transitions, leads to unambiguous identification of phonon-assisted laser operation of a strained layer $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ QWH. In addition, bandfilling is demonstrated through the entire well depth of an $L_z \approx 125$ Å $In_xGa_{1-x}As$ QW to well above 150 meV into the GaAs "QW" containing the strained layer.

PHOTOPUMPING OF QUANTUM WELL HETEROSTRUCTURES AT HIGH OR LOW Q: PHONON-ASSISTED LASER OPERATION

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Data are presented showing the basic difference in the stimulated emission spectrum of a photopumped $Al_xGa_{1-x}As$-GaAs or $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure (QWH) heat sunk in a high-Q versus a low-Q configuration. In the former case a 1-2 μm thick narrow (25-50 μm) cleaved rectangle, with the (100) GaAs substrate removed, is heat sunk compressed in In under a sapphire, giving a high cavity photon lifetime because of metal reflectors folded up along the four samples edges. In the latter case (low Q) the (100) QWH rectangle is clamped under a sapphire into simple contact with Au, leaving the four cleaved {110} sample edges lossy and yielding, compared to carrier thermalization times, a short resonator photon lifetime across the sample. For photopumping (77 K, Ar^+ laser, 5145 Å) of a low-Q QWH sample, only lower energy recombination radiation is observed, including phonon-assisted laser operation (if the QWH is designed with good carrier, phonon, and photon confinement and with low composition thermaliza-

tion layers generating GaAs-like phonons near the QW). For photopumping of an otherwise similar QWH heat sunk in the high-Q configuration (long photon lifetime across the sample), recombination at higher energy can compete with carrier thermalization, and laser operation is observed on the confined-particle transitions, thus making unambiguous the identification of phonon sideband laser operation. Comparison of various QWHs heat sunk low Q or high Q reveals the heterostructure configurations appropriate for phonon-assisted laser operation.

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Broadband long-wavelength operation (9700 Å $\gtrsim \lambda \gtrsim$ 8700 Å) of $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure lasers in an external grating cavity

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Data are presented on *p-n* $Al_yGa_{1-y}As$-GaAs-$In_xGa_{1-x}As$ quantum well heterostructure lasers showing that the large band filling range of a combined GaAs-$In_xGa_{1-x}As$ quantum well makes possible a very large tuning range in external grating operation. Continuous 300 K laser operation is demonstrated in the 8696–9711 Å range ($\Delta\lambda \sim 1000$ Å, $\Delta\hbar\omega \sim 150$ meV) and pulsed operation in the 8450-9756 Å range ($\Delta\lambda \sim 1300$ Å, $\Delta\hbar\omega \sim 200$ meV). The band filling and gain profile are shown to be continuous from the $In_xGa_{1-x}As$ quantum well ($L_z \sim 125$ Å, $x \sim 0.2$) up into the surrounding GaAs quantum well ($L_z \sim 430$ Å).

Ref. 21

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[54] **SEMICONDUCTOR LIGHT EMITTING DEVICE WITH STACKED ACTIVE REGIONS**

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[58] **Field of Search** 357/16, 17; 372/44, 372/45, 46, 50

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[57] **ABSTRACT**

A layered structure is disclosed which includes a stack of alternating active regions and confining layers arranged so that each active region is sandwiched between confining layers. Each active region preferably includes one or more quantum well layers disposed between barrier layers. Carrier injection means are provided for injecting carriers into the layered structure to cause phase locked light emission from the active regions. In this manner, an output laser beam can be obtained that has substantially improved far field divergence as compared, for example, to a beam emanating from a single active region.

28 Claims, 8 Drawing Sheets