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(57) Abstract

Disclosed is a method for controlling the emission wavelength of a vertical-cavity surface-emitting laser through the lateral mode size to achieve optical signal generation from two or more devices at two or more distinct wavelengths.

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DESCRIPTION

VERTICAL-CAVITY SURFACE-EMITTING LASER DIODE ARRAY WITH WAVELENGTH CONTROL THROUGH LATERAL INDEX-CONFINEMENT AND LONGITUDINAL RESONANCE

BACKGROUND OF THE INVENTION

The government owns rights in the present invention pursuant to grant number UOI-94-132 from DARPA.

1. Field of the Invention

The present invention relates generally to the fields of semiconductor light emitters. More particularly, it concerns the field of vertical-cavity surface-emitting lasers.

A goal of the semiconductor industry is to fabricate light emitting devices for use in either optical fiber or free space optical interconnects. For such applications laser diodes are preferable because of their capability for high speed modulation (>1GHz). In addition, the vertical-cavity surface-emitting laser (VCSEL) is highly preferred over other laser diode types for a variety of reasons that include ease of fabrication, single longitudinal cavity mode, good optical mode characteristics, ease of testing, and extension to 2-dimensional arrays for parallel signal transmission. Compared to the signal bandwidth of the laser diode, however, either free space or the actual fiber interconnects can have a much greater signal transmission bandwidth yet. Therefore, a useful means to take greater advantage of the signal carrying capacity of the optical channels is to transmit simultaneously through the same spatial channel multiple signals with each signal operating at its own distinct carrier wavelength. In the field of optoelectronics, this technique is commonly called wavelength division multiplexing. Wavelength division multiplexing can be implemented by connecting multiple lasers to a single spatial optical channel, with each laser designed to operate at its own distinct center wavelength. Each laser can then be individually modulated, and the output optical signals combined into the single spatial channel. A goal in the design of each laser diode transmitter is then to realize the optical cavity to yield lasing at the desired carrier wavelength, and to allow controllable change in the wavelength for different laser diodes of similar design, preferably in the VCSEL design.

Because the VCSEL represents a preferred form of the laser diode for optical signal transmission, past efforts have focused on means of controlling the emission wavelength through design of the round trip phase shift that occurs for field propagation in the cavity normal direction, in other words the effective cavity length. For example, in the work by Chang-Hasnain *et al.* (Chang-Hasnain, *et al.*, 1991), multiple wavelength emission is achieved from VCSELs using a thickness variation across an epitaxial wafer that results in different effective cavity lengths. The VCSELs are fabricated from an AlGaAs/GaAs/InGaAs heterostructure monolithically integrated onto a single GaAs substrate. In the Chang-Hasnain work a distinct operating wavelength is achieved for each VCSEL of a 7×20 element array in which the emission wavelength is set by the VCSEL's position on the wafer, due to the layer thickness variation across the wafer, and the total number of distinct operating wavelengths total 140. Although this means of wavelength control is readily implemented, its drawback is that the wavelength separation between two adjacent elements depends on the spatial separation between the two elements, and the spatial direction between the two elements. In the Chang-Hasnain *et al.* (1991) work the operating wavelengths range from (in free space) 9740Å to 9850Å, with 26Å wavelength separation for 354μm physical device separation achieved in one direction of the array, and 3Å wavelength shift for the same 354μm physical device separation achieved in the orthogonal direction of the array. For many future applications, it will be highly desirable to have the wavelength controlled by a means that is not dependent on the spatial separation of the devices on epitaxial wafer. For example, efficiency of optical coupling of multiple VCSELs into a single spatial optical channel can be improved by closely spacing the VCSELs to obtain strong overlap in their radiated far-fields, or for optical routing into a single optical fiber.

A second means of controlling the emission wavelength of a VCSEL array through control of the effective cavity length is demonstrated in the work by Wipiejewski *et al.* (Wipiejewski *et al.*, 1996) and involves a two step epitaxial crystal growth process. Only part of the optical cavity is fabricated in the first crystal growth step, and the individual VCSELs are modified through repeated steps of photoresist masking and etching to realize a thickness variation of the uppermost epitaxial layer across the wafer. The wafer is then reintroduced to the crystal growth system, and the remaining portion of the cavities epitaxially deposited. This process has the advantage over the Chang-Hasnain *et al.* work in that individual VCSEL spacing is limited by photolithographical masking and etching, and can yield spacings to a minimum limit of ~1μm (limitation of standard ultra-violet photolithography). Using this two-step crystal growth technique, Wipiejewski *et al.* (1996) have demonstrated a 2×4 VCSEL array with devices separated by 30μm. Eight distinct wavelengths are demonstrated from the array fabricated with three repeated etch steps (ranging from 9730Å to 9900Å), with the wavelengths separated by ~20Å. The drawback to this technique is the requirement of a second epitaxial regrowth.

It is highly desirable then for signal transmission schemes based on wavelength division multiplexing to fabricate VCSEL arrays in which the individual elements operate at distinct emission wavelengths, and in which the layout of the individual VCSEL elements is not restricted in the device spacing so that dense packing (close spacing) can be achieved. In addition, it is also highly desirable for the single VCSEL to consume as little power as necessary to generate the optical signal, so that the combined power consumption of the array does not limit its usefulness. Very low threshold current VCSELs are then required.

SUMMARY OF THE INVENTION

It is a purpose of the present invention to provide a vertical-cavity surface-emitter wherein the center emission wavelength is controlled through lateral index-confinement of the optical mode, and/or through post-growth control of the longitudinal cavity resonance. While previous teachings suggest that the precise wavelength of the vertical-cavity surface-emitter is set by the effective length of the low-loss vertical cavity, a discovery of the present invention is that the lateral boundary condition of index-confinement on the optical mode can also be used to adjust the lasing wavelength. This lateral boundary can be introduced using one of the techniques known in the art. One such technique is that of the selective oxidation of the III-V semiconductor, as has been demonstrated recently in the work by Huffaker *et al.* (Huffaker *et al.*, 1994). Another technique is through the introduction of an etched void within the laser cavity, as demonstrated by Hansing *et al.* (Hansing *et al.*, 1994) and Deng *et al.* (Deng *et al.*, 1996). It is of some importance that this wavelength control is exercised in very small and therefore very low threshold laser diodes, as it provides a means for fabricating a low power array of vertical-cavity lasers operating at distinct wavelengths to realize independent signal transmission through one spatial optical channel, also known as wavelength division multiplexing.

A second discovery of the present invention is that the longitudinal resonance of the vertical-cavity resonance can be controlled to a greater extent with a smaller change in device operating characteristics than previous methods (Chang-Hasnain et al., 1991, Wipiejewski et al., 1996) through the process of selectively etching thin layers from the central region of the cavity, and completing the laser cavity with high contrast dielectric layers. In the work by Huffaker (Huffaker, 1997) the upper dielectric layers are MgF/ZnSe and deposited by electron-beam evaporation, while the lower reflector is either an Al_xO_y/GaAs or AlAs/GaAs quarter-wave stack. The reduced sensitivity of the VCSEL to a change in the operating wavelength follows directly from the increased reflectivity bandwidth that can be achieved with a high index-contrast (large index ratio) dielectric mirror. The reduced sensitivity of the device operating characteristics to the lasing wavelength is critical for element uniformity in a multiple wavelength VCSEL emitter array. As with the wavelength control through the lateral boundary condition, the etching of thin layers and subsequent deposition of a high contrast dielectric mirror allows the wavelength to be controlled independent of individual element spacing.

Disclosed herein are small area vertical-cavity surface-emitting lasers (VCSELs) in which the lateral optical confinement is demonstrated to control the emission wavelength. The control becomes possible when the lateral size of the lasing mode results in a transverse wavevector component that is significant in establishing the quasi-mode frequency. With the normal component of the wavevector taken as $k_z = 2\pi / \lambda_o$ (fixed by the vertical cavity) and assuming $< k_{p,n}^2 >= \pi^2 / w_n^2$ where w_n is a transverse mode size, the lasing wavelength λ_n is given by $\lambda_n = \lambda_o / \sqrt{1 + \lambda_o^2 / (4w_n^2)}$, where the subscript n designates the nth element of an array. In the selectively oxidized VCSELs as described below $\lambda_o \sim 0.96\mu m$ and the lateral cavity dimensions range from 1.5 to 4.0μm ($5\lambda_o$ to $12\lambda_o$) and wavelength shifts on the order of 10Å due to the lateral cavity effect might be expected. Measured lasing wavelengths for a 2×2 array containing device sizes of 2.0, 2.5, 3.0, and 3.5μm are 9574, 9587, 9598, and 9608Å, respectively. The wavelength shift between elements is obtained only through lateral size variations intentionally introduced into the laser cavities. The lasers are fabricated with close proximity of 12μm separations to minimize any unintentional wavelength shift that might arise due to thickness variations across the epitaxial layers, as introduced intentionally in the work by Chang-Hasnain *et al.* The lasing threshold currents are low and range from 169μA for the smallest device to 240μA for the largest.

Also disclosed herein is a method of controlling the longitudinal cavity resonance through selective etching of semiconductor layers of the laser cavity and subsequent deposition of high contrast dielectric mirrors, and a method of patterning the dielectric mirror to only the laser cavity region. Again taking the lasing wavelength as $\lambda_n = \lambda_o / \sqrt{1 + \lambda_o^2 / (4 w_n^2)}$, this second method now controls λ_o. The patterning of the dielectric mirror is desirable to reduce surface strain on the semiconductor device, and to facilitate electrical contacting in a wide variety of applications. The patterning is accomplished by forming a semiconductor mesa on top of the laser cavity, which is then etched to form a recessed region from which thin semiconductor layers can be selectively etched. A dielectric mirror is subsequently deposited within the recesses region of the mesa, and removed from the semiconductor crystal surface elsewhere. To achieve optimum device performance, the control of the longitudinal resonance is used together with control of the lateral boundary condition to establish the lasing wavelength. For reasons of simplicity in device fabrication, however, either means be used separately with some sacrifice in the optimum device characteristics.

It is understood that the present disclosure is applicable to any group III-V crystal as that is understood in the art, and that AlAs/GaAs/InGaAs/AlGaAs are used by way of example only. Specifically, the same technique is applicable to VCSELs made from III-V materials containing In and P, as well as Al, Ga, and As, as is necessary to realize VCSELs emitting in the 0.6 to 0.7μm free space wavelength range, and the 1.1μm to 2.0μm free space wavelength range. Also more specifically, the wavelength range centered around 1.3μm and 1.55μm are important for silica fibers because of favorable transmission characteristics. A greater wavelength control can be obtained for devices of this wavelength range for standard ultraviolet photolithography (which is limited to ~0.5μm resolution), because of the larger characteristic emission wavelength.

BRIEF DESCRIPTION OF THE DRAWINGS

The following drawings form part of the present specification and are included to further demonstrate certain aspects of the present invention The invention may be better understood by reference to one or more of these drawings in combination with the detailed description of specific embodiments presented herein.

FIG. 1 Schematic illustration of a vertical-cavity surface-emitting laser consisting of a single InGaAs/GaAs quantum well and lateral index-confinement realized using a buried selectively oxidized layer. The lateral dimension "w" is chosen to select the precise lasing wavelength of the VCSEL. Smaller "w" yields a smaller emission wavelength.

FIG. 2A Scanning electron microscope image looking down on the 2×2 VCSEL array, and showing the different lateral sizes. FIG. 2B Optical microscope photograph showing the metallized array.

FIG. 3 Experimentally measured light versus current curves measured CW for the four different sized VCSELs of the 2×2 array.

FIG. 4 Experimentally measured emission spectra from the 2×2 array measured CW at $1.5xI_{th}$. Center wavelengths for the different device sizes are 9608Å (3.5μm), 9598Å (3.0μm), 9587Å (2.5μm), and 9574Å (2.0μm).

FIG. 5 Experimentally measured current versus voltage characteristics of the individual elements of the 2×2 array.

FIG. 6 Schematic illustration showing alternative means of introducing a lateral index-confinement based on introducing an etched void within the laser cavity. The lateral size control of the optical mode is demonstrated through the angular spread of the radiated far-field.

FIG. 7 Scanning electron microscope cross section showing the realization of an etched void buried within the laser cavity.

FIG. 8 Experimentally measured far-field radiation pattern showing the broadened far-field that occurs for a 4μm lateral sized device as compared to a 10μm lateral sized device. The broadened far-field evidences the effectiveness of the etched void in laterally confining the optical mode.

FIG. 9 Device schematic of a VCSEL showing a semiconductor mesa containing a recessed region that receives a deposition of a high contrast dielectric mirror. The mirror is removed elsewhere from the crystal surface by either etching, or lifted off by depositing on a layer of photoresist. (a) shows a device schematic for which the light emission is from the upper surface. (b) shows a device schematic for which the light emission is through the substrate.

FIG. 10 Device schematic showing the area within the recessed region and a tuning layer consisting of thin semiconductor layers that can be selectively etched to control the longitudinal cavity resonance.

FIG. 11 Calculated plot showing the influence of adjusting the tuning layer thickness on the wavelength set by the longitudinal resonance. The mirror materials represent lower and upper combinations.

FIG. 12 Calculated combined reflectivity (reflectivity product) versus resonant wavelength for different upper and lower mirror combinations. The higher contrast mirrors exhibit a reflectivity product that is much less sensitive to change in the resonant wavelength.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The performance characteristics of the VCSEL are highly sensitive to the optical cavity loss rate. If too strong of lateral optical confinement is used along the length of the VCSEL, scattering loss from edge imperfections can dominate performance. Huffaker *et al.* (1994) and Hansing *et al.* (1994) have demonstrated, on the other hand, that strong optical confinement can also be realized by introducing a thin dielectric aperture within the otherwise planar optical cavity yielding the beneficial result of strong lateral optical confinement while simultaneously maintaining low optical loss. Such demonstrations have been made with different cavity spacer thicknesses designated as either full wave or half-wave, depending on the optical thickness with respect to the emission wavelength within the cavity. The preferred embodiment of the invention is based on the introduction of such lateral index-confinement for the purpose of lateral control of the VCSEL resonant wavelength.

FIG. 1 shows a schematic illustration of a VCSEL design based on selective oxidation of the III-V AlGaAs and a half-wave cavity spacer. The selective oxidation has been described by Dallessasse *et al.* (1990) and converts the AlGaAs into a native oxide of Al_xO_y. The refractive index of the Al_xO_y is ~1.7, and significantly reduced from the AlGaAs crystal which is ~3.3. Even though only one thin layer of the crystal is oxidized, the refractive index change of this layer when placed within the vertical cavity results in a strongly laterally confined optical mode. The optical confinement allows lateral size reduction of the lasing mode, and very low threshold current (Huffaker *et al.*, 1994). For small enough lateral size, the lateral confinement shifts the resonant wavelength of the laterally confined mode to a smaller value. FIG. 2, FIG. 3, and FIG. 4 show measured data for such a structure, and FIG. 4 shows the ~10Å wavelength shift with size reduction for four different sizes of 3.5μm, 3.0μm, 2.5μm, and 2.0μm. As the lateral device size of the VCSEL is made larger the wavelength control due to the lateral size is lost, partly due to the role of confinement of the length of the vertical-cavity on the lateral mode size, and the small size of the wavelength shift due to size of the emission wavelength. Other schemes can also be used to provide the lateral confinement, and the similar effect of the lateral index-confinement can be realized when the dielectric layer takes the form of an etched void, as demonstrated by Hansing *et al.* (1994).

The following examples are included to demonstrate preferred embodiments of the invention. It should be appreciated by those of skill in the art that the techniques disclosed in the examples which follow represent techniques discovered by the inventor to function well in the practice of the invention, and thus can be considered to constitute preferred modes for its practice. However, those of skill in the art should, in light of the present disclosure, appreciate that many changes can be made in the specific embodiments which are disclosed and still obtain a like or similar result without departing from the spirit and scope of the invention. One example of such a change is to implement the lateral size control of the wavelength using a different material system such as to achieve a new range of emission wavelengths, such as by adding In or P to the III-V semiconductor.

Example 1

The VCSELs studied to demonstrate the lateral wavelength control use a half-wave cavity spacer design after Huffaker, *et al.* (1994). FIG. 1 shows a schematic illustration of device design. The actual heterostructure is grown by molecular beam epitaxy and consists of a lower n-type 26 pair AlAs/GaAs distributed Bragg reflector (DBR), an $Al_{0.97}Ga_{0.03}As$ half-wave cavity spacer layer surrounding a single 80Å $In_{0.20}Ga_{0.80}As$ quantum well and 100Å thick GaAs and 100Å thick $Al_{0.67}Ga_{0.33}As$ barriers, and a quarter-wave p-GaAs cap layer. The $Al_{0.97}Ga_{0.03}As$ layers are ~400Å thick, and after oxidation the Al_xO_y of the upper cavity spacer layer is ~200Å above the InGaAs quantum well (Huffaker, *et al.*, 1994). The VCSEL array is fabricated by defining square GaAs mesas by wet-etching on a 12μm grid and then oxidizing the exposed AlGaAs layer (upper part of the half-wave cavity spacer) in a steam environment. The steam oxidation is described in the work by Dallessasse *et al.* (1990). The lateral sizes of the square GaAs mesas are defined to be 7.5μm, 8.0μm, 8.5μm, and 9.0μm in order to obtain a lateral size variation in the oxidized VCSEL active regions. FIG. 2A shows a scanning electron microscope image looking down on an oxidized VCSEL array and demonstrates the lateral size variations achieved. The scale given in FIG. 2A shows that the lateral active region sizes range from 1.5 to 3.0μm. Because of the nearly planar surface maintained in the processing, electrical contacting is performed straightforwardly using standard photolithography and "lift-off" of the metallization, despite the close individual element spacings. FIG. 2B shows an expanded view of an optical photograph immediately after metallization. The upper mirror consists of a post-growth electron-beam deposited CaF/ZnSe DBR (Huffaker *et al.*, 1994).

The 2×2 arrays are characterized under continuous wave (CAW) operation to study the influence of the lateral mode size variation on lasing characteristics. The CW threshold currents range from 170 to 250μA depending generally on device size, with the smaller devices showing some threshold reduction as compared to larger ones. FIG. 3 shows the four light versus current characteristics from a single 2×2 array. The measured threshold currents for the 2.0, 2.5, 3.0, and 3.5μm sized devices are 169, 187, 214, and 240μA, respectively. Reasonable uniformity is also obtained in the differential slope efficiencies versus decreasing device size of 23% (3.5μm), 19% (3.0μm), 26% (2.5μm), and 21% (2.0μm). The reason for the small variations in slope efficiencies is unknown. Maximum CW output for the 3.5μm device was measured to be 380μW at 1.3mA, and limited by heating. FIG. 4 shows the lasing spectra at $1.5xI_{th}$ for each of the four individual VCSELs demonstrating the lateral cavity effect on the lasing wavelengths. The measured spectral widths are spectrometer limited with the center wavelengths of 9608Å (3.5μm), 9598Å (3.0μm), 9587Å (2.5μm), and 9574Å (2.0μm). To gain further information on the lateral size effect on the lasing wavelength the inventors have also measured the far-field radiation pattern. All four lasing modes are single lobed with characteristic half-angles (e^{-2} in intensity) of 14.6° (3.5μm), 16.7° (3.0μm), 18.3° (2.5μm), and 21.0° (2.0μm). Although the far-fields are not ideal Gaussian, it is seen that the mode angles track the lateral cavity sizes and lasing wavelengths.

An advantage of the half-wave cavity spacer design for densely packed arrays is the good electrical and thermal isolation provided between elements. FIG. 5 shows the current versus voltage characteristics of the four individual elements, with some resistance increase occurring as the device size is decreased. The electrical isolation between the individual elements is excellent due to the half-wave cavity spacer with the native-oxide layer placed ~200Å above the quantum well active region (see FIG. 3 inset). Interelement leakage current remains less than 1μA at 5V between adjacent devices. The thermal impedance between elements is also expected to be decreased due to the oxide placement within the cavity spacer. Assuming a lasing wavelength shift with temperature of $\Delta\lambda/K=0.56Å$, the inventors measure a thermal impedance of 2.55K/mW for the 2.0μm square device, and 2.28K/mW for the 3.5μm sized device. Interelement thermal impedance is measured by monitoring the wavelength of one element while the dissipated power is changed in an adjacent element. With this technique the inventors measure a cross thermal impedance of 0.14K/mW for adjacent devices.

The previous means of controlling the lasing wavelength of VCSELs for multi-element arrays is through adjustment of the cavity length. Such a control can be achieved by intentionally introducing a thickness gradient across the wafer during the epitaxial growth. The interelement wavelength shift is then proportional to the emitter separation, with a wavelength shift of $\Delta\lambda\sim26Å$ for a center-to-center spacing of 354μm reported by Chang-Hasnain *et al.* (1990). This cavity tuning of the wavelength becomes ineffective for closely spaced emitters, and would yield less than 1Å wavelength shift between elements for the 12μm center-to-center spacing for the 2×2 array described above. Although in the design one can also consider adjusting the cavity length through post-growth deposited layers before application of the dielectric DBR, this requires several additional masking steps and is labor intensive. The lateral cavity size effect provides a simple means of controlling the lasing wavelength that is independent of the interelement center-to-center spacings. It is therefore suitable for low threshold, densely packed VCSEL arrays of small element number.

For larger element number multiwavelength arrays it becomes feasible to use the lateral cavity control in addition to vertical cavity tuning and realize thirty-two or greater wavelengths while retaining both dense packing and low threshold. An advantage of the dense packing possible with the nearly planar processing and selective oxidation is the prospect for simultaneously coupling the individual elements into a single waveguide or optical fiber. For example, with a linear array one can consider routing the four VCSEL outputs into a single waveguide with minimal bending loss.

Example 2

We present characterization data for VCSELs fabricated with an etched void confining layer using a two-step molecular beam epitaxial (MBE) growth and device fabrication process to realize a CW threshold current of 470μA for a 4μm diameter device (Hansing *et al.*, 1994). The void confinement is realized through a selective etching process to define a thin buried etched region around the optically active part of the VCSEL. The void confinement yields the lateral optical confinement necessary to reduce the lateral size of the optical mode, as determined by the radiated far-field.

FIG. 6 shows a schematic cross-section of the VCSEL laser. The initial MBE growth consists of a 0.5μm n-type GaAs buffer layer followed by a 27 pair AlAs/GaAs, n-type, distributed Bragg reflector tuned to 0.98μm, an n-type quarter-wave layer of $Al_{0.67}Ga_{0.33}As$, a one-wavelength-thick GaAs cavity with an active region of three 60 Å $In_{0.2}Ga_{0.8}As$ QWs separated by 100Å GaAs barriers, a p-type quarter-wave layer of $Al_{0.67}Ga_{0.33}As$, a one-eighth-wavelength-thick p-type GaAs layer, a 1000Å undoped low growth temperature (LT) $Al_{0.67}Ga_{0.33}As$ layer, and a one-eighth-wavelength-thick p-type GaAs layer. The structure is grown at a substrate temperature of 610_C except for the QW active region which is grown at 540_C and the LT-AlGaAs layer at 270_C. All n-type layers are Si-doped to $1\times10^{18}/cm^3$, and all p-type layers are Be-doped to $2\times10^{18}/cm^3$.

After the initial growth, 4μm diameter openings are photolithographically defined in a photoresist layer, and the top GaAs layer is selectively etched with an H_2O_2:NH_4OH (pH~7.2) solution. The exposed LT-AlGaAs layer is next selectively etched using a 4:1 HF:H_2O solution, with the etch time adjusted to undercut the top

GaAs layer ~3μm. The photoresist is then stripped, followed by a 30 second O_2 plasma clean. The sample is then returned to the MBE system for regrowth, which consists of a one-eighth wavelength p-type GaAs layer followed by a 4-pair p-type AlAs/GaAs quarter-wave stack, with superlattice grading layers inserted at each AlAs/GaAs interface.

The schematic cross-section of FIG. 6 is representative of the regrown epitaxial layers as evidenced by scanning electron microscopy (SEM) and profiling with a Tencor surface profilometer. The SEM cross section is shown in FIG. 7. At the edge of the undercut region a void of ~1000Å thickness exists, as evidenced by SEM, which tapers thinner closer to the laser active region as shown in FIG. 7. Surface profiling shows that the tapered region extends smoothly to the edge of the laser active region, at which point a 300Å step is measured due to the GaAs of the first epitaxial growth which remains after undercutting. At the edge of the active region the void is quite thin, its influence on the lasing performance is therefore best characterized through comparison of the present laser devices with similar devices grown previously in which the undercutting before the MBE regrowth did not occur. In previous devices without the etch undercutting, lasing has not been achieved when the active diameter is less than 10μm.

A Cr/Au metallization with 30-μm-diameter openings around the active regions is defined by "lift-off" and is used to electrically contact the devices. After isolating the emitters into separate contact pads of 400μm squares, the inventors deposit four pairs of quarter-wave ZnSe/CaF_2 on the p-side using electron-beam evaporation. Devices are characterized under CW room temperature operation in terms of the lasing threshold, spectral characteristics, far-field radiation patterns, and current-voltage characteristics. The CW threshold current is 470μA for the 4μm diameter device, while the threshold current of the 10μm device measured to be 1.1mA. A small but consistent blue shift in lasing wavelength of ~60Å is measured for the 4μm as compared to the 10μm diameter lasers for devices in close proximity on the wafer, demonstrating the lateral confinement effect on the lasing wavelength.

To gain further insight into the influence of the reduction of the active diameter in the MBE regrowth on the optical beam characteristics, the inventors have also measured the far-field radiation patterns for different diameter devices. These are shown in FIG. 8 for photolithographically defined diameters of 10, 8, and 4μm. The beam divergences give calculated lasing spot sizes 7.6, 6.1, and 3.2μm, respectively. The optical confinement of the lasing spot to the photolithographically defined gain region therefore appears to be strong, in agreement with the low threshold currents, and yields the 60Å blue shift measured for the smaller (4μm) sized devices.

Example 3

Figure 9 shows device schematics in which the dielectric Bragg reflector is deposited within a recessed region of a semiconductor mesa. The semiconductor mesa is used to achieve localization of the dielectric mirror to a small area, either through photoresist lift-off or etching of the mirror. In Fig. 9(a) the light is emitted from the expitaxial surface of the VCSEL, and in Fig. 9(b) the light is emitted through the semiconductor substrate. In the case of light emission through the substrate, the upper mirror can be made from a combination of dielectric layers and a metal film such as Au or Ag. Figure 10 shows the detailed semiconductor layers within the laser cavity that can be selectively etched to achieve tuning of the resonant wavelength. Figure 11 shows the dependence of the lasing wavelength on the thickness of the tuning layer for different possible dielectric mirror combinations. The broadest tuning range is achieved using the largest ratio of refractive indices between the high index and low index layers of the mirror stack (Huffaker, 1997).

Figure 12 shows the reflectivity product of the upper and lower mirrors for different resonant wavelengths, and for different dielectric mirror materials. The least sensitivity in mirror reflectivity product, and therefor in device operating characteristics, is achieved with the highest index ratio materials (Huffaker, 1997).

* * *

While the compositions and methods of this invention have been described in terms of preferred embodiments, it will be apparent to those of skill in the art that variations may be applied to the composition, methods and in the steps or in the sequence of steps of the method described herein without departing from the concept, spirit and scope of the invention. More specifically, it will be apparent that certain agents which are both chemically and physically related may be substituted for the agents described herein while the same or similar results would be achieved. All such similar substitutes and modifications apparent to those skilled in the art are deemed to be within the spirit, scope and concept of the invention, for example, as defined by the appended claims.

REFERENCES

The following references, to the extent that they provide exemplary procedural or other details supplementary to those set forth herein, are specifically incorporated herein by reference.

Chang-Hasnain, C.J., J.P. Harbison, C.-E. Zah, M.W. Maeda, L.T. Florez, N.G. Stoffel, and T.-P. Lee, "Multiple wavelength tunable surface-emitting laser arrays," *IEEE J. Quant. Electron.*, 27:1368-1376, 1991.

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Deng, H. and D.G. Deppe, "Oxide-Confined Vertical-Cavity Surface-Emitting Lasers with Additional Etched Void Confinement," *Electron. Lett.*, 32:900-901, 1996.

Hansing, C.C., H. Deng, D.L. Huffaker, D.G. Deppe, B.G. Streetman, and J. Sarathy, "Low-threshold continuous-wave surface emitting lasers with etched void confinement," *IEEE Phot. Tech. Lett.*, 6:320-322, 1994.

Huffaker, D.L., "Dependence of wavelength control on dielectric structure for vertical-cavity-surface-emitting lasers," *J. Appl. Phys.*, 81:1598-1600, 1997.

Huffaker, D.L., D.G. Deppe, K. Kumar, and T.J. Rogers, "Native oxide defined ring contact for low threshold vertical cavity lasers," *Appl. Phys. Lett.*, 65:97-99, 1994.

Huffaker, D.L., J. Shin, and D.G. Deppe, "Low threshold half-wave vertical-cavity lasers," *Electron. Lett.*, 30:1946-1947, 1994.

Wipiejewski, T., J. Ko, B.J. Thibeault, L.A. Coldren, "Molecular beam epitaxy regrowth of top reflectors for multiple wavelength vertical-cavity laser arrays." In: *Conference on Lasers and Electro-Optics, 1996 OSA Technical Digest Series,* Optical Society of America, Washington, D.C., 9:362-363, 1996.

CLAIMS

1. An array consisting of two or more monolithic vertical-cavity surface-emitting lasers comprising lateral index-confinement, wherein the lateral size of the laser cavities are altered so that said index-confinement results in two or more distinguishable wavelengths of emission.

2. An optical signal transmission system that incorporates two or more vertical-cavity surface-emitting lasers comprising lateral index-confinement, wherein the lateral size of the laser cavities are altered so that said index-confinement results in two or more distinguishable wavelengths of emission.

3. An array consisting of two or more monolithic vertical-cavity surface-emitting lasers comprising lateral index-confinement, wherein the lateral size of the laser cavities are altered so that said index-confinement results in partial wavelength control of the individual elements and partial wavelength control comes through the additional adjustment of the vertical-cavity effective length to generate two or more distinguishable wavelengths of emission.

4. An optical signal transmission system that incorporates two or more vertical-cavity surface-emitting lasers comprising lateral index-confinement, wherein the lateral size of the laser cavities are altered so that said index-confinement results in partial wavelength control of the individual elements and partial wavelength control comes through the additional adjustment of the vertical-cavity effective length to generate two or more distinguishable wavelengths of emission.

5. The vertical-cavity surface-emitting laser array of claim 1, wherein the lateral confinement is realized using the process of selective oxidation of a III-V semiconductor.

6. The optical signal transmission system of claim 2, wherein the lateral confinement is realized using the process of selective oxidation of a III-V semiconductor.

7. The vertical-cavity surface-emitting laser array of claim 3, wherein the lateral confinement is realized using the process of selective oxidation of a III-V semiconductor.

8. The optical signal transmission system of claim 4, wherein the lateral confinement is realized using the process of selective oxidation of a III-V semiconductor.

9. The vertical-cavity surface-emitting laser array of claim 1, wherein the lateral confinement is realized using the process of selective etching of a III-V semiconductor.

10. The optical signal transmission system of claim 2, wherein the lateral confinement is realized using the process of selective etching of a III-V semiconductor.

11. The vertical-cavity surface-emitting laser array of claim 3, wherein the lateral confinement is realized using the process of selective etching of a III-V semiconductor.

12. The vertical-cavity surface-emitting laser array of claim 4, wherein the lateral confinement is realized using the process of selective etching of a III-V semiconductor.

13. The vertical-cavity surface-emitting laser array of claim 1, wherein the emission wavelength is in the operating range of 0.6μm to 2.0μm wavelength.

14. The optical signal transmission system of claim 2, wherein the emission wavelength is in the operating range of 0.6μm to 2.0μm wavelength.

15. The vertical-cavity surface-emitting laser array of claim 3, wherein the emission wavelength is in the operating range of 0.6μm to 2.0μm wavelength.

16. The optical signal transmission system of claim 4, wherein the emission wavelength is in the operating range of 0.6μm to 2.0μm wavelength.

17. A vertical-cavity surface-emitting laser fabricated with a semiconductor mesa containing a recessed semiconductor region with the recessed semiconductor region containing at least one dielectric material to form a Bragg reflector.

18. An array consisting of two or more monolithic vertical-cavity surface-emitting lasers, wherein the longitudinal resonance of the laser cavities are altered by selectively etching thin semiconductor layers, and the upper mirrors are completed with dielectric materials.

19. The array of claim 18, wherein one dielectric material is ZnSe.

20. The array of claim 18, wherein one dielectric material is MgF.

21. The array of claim 18, wherein said dielectric materials are deposited into a recessed region for in semiconductor mesas.

22. The array of claim 21, wherein one of said dielectric materials deposited in the recessed region of a semiconductor mesa is ZnSe.

23. The array of claim 21, wherein one of said dielectric materials deposited in the recessed region of a semiconductor mesa is MgF.

24. An optical signal transmission system that incorporates at least two vertical-cavity surface-emitting lasers, wherein longitudinal resonance of the laser cavities is altered by selectively etching thin semiconductor layers, wherein the system comprises upper mirrors that are completed with dielectric materials, and the vertical-cavity lasers are used to generate two distinguishable wavelengths of emission.

21. The optical system of claim 24, wherein said dielectric materials of the vertical-cavity lasers are deposited into a recessed region formed in semiconductor mesas.

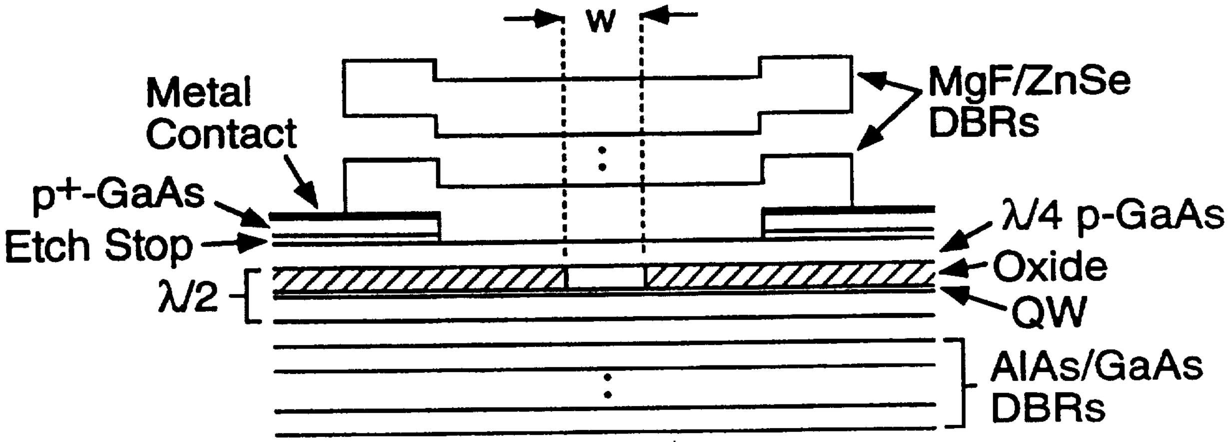
w
Metal
Contact
MgF/ZnSe
DBRs
p+-GaAs
Etch Stop
λ/4 p-GaAs
Oxide
λ/2
QW
AlAs/GaAs
DBRs

FIG. 1

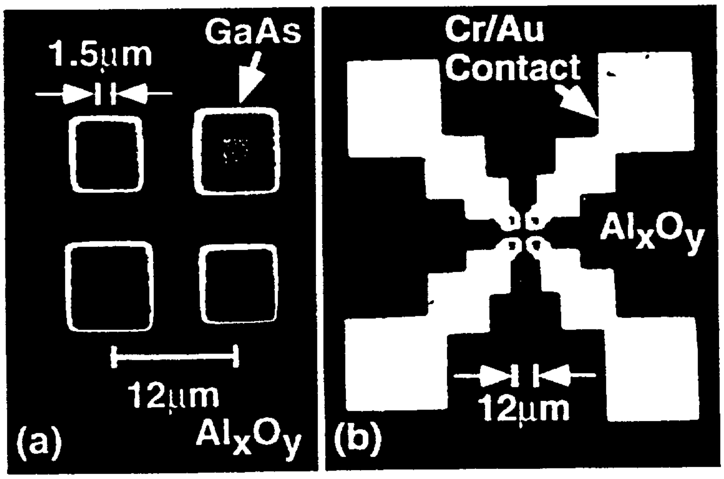

FIG. 2

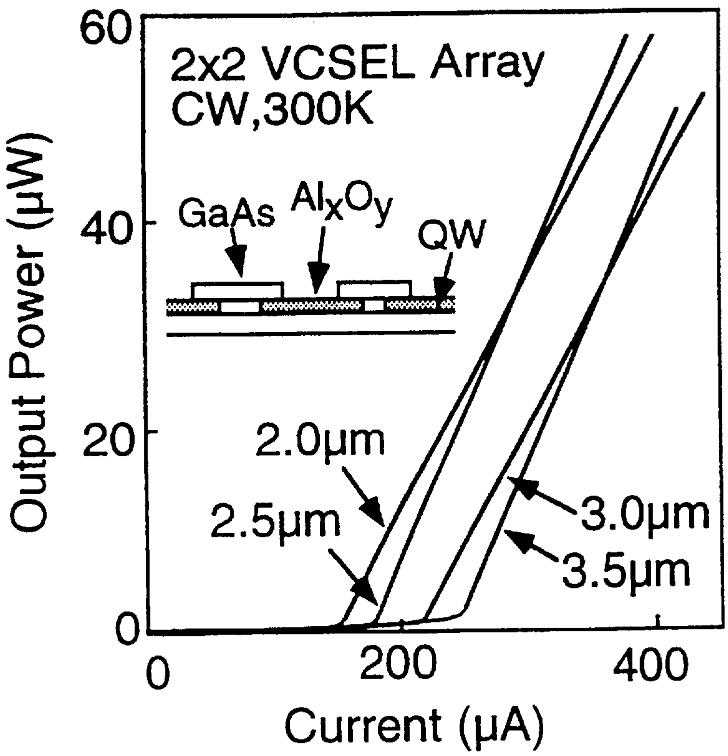
2x2 VCSEL Array
CW,300K
GaAs
Al_xO_y
QW
2.0µm
2.5µm
3.0µm
3.5µm
Output Power (µW)
60
40
20
0
0
200
400
Current (µA)

FIG. 3

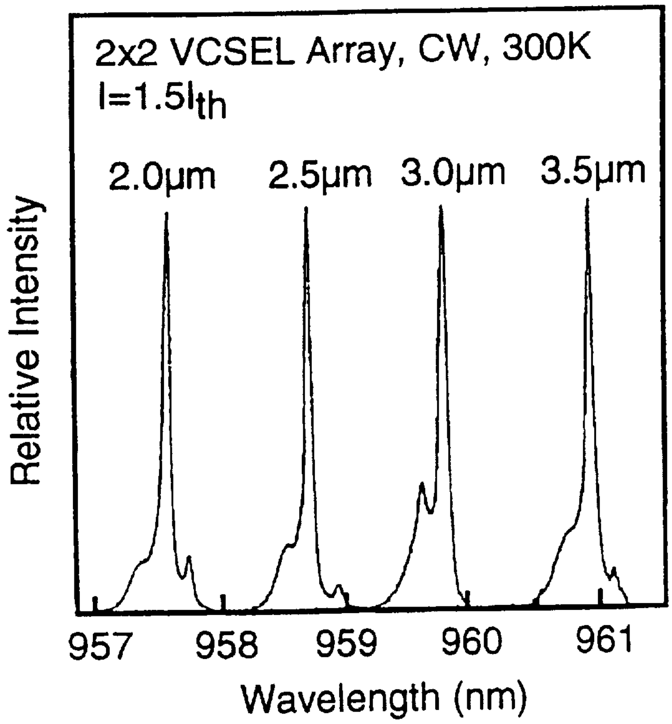
2x2 VCSEL Array, CW, 300K
I=1.5Ith
2.0μm
2.5μm
3.0μm
3.5μm
Relative Intensity
957
958
959
960
961
Wavelength (nm)

FIG. 4

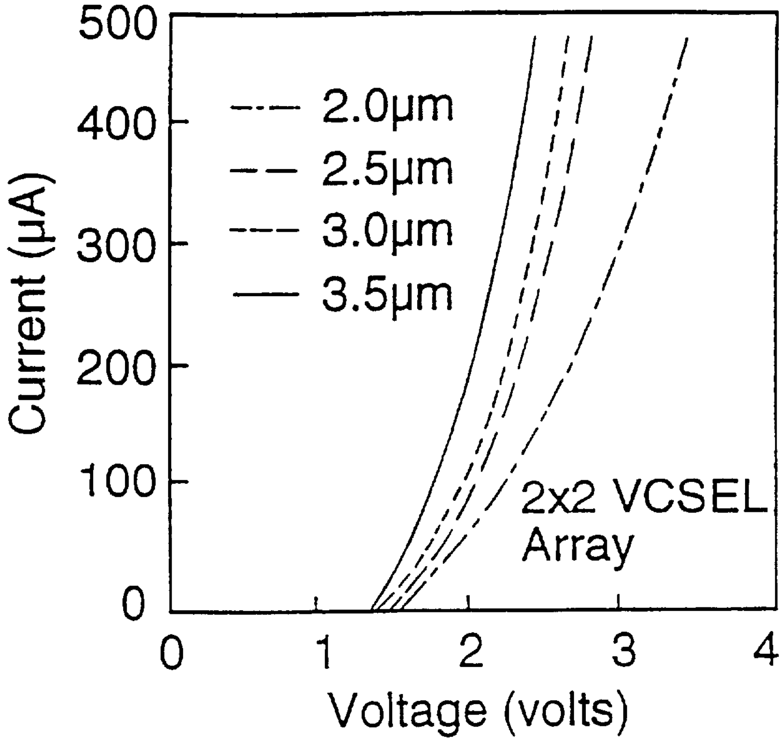
500
400
300
200
100
0
Current (μA)
0
1
2
3
4
Voltage (volts)
2.0μm
2.5μm
3.0μm
3.5μm
2x2 VCSEL
Array

FIG. 5

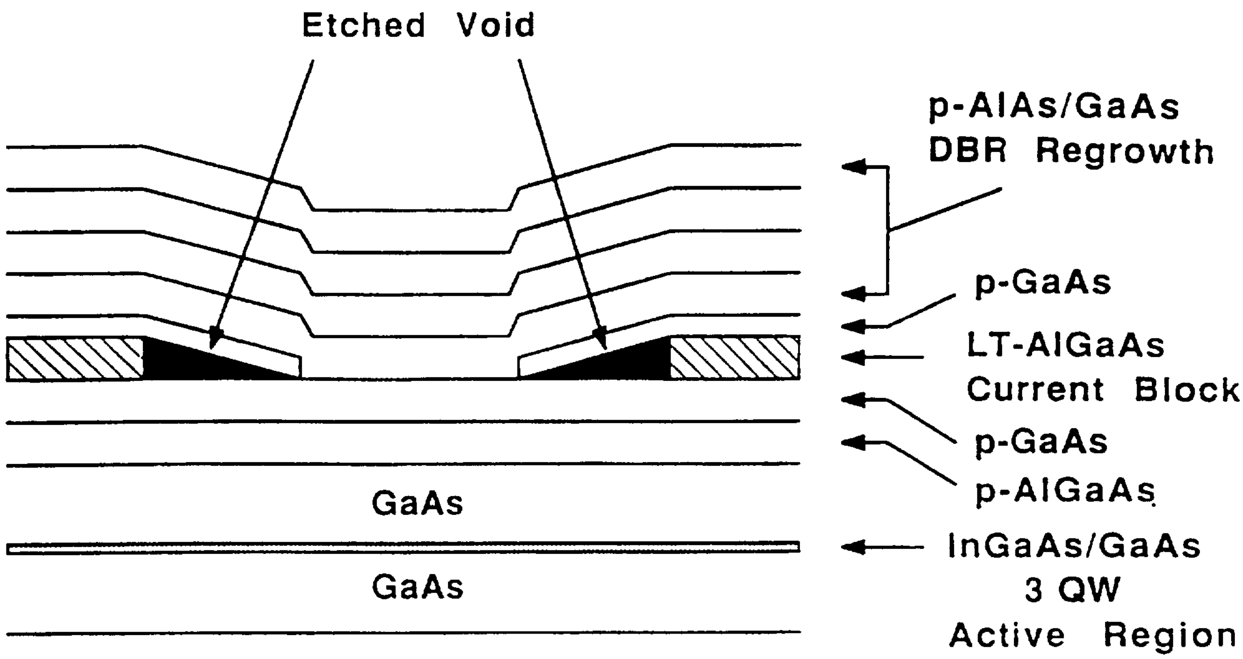
Etched Void
p-AlAs/GaAs
DBR Regrowth
p-GaAs
LT-AlGaAs
Current Block
p-GaAs
p-AlGaAs
GaAs
InGaAs/GaAs
3 QW
Active Region
GaAs

FIG. 6

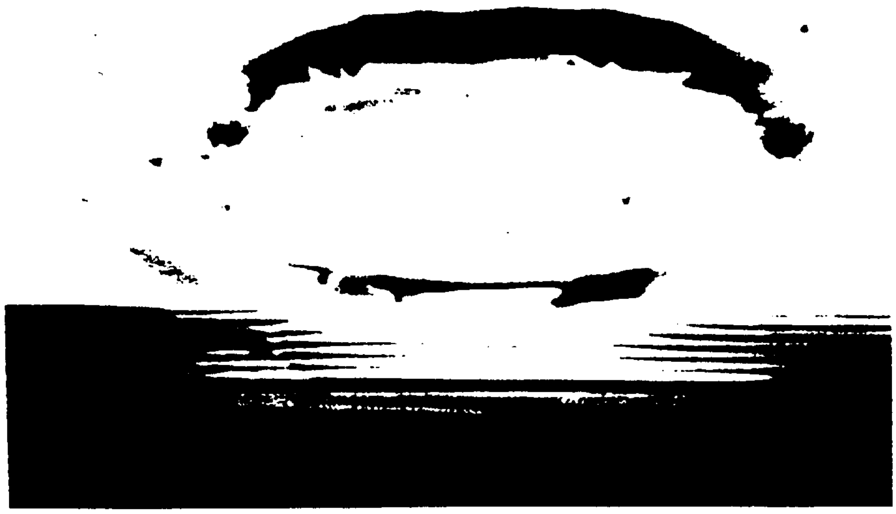

FIG. 7

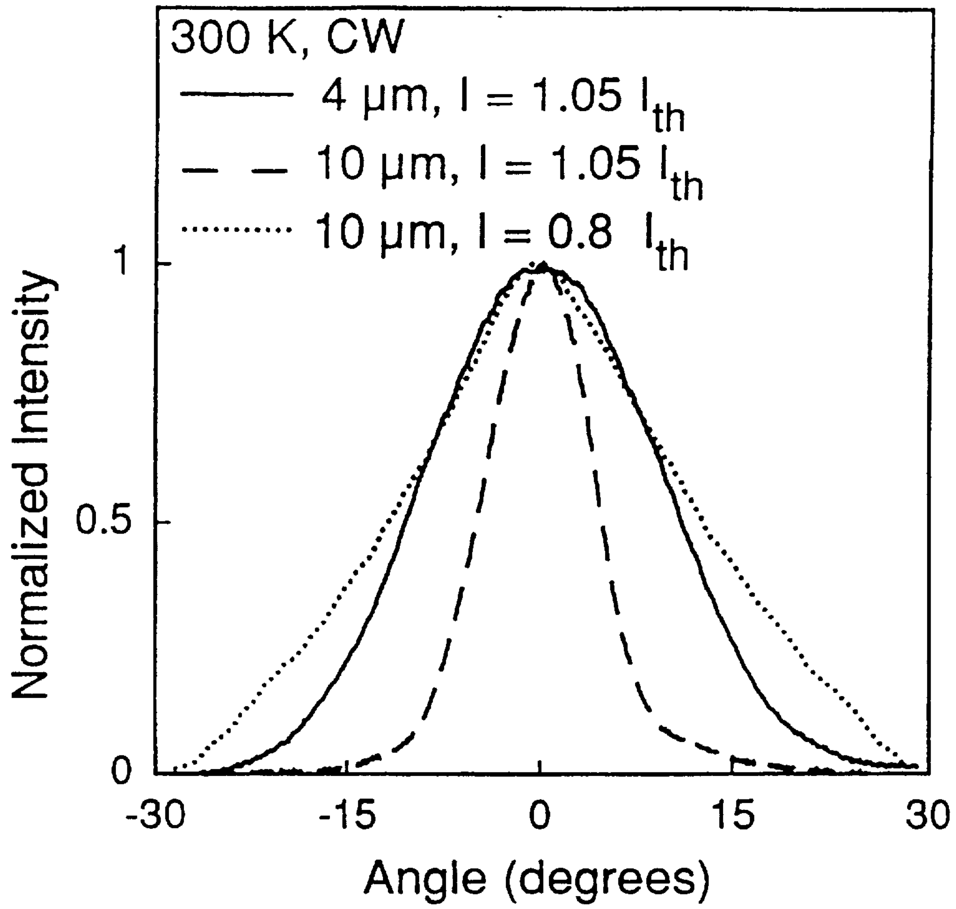
300 K, CW
4 μm, I = 1.05 I_th
10 μm, I = 1.05 I_th
10 μm, I = 0.8 I_th
Normalized Intensity
1
0.5
0
-30
-15
0
15
30
Angle (degrees)

FIG. 8

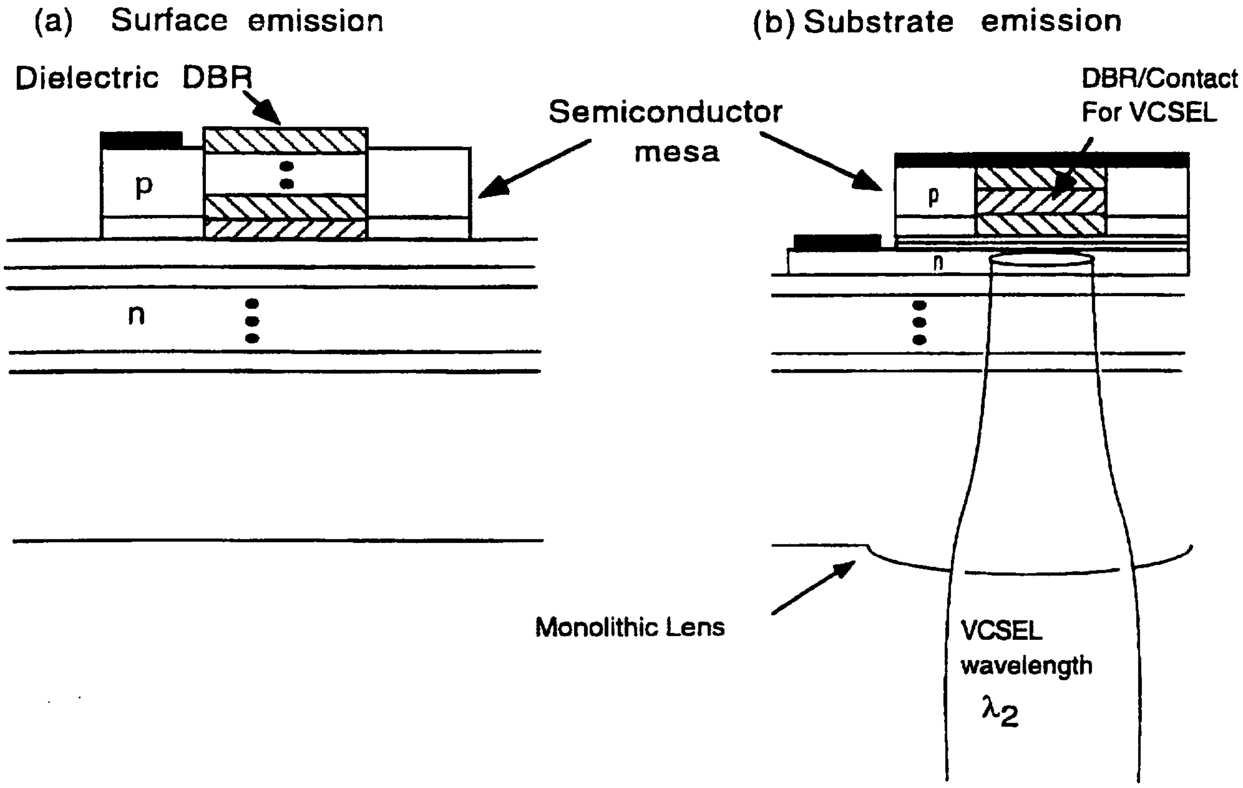
(a) Surface emission
(b) Substrate emission
Dielectric DBR
Semiconductor mesa
DBR/Contact For VCSEL
p
n
p
n
Monolithic Lens
VCSEL wavelength
λ2

FIG. 9

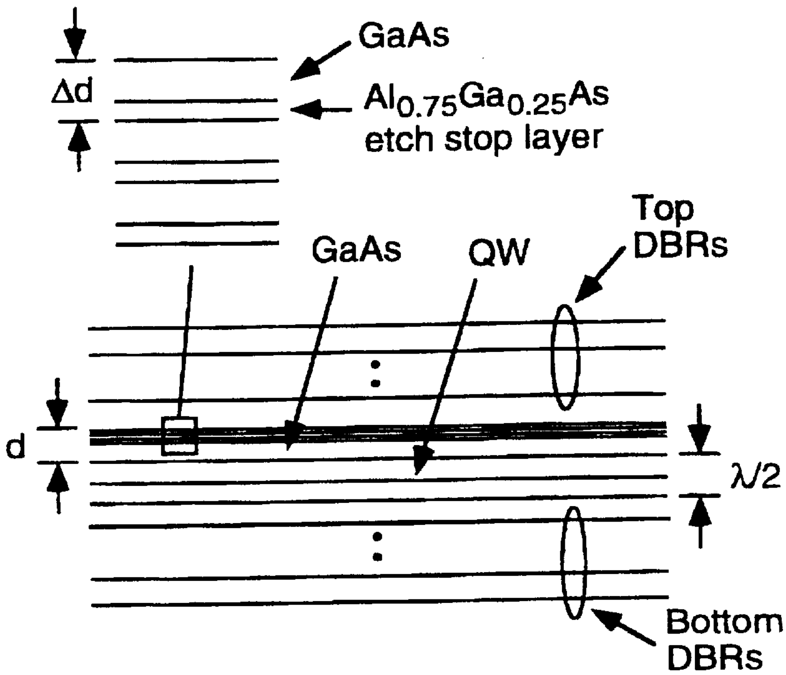
GaAs
Δd
$Al_{0.75}Ga_{0.25}As$
etch stop layer
Top
DBRs
GaAs
QW
d
λ/2
Bottom
DBRs

FIG. 10

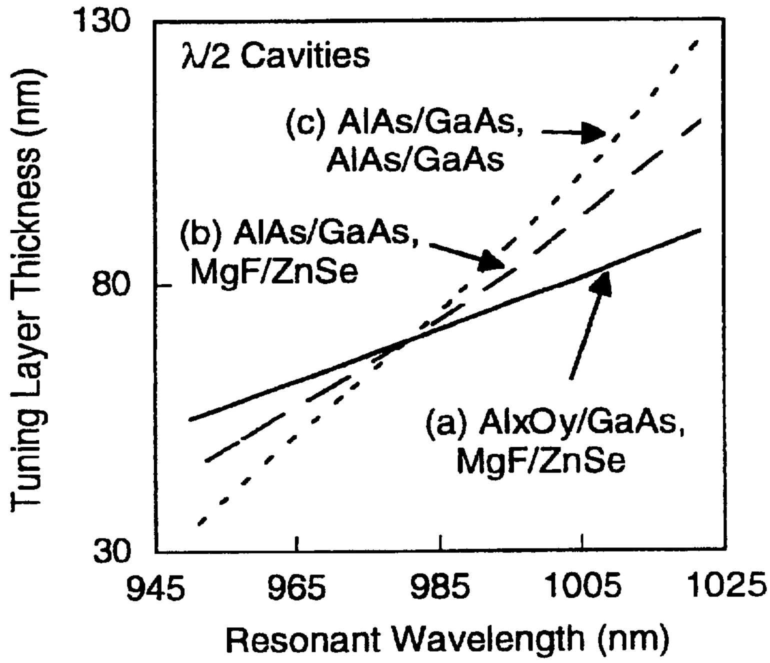
λ/2 Cavities
(c) AlAs/GaAs,
AlAs/GaAs
(b) AlAs/GaAs,
MgF/ZnSe
(a) AlxOy/GaAs,
MgF/ZnSe
Tuning Layer Thickness (nm)
130
80
30
945
965
985
1005
1025
Resonant Wavelength (nm)

FIG. 11

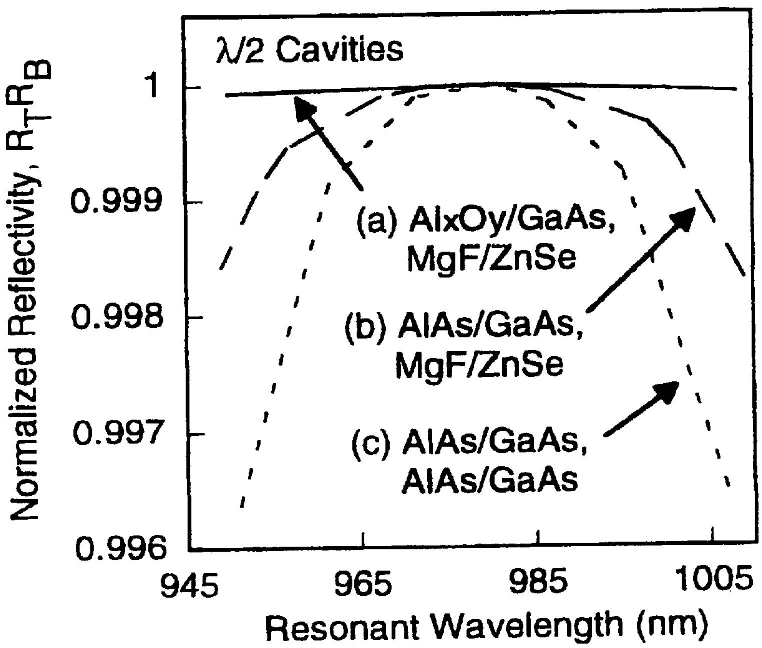
λ/2 Cavities
Normalized Reflectivity, $R_T R_B$
1
0.999
0.998
0.997
0.996
945
965
985
1005
Resonant Wavelength (nm)
(a) AlxOy/GaAs, MgF/ZnSe
(b) AlAs/GaAs, MgF/ZnSe
(c) AlAs/GaAs, AlAs/GaAs

FIG. 12