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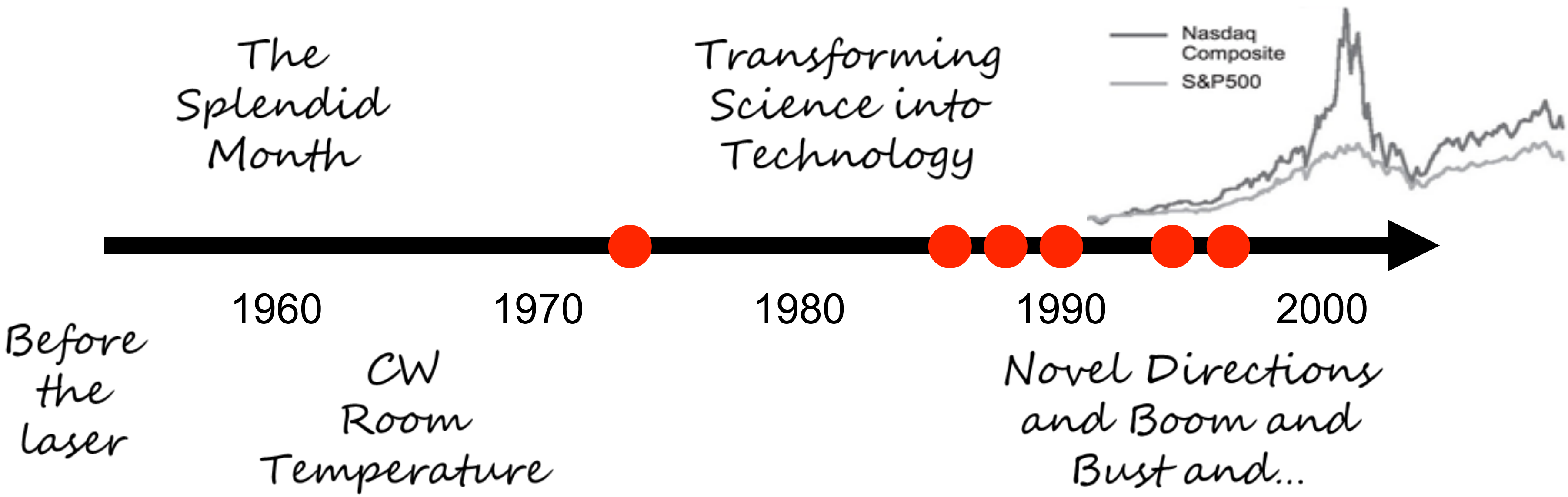
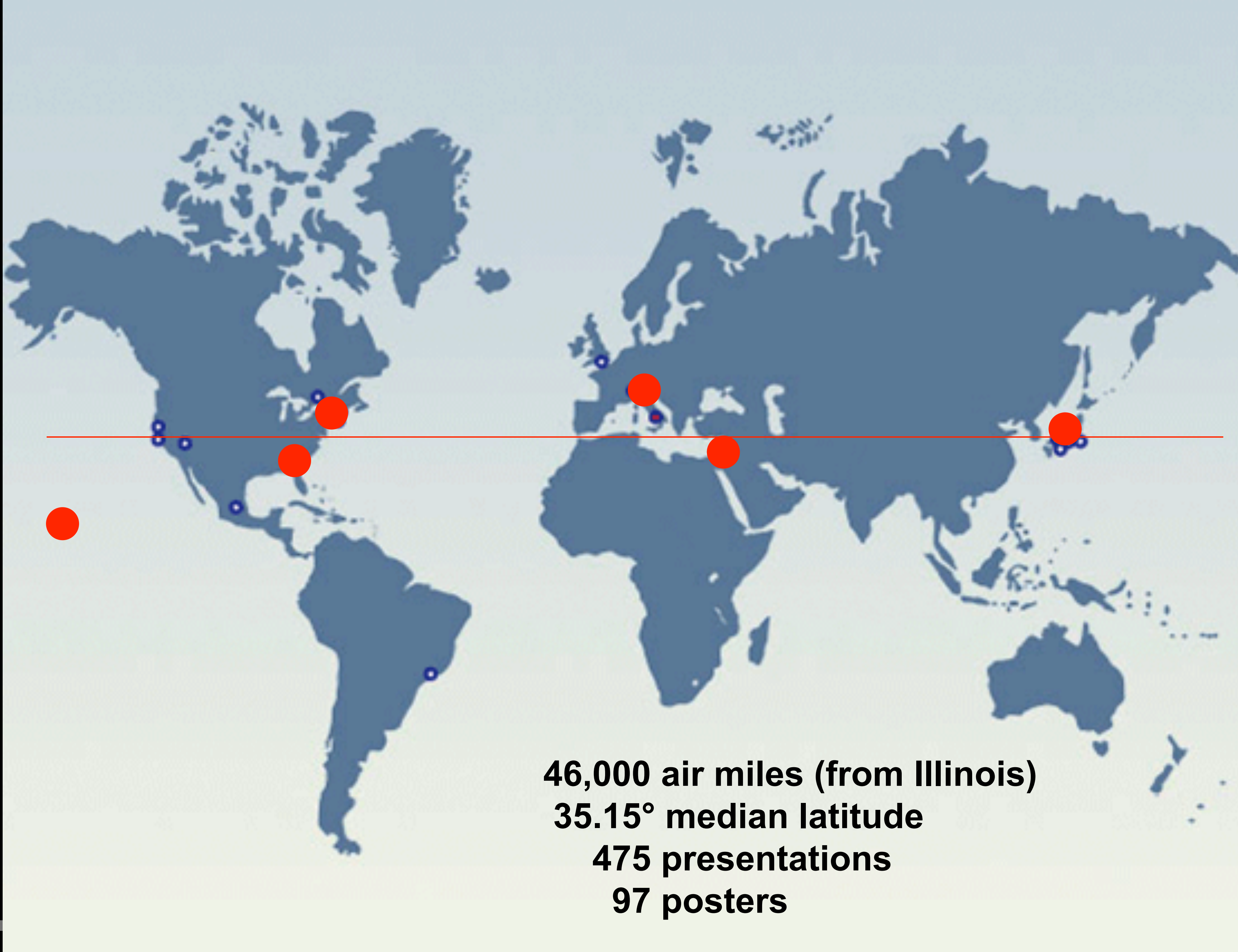
Forty$^{(+)}$ Years of the Semiconductor Laser Conference

James J. Coleman

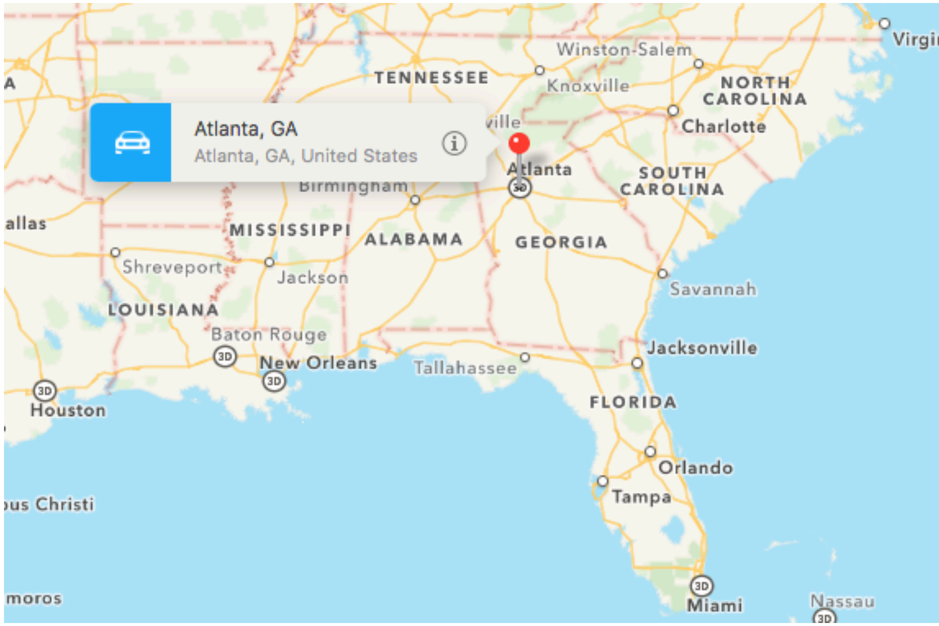
Outline

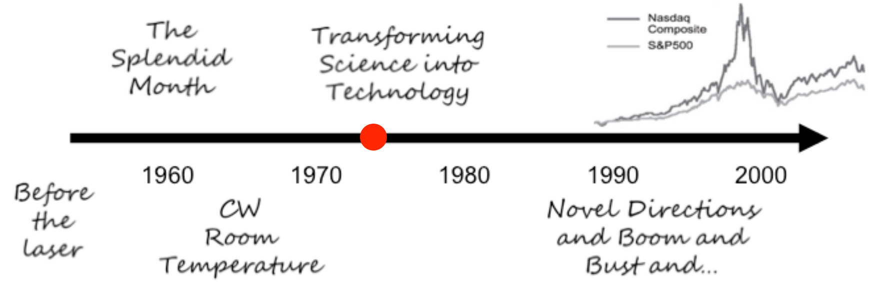


The Splendid Month
Transforming Science into Technology
Nasdaq Composite
S&P500
1960
1970
1980
1990
2000
Before the laser
CW Room Temperature
Novel Directions and Boom and Bust and...


46,000 air miles (from Illinois)
35.15° median latitude
475 presentations
97 posters

1974 Atlanta





46 papers in 6 sessions

Modal properties of lasers
Distributed feedback lasers
Laser degradation
Transient effects
Lead-salt lasers
Visible lasers

*"GaAs-GaA1As double heterostructure injection lasers with distributed feedback," *M. Nakamura, K. Aiki, J. Umeda, A. Katzir, A. Yariv, and H. W. Yen.*

*"Integrated twin-guide A1GaAs laser with multi-hetero structure," *Y. Suematsu, M. Yamada, K. Hayashi, K. Furuya, and S. Ibukuro.*

*"Grating-coupled A1GaAs double-heterostructure diode lasers," *P. Zory and L. D. Comerford.*

1974

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-11, NO. 7, JULY 1975 471

Liquid Phase Epitaxial $In_{1-x}Ga_xP_{1-z}As_z/GaAs_{1-y}P_y$ Heterojunction Lasers

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Abstract—The growth and laser properties of $In_{1-x}Ga_xP_{1-z}As_z/GaAs_{1-y}P_y$ single heterojunction laser diodes are described. High-quality p-type $In_{1-x}Ga_xP_{1-z}As_z$ layers are grown by liquid phase epitaxy (LPE) on n-type VPE $GaAs_{1-y}P_y$ substrates of composition $y = 0.32 - 0.40$. Laser operation (77 K) of these quaternary-ternary heterojunctions is demonstrated at shorter wavelengths (<6300 Å) and lower thresholds ($J_{th} \lesssim 6.2 \times 10^4$ A/cm²) than comparable $GaAs_{1-y}P_y$ homojunctions. The increase observed in threshold current (5x) between $y = 0.38$ and $y = 0.40$ $GaAs_{1-y}P_y$ substrates is attributed to the usual effect of E_X approaching E_Γ near the direct-indirect transition. From the well-defined cavity mode structure observed on these heterojunctions, data are obtained at relatively high energy on the index dispersion quantity $\{n - \lambda(dn/d\lambda)\}$, which increases monotonically with photon energy and provides a reference for the distinctly different behavior observed on N-doped $GaAs_{1-y}P_y$ ($h\nu \sim E_\Gamma \sim E_N$).

Introduction

FROM earlier work it is known that by means of liquid phase epitaxy (LPE) the quaternary AlGaAsP can be grown on the ternary GaAsP, thus permitting the formation of single and double heterojunction lasers [1], [2]. Unfortunately this method of forming a heterojunction on $GaAs_{1-y}P_y$ is difficult if the GaP percentage y in the ternary is appreciable ($y \gtrsim 0.10$), higher compositions y leading to relatively high (inconvenient) growth temperatures [3]. A different approach to the problem of growing a wide-gap emitter on $GaAs_{1-y}P_y$ is to utilize $In_{1-x}Ga_xP$, which can be grown of laser quality on $GaAs_{1-y}P_y$ or GaAs ($x = 0.52 + 0.48y$, $0 \leq y \leq 1$) by means of constant-temperature LPE [4]-[7]. The only problem relative to heterojunction fabrication via the approach of growing a second epitaxial layer (LPE) on a previously grown first layer (VPE) is that of defect formation at the metallurgical junction (not necessarily in the LPE layer itself) if a good lattice match is not accomplished. Achieving a good lattice match turns out to be a difficult procedure. That is, it is quite difficult to control all of the LPE growth parameters so that the $In_{1-x}Ga_xP$ layer is well lattice matched on the $GaAs_{1-y}P_y$ substrate in the sense that the metallurgical junction is adequately free of boundary ("surface") defects, and likewise the LPE layer itself (etch pit density $\lesssim 10^4/cm^2$).

We find that the problem of lattice matching $In_{1-x}Ga_xP$ on a $GaAs_{1-y}P_y$ substrate is eased if the ternary is rendered a quaternary by the incorporation of a small amount ($z \sim 0.01$) of As in the LPE layer changing it to $In_{1-x}Ga_xP_{1-z}As_z$ [8]. Small deviations Δx in the Ga composition x of $In_{1-x}Ga_x \cdot P_{1-z}As_z$ from the lattice-match condition on $GaAs_{1-y}P_y$ then are capable of being balanced by compensating small deviations Δz in As composition z that hardly change the electrical and optical behavior of the quaternary LPE layer, which itself ($z \sim 0.01$) is not much different in electrical and optical behavior from the ternary $In_{1-x}Ga_xP$ that lattice matches the $GaAs_{1-y}P_y$ substrate. If an increase (decrease) Δx in Ga percentage occurs in the $In_{1-x}Ga_xP_{1-z}As_z$ LPE layer from the proper composition for a lattice match on $GaAs_{1-y}P_y$, the lattice constant decreases (increases; see Fig. 1). This change in lattice constant is compensated by a corresponding increase (decrease) Δz of As in the crystal, which increases (decreases) the lattice constant sufficiently to keep it constant. The net

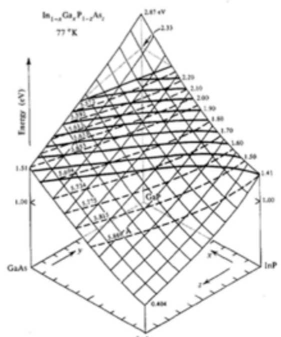

Fig. 1. Energy-gap surface (77 K) as a function of crystal composition for the quaternary alloy system $In_{1-x}Ga_xP_{1-z}As_z$. The edges are divided into mole fractions of the individual binary constituents. Plotted also on the surface are isolattice-constant lines (dashed, 5.869–5.572 Å) and isoenergy-gap lines (solid, 1.41–2.20 eV). From the fact that the isolattice-constant and isoenergy-gap lines intersect, it is apparent that a wide range of compositions of $In_{1-x}Ga_xP_{1-z}As_z$ of higher energy gap can be grown along an isolattice-constant line on $GaAs_{1-y}P_y$ of lower energy gap, making possible also the growth of $In_{1-x}Ga_xP_{1-z}As_z/In_{1-x'}Ga_{x'}P_{1-z'}As_{z'}$ ($x \neq x'$, $z \neq z'$) homoheterojunctions.

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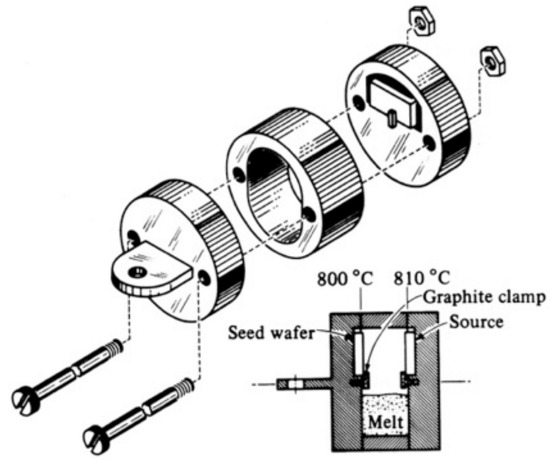
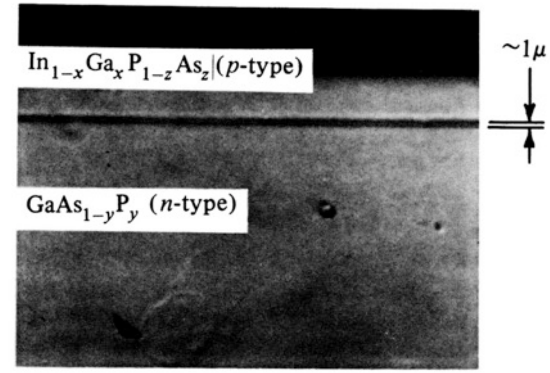
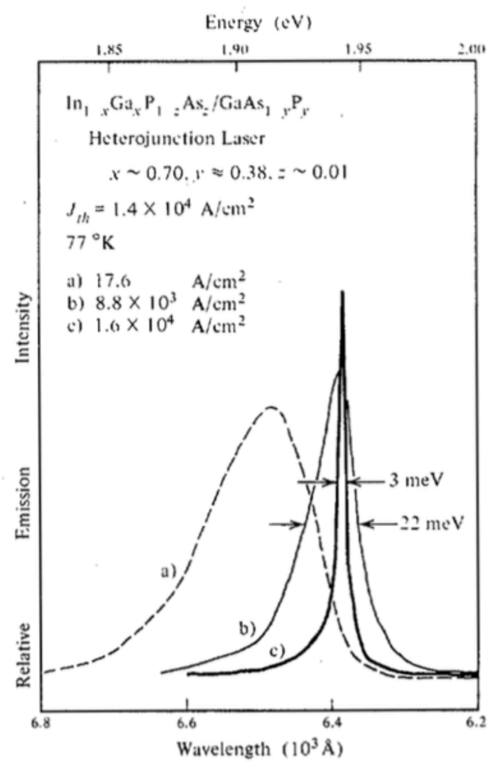
W. O. Groves and D. L. Keune are with the Monsanto Company, St. Louis, Mo. 63166.

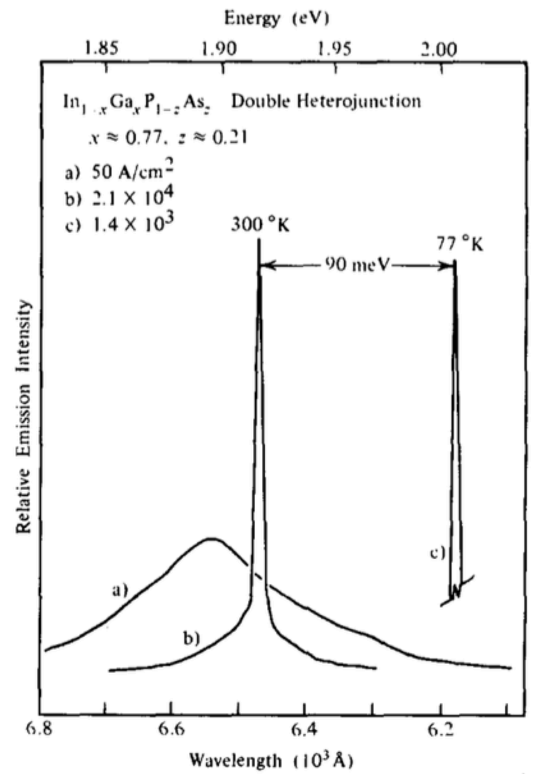




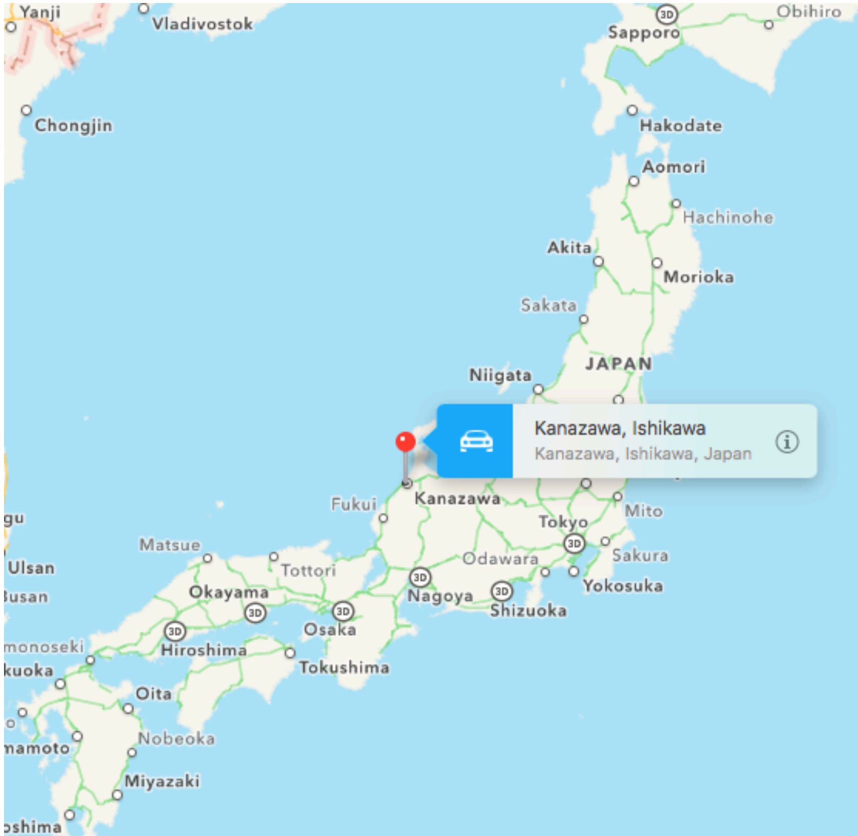
$In_{1-x}Ga_xP_{1-z}As_z/GaAs_{1-y}P_y$ Heterojunction

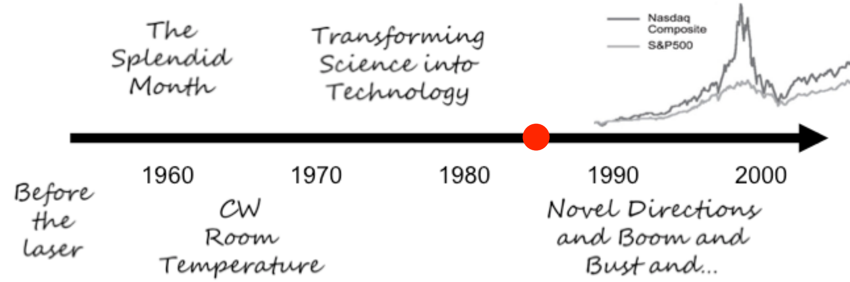
$x \sim 0.70$, $y \approx 0.38$, $z \sim 0.01$





1986

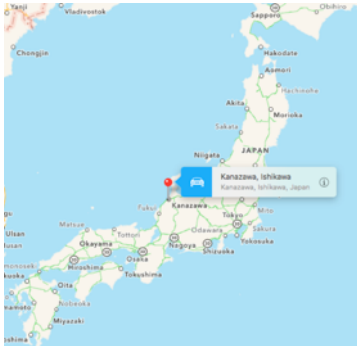




99 papers in 16 sessions

Visible lasers
Integrated lasers
Distributed feedback lasers (2)
Laser arrays
High power lasers
Quantum well lasers
Long wavelength lasers

1986


Kanazawa, Ishikawa
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Morioka
Sakata
Niigata
Kanazawa
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Tokyo
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NTH IEEE INTERNATIONAL
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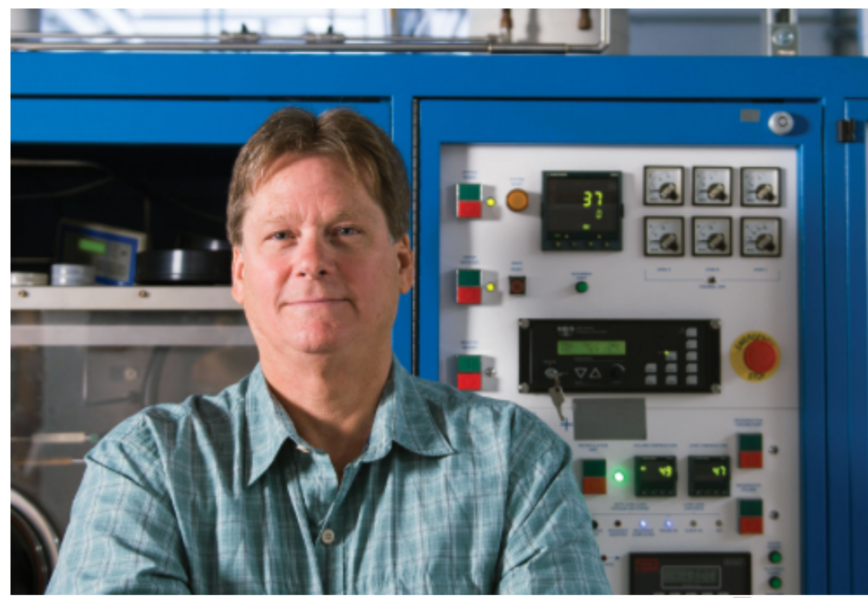
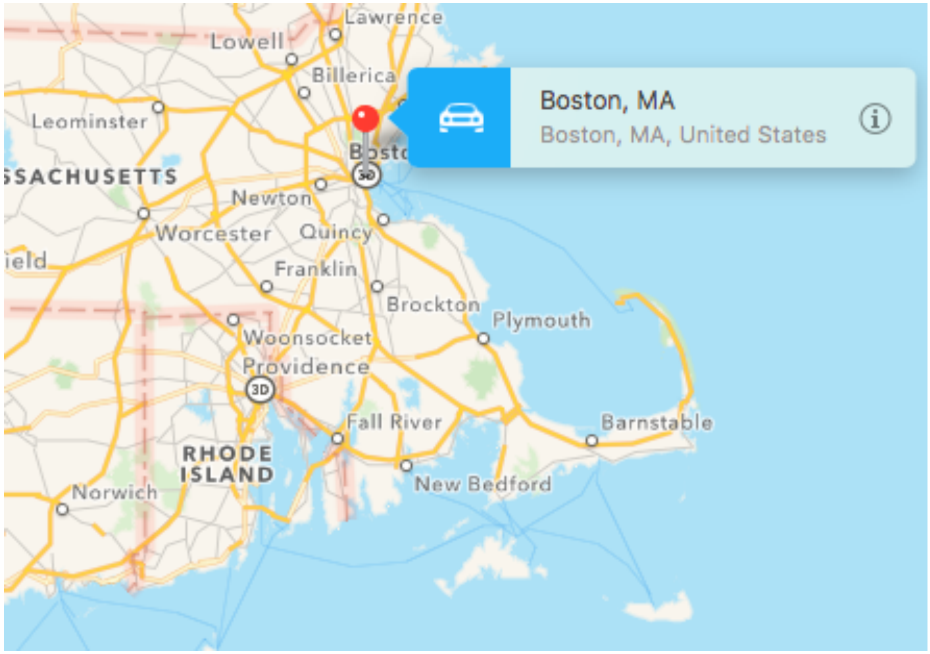
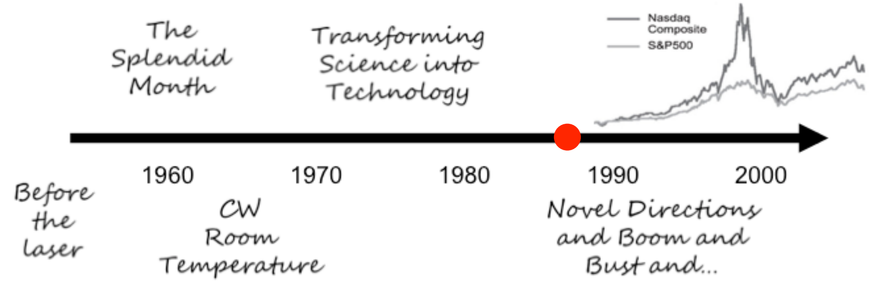
1986 Kanazawa



1988





92 papers in 17 sessions

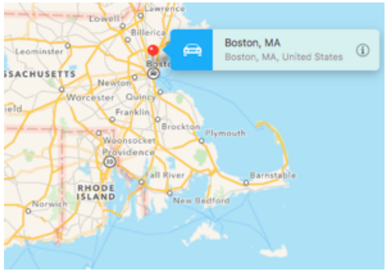
Grating lasers (3)

Quantum well lasers (3)

Phase locked arrays

Surface emitters (VCSEL)

1988



Nonplanar index-guided quantum well heterostructure periodic laser array

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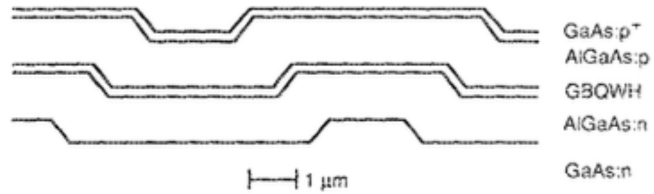
Data are presented on nonplanar index-guided quantum well heterostructure periodic laser arrays grown by metalorganic chemical vapor deposition (MOCVD). The nonplanar array structure, formed by a single MOCVD growth over a selectively etched corrugated substrate, not only provides index guiding for the individual array elements, but also suppresses lateral lasing and amplified spontaneous emission for the entire array. As a result, the entire width of the device is utilized for optical emission, and no additional processing steps are required. Devices tested exhibit uniform emission and show no signs of lateral lasing or amplified spontaneous emission for array widths up to 3.3 times the cavity length. required for device fabrication is therefore minimized by taking advanta MOCVD growth over nonplanar substrates.

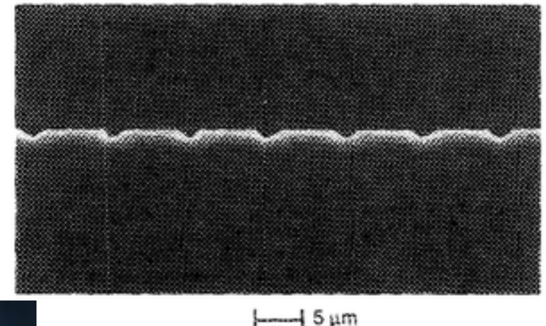
Multiple stripe laser arrays have proven to be a most promising source of high-power emission from semiconductor materials which are suitable for such applications as pumping solid-state neodymium: yttrium aluminum garnet lasers.[1] The maximum total optical power obtainable from a semiconductor laser or laser array is generally limited[2] by catastrophic optical degradation (COD) of the laser facets which occurs at a given facet output power density. Increasing the effective width of the emitting facet by distributing the laser emission over a number of elements in an array decreases the power density, thereby raising the total output power at COD. In most laser structures, the aperture width can only be increased to a value on the order of the cavity length ($\approx 400\,\mu m$), at which point lateral lasing and amplified spontaneous emission mechanisms become large with respect to the desired front facet emission. Lateral lasing and amplified spontaneous emission can be inhibited by isolating suitably narrow active regions of the array either by defining unpumped absorbing regions[3] or by etching deep grooves through the laser structure[4,5] at periodic intervals. However, these solutions result in a fraction of the array width not being utilized for optical output and require additional processing steps.

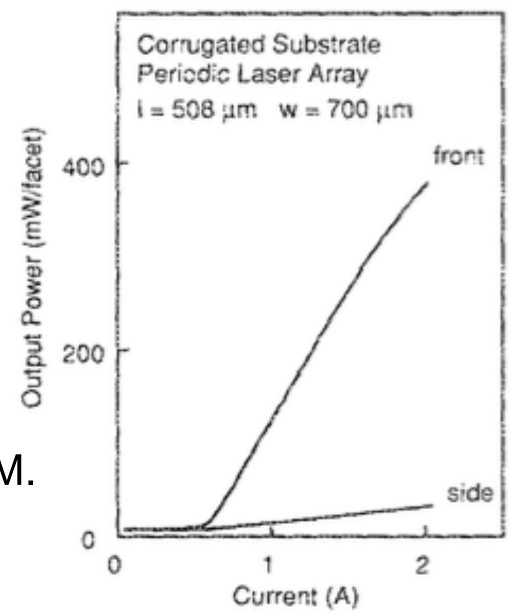
In this letter, we report the growth and fabrication of a simple nonplanar index-guided quantum well heterostructure periodic laser array structure in which lateral lasing is prevented in a manner that still allows for uniform and continuous front facet light emission. Growth over a periodically patterned substrate[6,7] is utilized to provide an index-guided structure and to define the individual elements of the array. In addition, the resulting nonplanar structure of the array itself serves to inhibit lateral lasing, in contrast to previously utilized methods which require additional fabrication steps. The array is formed simply by etching a corrugated stripe pattern into the substrate surface, growth of the laser structure by metalorganic chemical vapor deposition (MOCVD), and contact metallization. No further processing steps, such as proton bombardment, chemical etching, diffusion, epitaxial regrowth, or insulator deposition, which

... and (111)A planes are approximately equal such that successive epilayers were deposited uniformly over the nonplanar growth surface. These nearly equal growth rates resulted in an effective widening of the stripe geometry mesas and narrowing of the adjacent grooves as the total epitaxial layer thickness increased, although the corrugated contour

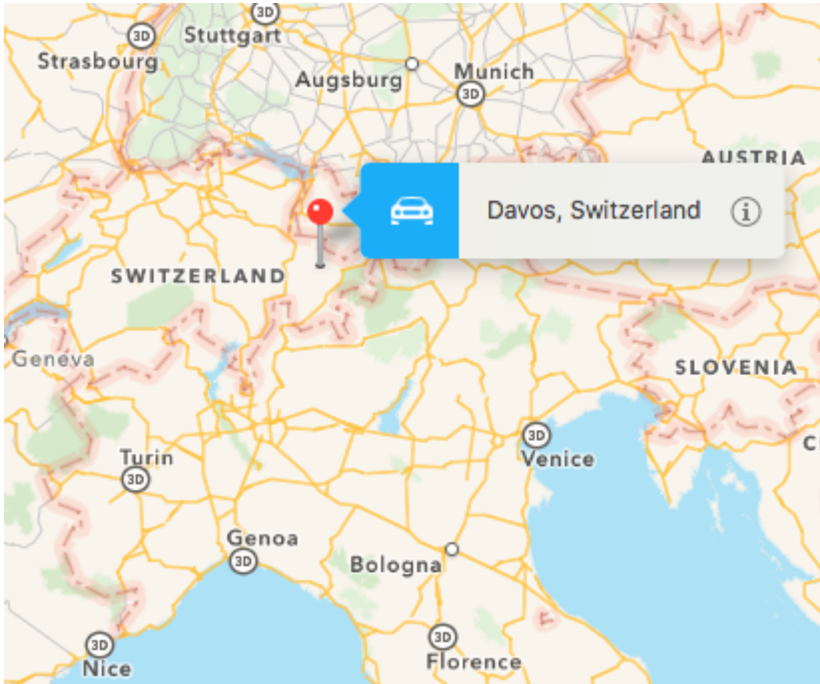
Rev. Charles Zmudzinski, C.P.M.

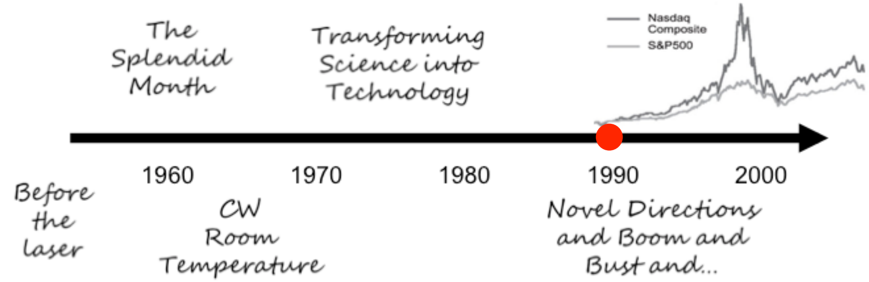






1990





88 papers in 15 sessions and 31 posters

VCSELs

Visible lasers

Strained layer lasers

DFB lasers

Quantum wells

Phase locked arrays

Integrated lasers

High power lasers

1990

In-phase operation of high-power nonplanar periodic laser arrays

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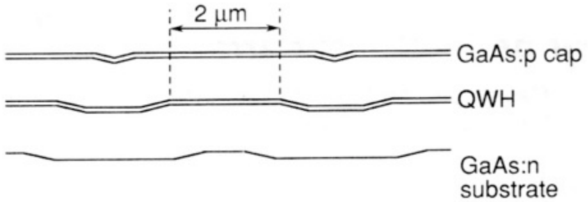
The transformation of nonplanar periodic laser array modes from weakly locked out-of-phase to locked in-phase operation is investigated. A comparison study of near-field and far-field patterns is made for devices with differing mesa widths and heights. Data are presented which show that the mesa height and width can be adjusted to force in-phase operation. An array of 19 elements shows an essentially single-lobed far-field pattern centered at 0° with full width at half maximum of 1.6°, to output powers of more than 500 mW/uncoated facet.

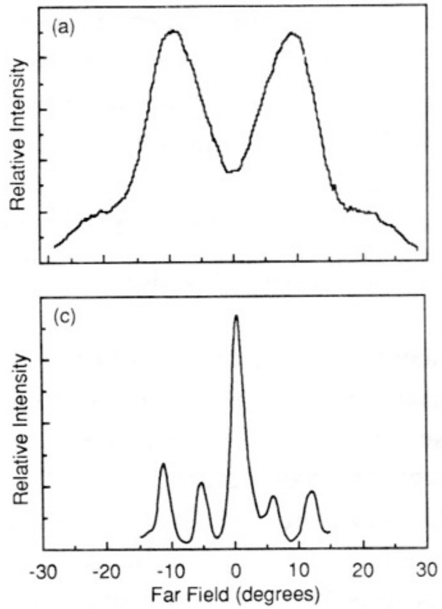
Recently there has been considerable interest in developing high-power arrays[1–5] which may be used in such applications as pumping of solid-state lasers, long distance communication, lidar, high-speed modulation, and optical recording. In many applications, the optical output power needs to be a nearly diffraction limited single-lobed beam. However, coherent semiconductor laser arrays typically operate with each element locked out of phase which leads to a double-lobed far-field pattern. Several array structures including leaky waveguide arrays,[3] Y-coupled arrays,[1,6,7] diffraction-coupled arrays,[8] and offset stripe arrays[9] have been developed which exhibit stable, single-lobed far-field patterns. However, in general, these methods require some combination of multiple growths and sophisticated or complex processing. We report in this letter a relatively simple procedure to obtain high-power, in-phase operation of wide aperture laser arrays which require only simple processing and a single metalorganic chemical vapor deposition (MOCVD) growth. Index-guided laser structures grown on patterned substrates[10] can be formed into high power, wide aperture laser arrays[11,12] made possible by the incorporation of a nonplanar active region in the form of a regular pattern of mesas and grooves to suppress lateral lasing and amplified spontaneous emission. We have investigated the characteristics and, in particular, the far-field pattern of devices with various mesa heights and widths. By varying the width and the height of the mesas, we are able to transform the array elements from being weakly locked out of phase to being locked in phase. Consequently, we obtain a single-lobed far-field pattern from the laser array. Stable, near-diffraction-limited operation is obtained to over five times threshold with more than 500 mW/per facet of optical power for devices 150 μm wide and 380 μm long.

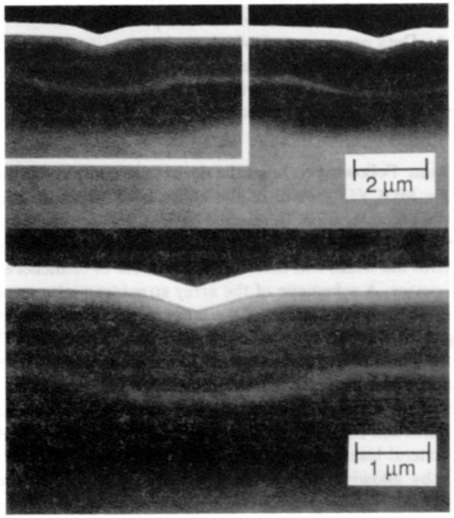
The laser device configuration utilized for this study is similar to nonplanar periodic laser arrays reported previously.[10,11] The laser structure is an AlGaAs-GaAs graded barrier quantum well heterostructure with a 50 Å quantum well grown by MOCVD. The first step in forming the array is wet chemical etching of a periodic pattern of mesa stripes into a GaAs substrate. We have investigated devices with shallow and deep mesas (0.3 μm and 0.6 μm etch depth respectively) as well as wide and narrow mesas (3.1 μm and 2 μm width at the active region, respectively). The center-to-center spacing between mesas was kept constant at 8 μm. Following etching, the devices are completed by a single MOCVD growth of the entire laser structure and contact metallization. In selected devices, 150-μm-wide oxide defined stripes were incorporated in order to accurately control the width and therefore the number of elements of the device. A schematic of the array structure and a scanning electron micrograph of the cross section are shown in Fig. 1 of the narrow, shallow mesa array. The MOCVD growth on a corrugated substrate forms a nonplanar active region which provides[10,11] definition of the individual emitters of the array, formation of a step in the effective index of refraction for stable mode operation, and suppression of the lateral lasing and the amplified spontaneous emission, thereby allowing high-power operation of wide aperture devices.

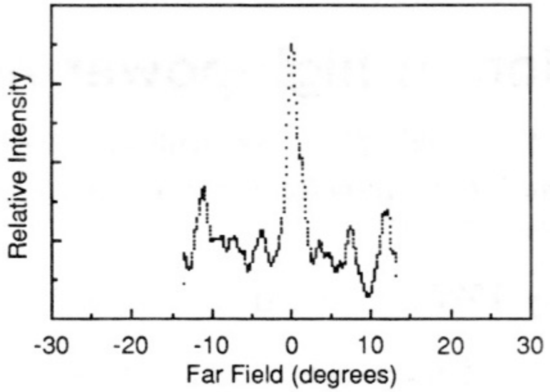
As reported previously,[12] the far-field patterns of devices with wide, deep mesas are very broad and double lobed. In order to determine the parameters which lead to the transformation from weakly locked out-of-phase to stable in-phase operation, we compared the far-field pattern of devices with different widths and heights of the mesas. For the comparison, the length and the width of the devices were kept relatively constant at 380 and 560 μm, respectively. Figure 2(a) shows the far-field pattern for a nonplanar laser array with mesas 0.6 μm high and 3.1 μm wide. The far-field pattern consists of two broad lobes at approximately ±10°. The full width at half maximum (FWHM) for each is ~12° with no null at 0°. These patterns indicate that the emitters of the device are weakly locked out of phase. In the far field of the wide (3.1 μm), shallow (0.3 μm) mesa devices we observe a reduction of the width of the lobes as shown in Fig. 2(b). The far-field pattern is also double lobed with a narrower FWHM (~5°) for these devices and the minimum at zero is more pronounced. For narrow (2 μm), shallow (0.3 μm) mesa devices the far-field pattern narrows to a predominantly single-lobed pattern. The FWHM for the main lobe is 2.2° with sidemodes spaced at 5.8–6.0° as shown in Fig. 2(c).

By reducing the mesa width at the active region from 3.1 to 2 μm and reducing the etch depth to only 0.3 μm, the far-field pattern switches from being a double-lobed pattern to a sharply peaked single-lobed pattern as seen in Fig. 2. Limiting the number of elements to nineteen with 150 μm oxide defined stripes further reduces the FWHM of the far-field pattern to 1.6° as shown in Fig. 3. Although









1990

Dependence of threshold current density on quantum well composition for strained-layer InGaAs-GaAs lasers by metalorganic chemical vapor deposition

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(Received 31 July 1989; accepted for publication 26 September 1989)

A series of separate confinement $In_xGa_{1-x}As$-GaAs ($0.08 < x < 0.42$) strained-layer quantum well lasers with 70 Å well thickness has been grown by metalorganic chemical vapor deposition. Data are presented on emission wavelengths and threshold current densities (J_{th}) as a function of composition. A minimum in J_{th} of 140 A/cm^2 was observed for devices with $In_{0.24}Ga_{0.76}As$ wells. The dependence of J_{th} on well composition is explained by a balance between strain effects and carrier confinement in the quantum well.

The use of lattice-mismatched thin layer structures in which the strain is accommodated elastically allows for greater flexibility in the design of semiconductor devices. One example is the utilization of strained-layer InGaAs active regions in AlGaAs/GaAs heterostructure laser diodes to increase the available range of wavelengths to $\lambda \sim 1.1$ μm.[1-11] Reports of high-power arrays,[4,6] cw reliability testing,[7,8] and low threshold current devices[5,9-11] indicate a strong future for strained-layer InGaAs-GaAs-AlGaAs laser diodes. The potential use of these strained-layer lasers in the 0.9–1.1 μm wavelength range for such applications as pumping Er^{3+}-doped optical fiber amplifiers,[12] Nd:YAG lasers, and other solid-state hosts calls for the characterization of these structures to determine the range of practical compositions and well sizes for a particular application. In this letter we report wavelengths and threshold current densities of broad-area separate confinement heterostructure (SCH) strained-layer InGaAs quantum well laser diodes with 70 Å well thickness and indium fractions ranging from 0.08 to 0.42. The emission wavelengths of these devices agree well with values calculated from a model which accounts for strain and quantum size effects. A minimum in threshold current density J_{th} is observed for wells with an indium fraction of ~0.25, and devices with well compositions in a range $0.16 < x < 0.30$ around this "optimum" composition also operated with acceptably low threshold current densities. The trend in J_{th} is explained by a balance between carrier confinement in the quantum well and strain effects.

The laser structures described here were grown by[13] metalorganic chemical vapor deposition (MOCVD) at atmospheric pressure in a vertical geometry reactor using ethyldimethylindium,[14] trimethylgallium, trimethylaluminum, and arsine. Silane and diethylzinc were used for *n*- and *p*-type dopants, respectively. Each structure consists of a 0.25-μm-thick GaAs:n^+ buffer layer grown on a (100) GaAs:n^+ substrate, *n*- and *p*-type 1.5-μm-thick $Al_{0.20}Ga_{0.80}As$ confining layers surrounding a single $In_xGa_{1-x}As$ ($0.08 < x < 0.42$) undoped strained-layer quantum well centered in a 0.2-μm-thick GaAs carrier collection layer, and a 0.2 μm GaAs:p^+ contact layer. Six different laser structures were grown sequentially with nominal $In_xGa_{1-x}As$ well compositions of $x = 0.08$, 0.16, 0.20, 0.24, 0.33, and 0.42.

Standard processing was used to fabricate 150-μm-wide oxide-defined stripes on each sample. The substrates were lapped and polished to a thickness of approximately 125 μm, and *n*-type contacts were formed by evaporating 250 Å Ge/2000 Å Au and alloying for 10 s at 400 °C. Nonalloyed 300 Å Cr/1500 Å Au contacts were evaporated on the *p* side. Various cavity lengths were formed by cleaving, and the resulting bars were cleaved into individual diodes for testing. Devices were tested under pulsed conditions (1.5 μs pulse width, 2 kHz repetition rate) at room temperature.

The emission wavelengths of devices with 815-μm-long cavities are shown as circles in Fig. 1. Devices with the largest indium fraction in this study ($In_{0.42}Ga_{0.58}As$ wells) emitted only very weak spontaneous emission for drive currents up to 2 A and we were unable to measure the wavelength of this light. There is good agreement between the measured wavelengths and the calculated values represented by the line in Fig. 1. The calculation of wavelength follows that of Pan *et al.*,[15] and accounts for both quantum size effects and the strain-induced shift of the InGaAs band-gap energy. The unstrained band gap used in these calculations is[16]

$$Eg(In_xGa_{1-x}As) = 1.42 - 1.615x + 0.555x^2 \text{ eV}.$$

All other material parameters were from Ref. 15. A 70/30 split of the heterojunction discontinuity between conduction and valence bands was assumed in the calculation.

The measured threshold current density J_{th} as a function of well composition for 815-μm-long devices is shown in Fig. 2. Note that all devices with $In_{0.42}Ga_{0.58}As$ wells failed

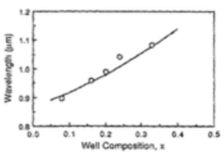
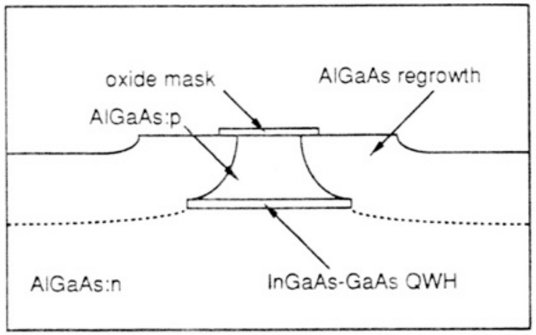
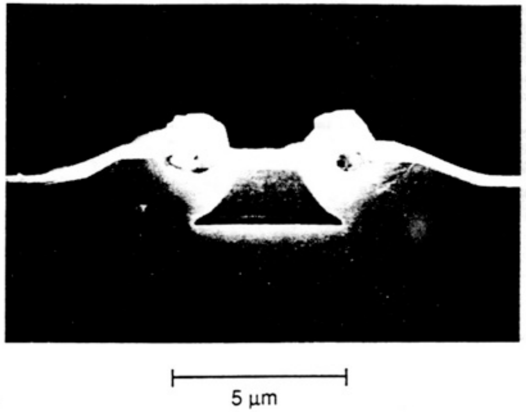
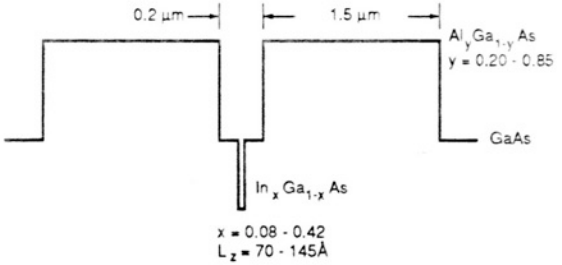
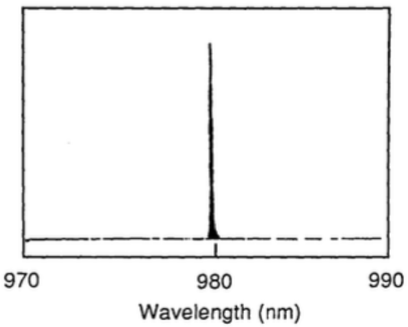


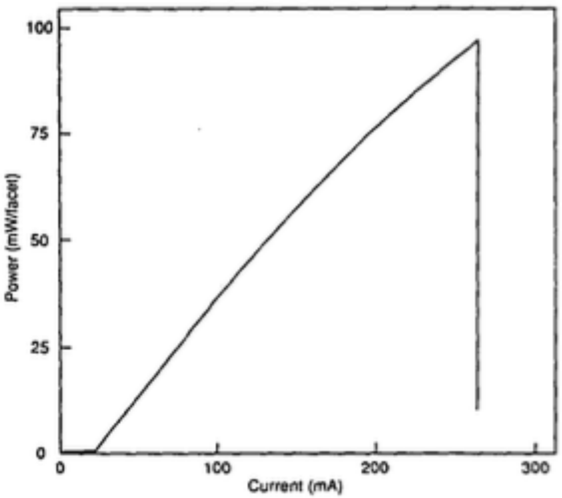
FIG. 1. Calculated and experimental emission wavelengths for 150×815 μm^2 devices with 70 Å $In_xGa_{1-x}As$ quantum wells.











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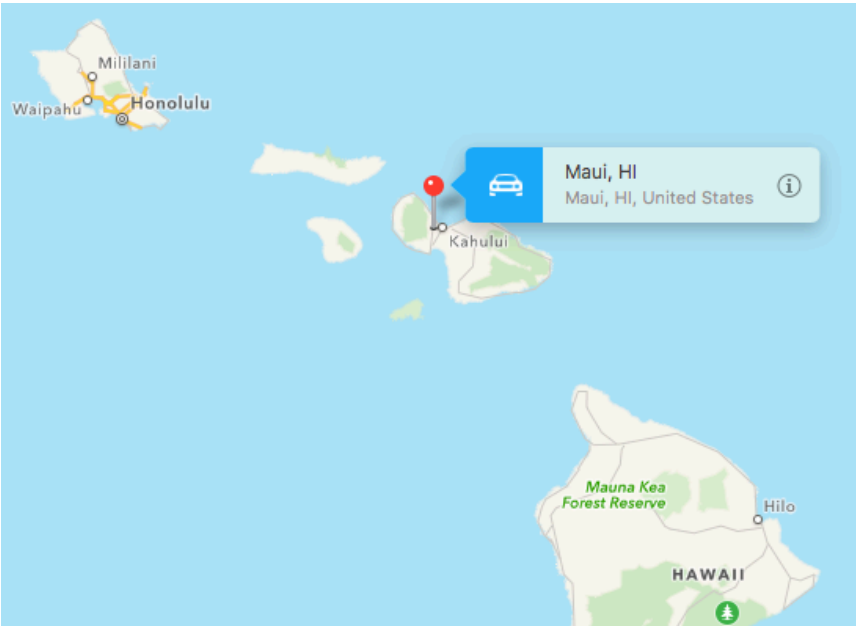

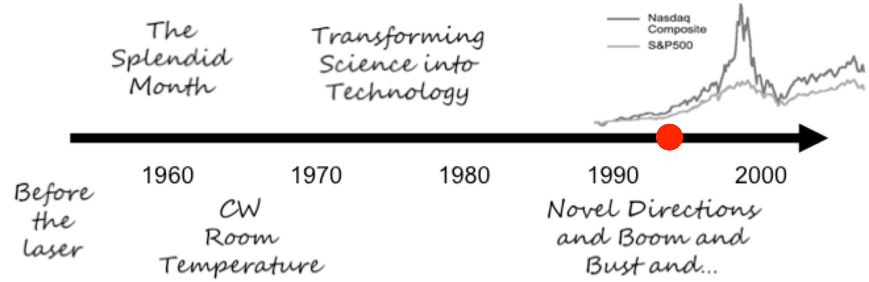

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VCSELs

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IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 30, NO. 2, FEBRUARY 1994 441

Strained-Layer InGaAs–GaAs–AlGaAs Buried-Heterostructure Quantum-Well Lasers by Three-Step Selective-Area Metalorganic Chemical Vapor Deposition

Timothy M. Cockerill, *Member, IEEE*, David V. Forbes, Jonathan A. Dantzig, and James J. Coleman, *Fellow, IEEE*

***Abstract*—Strained-layer $In_xGa_{1-x}As-GaAs-Al_yGa_{1-y}As$ buried-heterostructure (BH) quantum-well lasers have been fabricated using three-step selective-area atmospheric pressure metal-organic chemical vapor deposition. Selective-area epitaxy is used to produce BH lasers involving only GaAs on GaAs regrowth, eliminating the detrimental effects associated with exposed $Al_yGa_{1-y}As$ found in other fabrication methods. Additionally, selective-area epitaxy provides inplane bandgap energy control to fabricate BH devices with different wavelengths on the same wafer. Threshold currents as low as 11 mA are obtained for a 540-μm-long, 4-μm-wide device with uncoated cleaved facets. The devices operate at room temperature to more than 200 mW/uncoated facet with 40% external differential quantum efficiency. In-plane bandgap energy control results in a wide range of possible laser emission wavelengths for BH lasers grown on the same substrate.**

I. Introduction

Buried heterostructure (BH) lasers have been fabricated by a variety of techniques [1]–[9]. The most common method involves growing the entire laser structure, forming an active region mesa by wet or dry etching, and regrowing the burying layer [1]. For strained-layer $In_xGa_{1-x}As$-GaAs-$Al_yGa_{1-y}As$ quantum well lasers, this method exposes the easily oxidized $Al_yGa_{1-y}As$ optical confining layer, and requires the subsequent regrowth of $Al_yGa_{1-y}As$ on $Al_yGa_{1-y}As$. Since oxides of $Al_yGa_{1-y}As$ have desorption temperatures much higher than normal growth temperatures, they remain in the grown device causing poor crystalline quality and an optically lossy interface region. Etched mesa strained-layer BH lasers have been fabricated by hybrid growth techniques using either MOCVD or molecular beam epitaxy (MBE) for the initial growth and liquid phase epitaxy (LPE) for the regrowth [2]–[6]. All-MOCVD grown etched mesa strained-layer BH lasers have been reported which require the use of low aluminum composition optical confining and burying layers [7]. It is desirable to fabricate BH lasers without exposing $Al_yGa_{1-y}As$ and without initiating regrowth with $Al_yGa_{1-y}As$. This can be accomplished using selective-area conventional atmospheric pressure MOCVD growth over an oxide mask [10], [11].

Selective-area epitaxy over an oxide mask gives the advantage of GaAs on GaAs regrowth for fabricating strained-layer In_xGa_{1-x} As-GaAs-$Al_yGa_{1-y}As$ BH quantum-well lasers, and provides in-plane bandgap energy control to fabricate devices with different wavelengths on the same wafer for integrated optoelectronic applications. This process also enables the use of high composition $Al_yGa_{1-y}As$ for the burying layer, since no $Al_yGa_{1-y}As$ on $Al_yGa_{1-y}As$ regrowth is necessary. Control of the width of the mesa is provided by the spacing between pairs of oxide stripes. This gives improved width reproducibility over both wet etched BH lasers where undercutting determines the width and LPE regrown BH lasers where meltback affects the width. In this paper, we describe the fabrication process and show experimental results for strained-layer index guided $In_xGa_{1-x}As$-GaAs-$Al_yGa_{1-y}As$ BH quantum-well lasers fabricated using three-step selective-area atmospheric pressure metalorganic chemical vapor deposition. These lasers show a wide range of emission wavelengths, which is essential for optoelectronic integration applications, from in-plane bandgap energy control provided by selective-area growth rate enhancement of the strained-layer $In_xGa_{1-x}As$-GaAs active region.

II. MOCVD Growth

The devices used in this study were grown by conventional atmospheric pressure MOCVD in a vertical reactor on vertical gradient freeze grown epi-ready (100) GaAs:n substrates. The column III sources are trimethylgallium, trimethylaluminum, and trimethylindium and the column V source is 10% arsine in hydrogen. The n-type dopant is disilane, and the p-type dopant is diethylzinc. A three-step growth process is used to take advantage of the oxide-masked selective growth of GaAs and $In_xGa_{1-x}As$, and avoid the problematic growth of $Al_yGa_{1-y}As$ over an oxide [10]. Fig. 1 shows the three-step growth sequence used to fabricate the BH lasers. The first growth, shown in Fig. 1(a), consists of a 0.1-μm GaAs:n buffer

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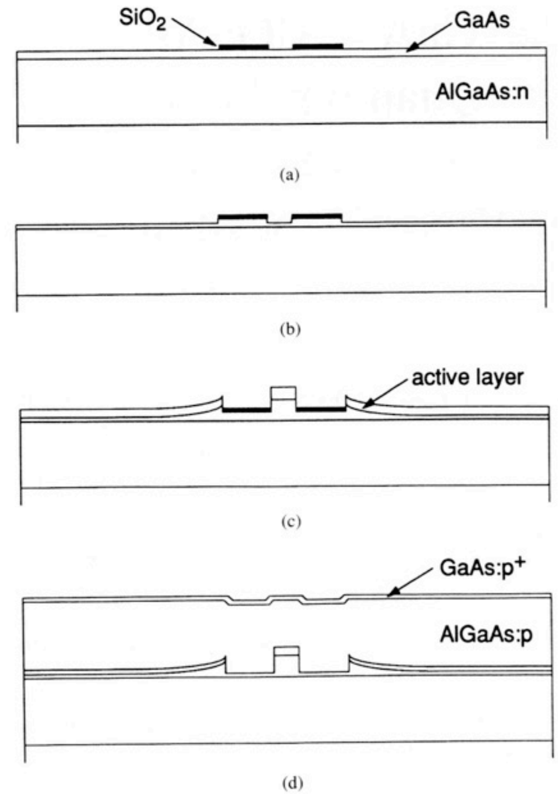

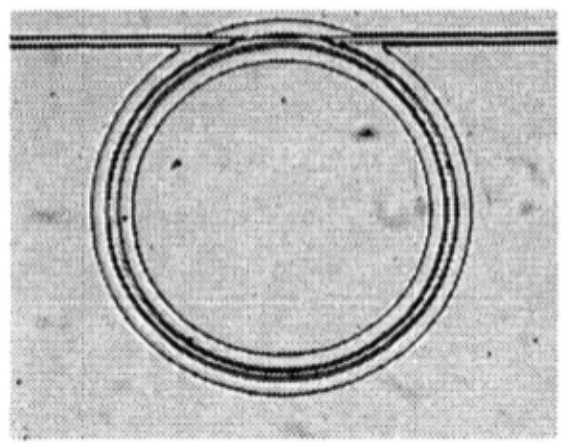

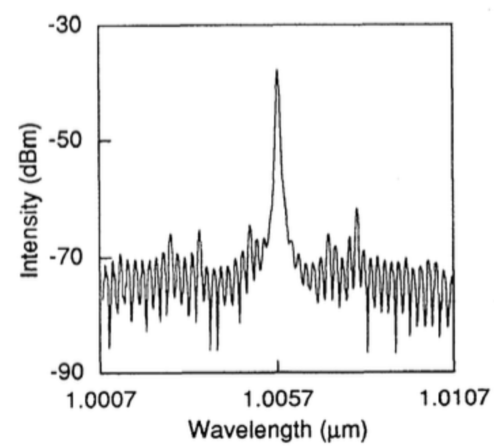

1994

IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 6, NO. 9, SEPTEMBER 1994 1073

Submilliampere Threshold Buried-Heterostructure InGaAs/GaAs Single Quantum Well Lasers Grown by Selective-Area Epitaxy

R. M. Lammert, T. M. Cockerill, D. V. Forbes, G. M. Smith, and J. J. Coleman

***Abstract*— Strained-layer InGaAs-GaAs-AlGaAs single quantum well buried heterostructure lasers grown by selective-area MOCVD are described. Threshold currents of 2.65 mA for an uncoated device and 0.97 mA for a coated device have been obtained. A peak optical output power of 170 mW per uncoated facet for a device with a 4 μm active region width was also achieved. Peak emissions wavelengths range from 0.956 to 1.032 μm.**

I. Introduction

BURIED heterostructure (BH) lasers are desirable because of the strong index guiding and current confinement provided by the heterostructure discontinuity in the lateral direction. These features allow the BH laser to operate with low threshold current and high efficiency. Fabrication of BH laser structures containing AlGaAs can be difficult because the formation of a stable native oxide often results in poor quality interfaces upon regrowth. Low threshold BH lasers containing AlGaAs have been fabricated using liquid phase epitaxy (LPE) for the regrowth in order to melt-back the oxidized interface [1], [2]. Impurity-induced layer disorder (IILD) has also been used to fabricate low threshold BH lasers [3], [4] but this technique has the disadvantage of a long anneal at high temperatures which can lead to interdiffusion at the InGaAs-GaAs interface. A third method used in fabricating low threshold BH lasers is growth on a non-planar substrate [5]. This method has the advantage of being able to produce very narrow as-grown active region widths but the final structure is non-planar with deep grooves (>2 μm in some cases) which can cause problems for subsequent processing of the sample. Recently, a three step selective-area epitaxy has been demonstrated [6] that eliminates much of the difficulty associated with regrowth over exposed AlGaAs. This process also permits wavelength "tuning" over the wafer, allowing for a single wafer containing BH lasers which are designed to operate at various wavelengths. In this work, we report the fabrication of optimized strained-layer, InGaAs-GaAs-AlGaAs single quantum well (SQW) BH lasers by three-step selective-area growth using only atmospheric pressure metalorganic chemical vapor deposition (MOCVD). These lasers exhibit extremely low threshold currents for as-cleaved facet devices (I_{th} = 2.65 mA) and submilliampere thresholds for high reflectivity (HR) coated devices (I_{th} = 0.97 mA).

II. Device Fabrication

Selective-area MOCVD growth utilizing a patterned silicon dioxide mask was used to fabricate the strained-layer InGaAs-GaAs-AlGaAs SQW BH lasers [7]. No deposition takes place on the silicon dioxide and the growth rate everywhere else is enhanced. The amount of growth rate enhancement and, hence, quantum well thickness and composition, is determined by the geometry of the mask pattern. For these devices, a dual oxide stripe geometry is employed with the oxide stripe width defining the emission wavelength and the spacing between stripes defining the lateral waveguide width. The three-step growth process begins with growth of a buffer layer, a 1 μm $Al_{0.60}Ga_{0.40}As$ lower cladding (T_g = 800°C) and a thin (150 Å) GaAs layer to prevent oxidation. The sample is removed from the chamber and a 600 Å SiO_2 mask is deposited on the sample and patterned by standard lithography methods. An H_2SO_4:H_2O (1:80) etch is used to remove process contamination before the sample is returned to the reactor for the selective growth of the active region. The active region consists of a nominal 40 Å $In_{0.18}Ga_{0.82}As$ (T_g = 620°C) QW surrounded by lower and upper GaAs barrier layers with nominal thicknesses of 400 and 900 Å, respectively. The oxide mask is then removed and another H_2SO_4:H_2O (1:80) etch is performed prior to the final growth, consisting of a 50 Å GaAs layer, a 1 μm $Al_{0.60}Ga_{0.40}As$ upper cladding layer (T_g = 800°C) and a 0.15 μm GaAs p^+ cap (T_g = 650°C). For the 2 μm wide BH lasers described in this letter, the dual oxide stripes are 14.5 μm wide each. The lower and upper GaAs barrier thicknesses for the 2 μm wide BH laser are calculated, taking into effect the enhancement of the selective growth of the active region and the GaAs deposited prior to and after the selective growth of the active region, to be 1020 and 2120 Å, respectively. The QW layer after growth enhancement is 94 Å thick with composition shifting to x = 0.24 from 0.18. Slight further optimization of the active layer structure is possible along with, perhaps, extension to multiple quantum wells. A scanning electron micrograph and schematic diagram of the cleaved cross section of a BH with a 2 μm active region width are shown in Fig. 1. The

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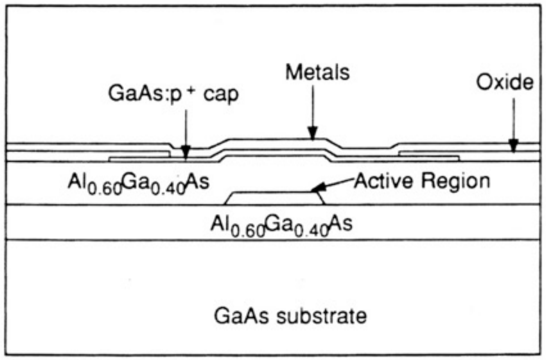

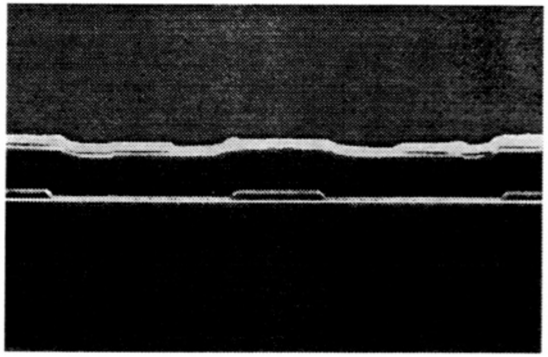

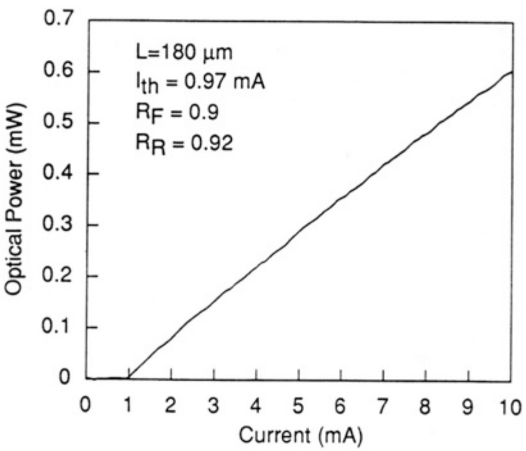

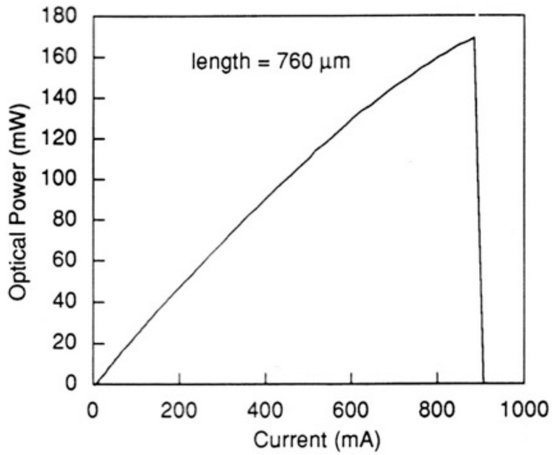

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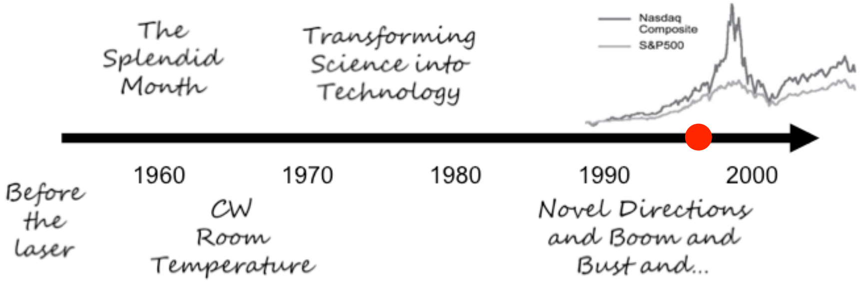

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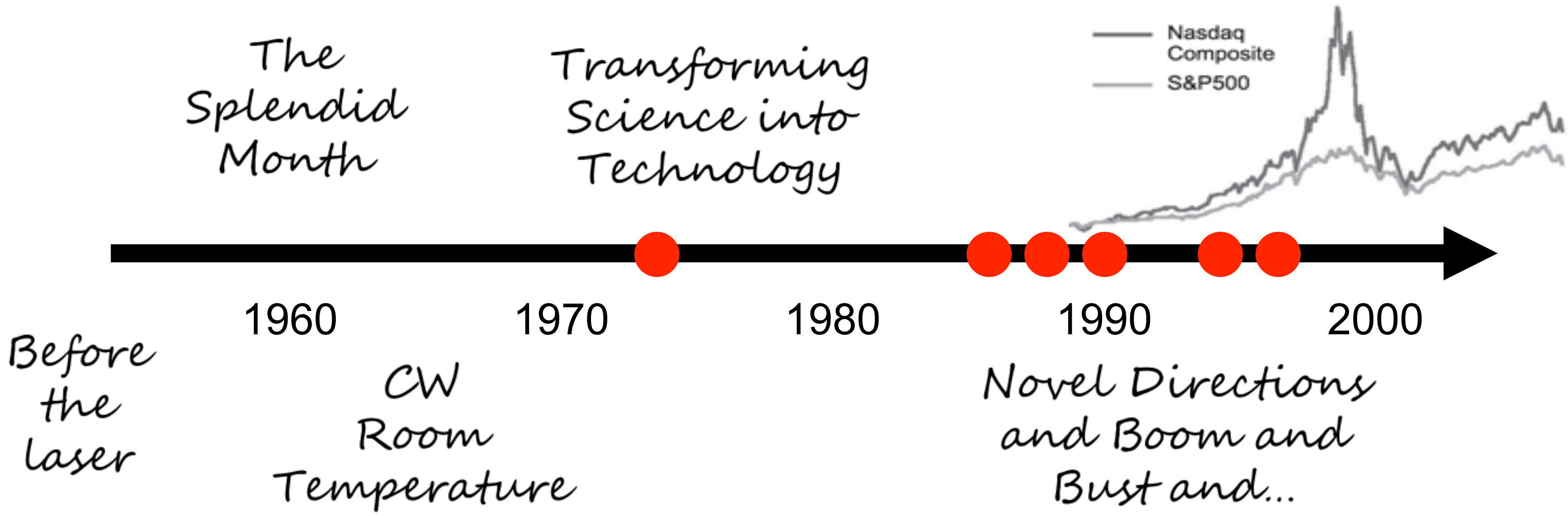

ありがとうございました

Thank you