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Multiple-wavelength vertical-cavity laser arrays based on postgrowth lateral-vertical oxidation of AlGaAs

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We demonstrate that combined lateral-vertical oxidation of AlGaAs can be used to change the resonant wavelength of an optical cavity after the single epitaxial growth. A multiple-wavelength array of vertical-cavity surface-emitting lasers with a 48 nm wavelength span has been realized using this technique. © 1998 American Institute of Physics. [S0003-6951(98)02929-5]

Multiple-wavelength arrays of lasers and detectors are required for wavelength division multiplexing (WDM) systems. Vertical-cavity surface-emitting lasers (VCSELs) on GaAs substrates are ideally suited as sources in short-haul WDM systems, as densely-packed 2D arrays of surface emitters can be fabricated. Recently, a compact, “pie-shaped” array of VCSELs direct coupled to a single multimode fiber has been demonstrated.¹ This opens the way to WDM communication between multiple-wavelength arrays of emitters and detectors coupled to the same fiber.^{1,2} However, realization of these arrays requires a good control of the lasing wavelength over small areas of the epitaxial wafer [typically the area of a multimode fiber, $\approx \pi(30 \mu\text{m})^2$]. The lasing wavelength in a VCSEL is determined by the resonant wavelength of the vertical cavity, since only one longitudinal mode exists within the gain bandwidth. A variation in the physical thickness of the cavity can be achieved by varying the growth conditions (e.g., the temperature) over the wafer.³ However, this technique is difficult to apply to densely-packed arrays with arbitrary wavelength placement, and also requires unconventional growth techniques. On the other hand, the physical length^{4,5} of the cavity can be varied by anodic oxidation and etching of a controlled thickness of semiconductor.⁶ This requires an interruption of the epitaxial growth at the end of the cavity, a multistep etching, and then a regrowth of the top mirror, which makes this technique not suitable for low-cost device production. A recently proposed technique⁷ to change the phase of mirror reflection also allows tuning of resonant wavelength, but gives a limited tuning range. It would be most desirable to be able to access the optical cavity and change its optical thickness after the epitaxial growth of the entire structure. In this letter, we demonstrate that wet oxidation⁸ of AlGaAs can provide a remote access to the cavity and realize the desired tuning. The principle is shown in Fig. 1. A high Al-composition AlGaAs layer (e.g., AlAs, “supply layer”) is laterally oxidized from the two etched sides of a mesa in a water-vapor atmosphere at 400–500 °C. This provides a path for rapid lateral supply of the oxidizing species to the center of the mesa. An adjacent $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x \approx 0.7-0.9$) “tuning layer” is then oxidized vertically from this oxide layer, at a (slower) rate controlled by the Al composition, and by the oxidation

temperature. The same process of combined lateral-vertical oxidation is responsible for the short-scale tapering of the oxide profile in oxide-apertured VCSELs.⁹ The change in the refractive index from semiconductor ($n \approx 3.0-3.6$) to oxide ($n \approx 1.6$) determines a variation of the optical thickness, hence of the cavity wavelength. The amount of tuning is controlled by the position of the tuning layer and its Al composition, by the temperature and duration of the oxidation, and by the distance of the device from the etched side. Arrays of devices with different cavity wavelengths can then be realized by varying the size of the oxidation mesa. Devices having larger mesas are in fact oxidized more slowly (resulting in longer wavelengths), since the lateral oxidation takes a longer time to reach the device. Another approach is to place several devices at varying distance from the same etched side. These approaches can be easily extended to 2D arrays of VCSELs and resonant detectors.

As a first demonstration of the concept, we have designed and realized a multiple-wavelength VCSEL array. The lasers (see schematics in Fig. 1) are top emitting and double intracavity contacted. The bottom mirror consists of 24.5 periods of undoped GaAs/ $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ distributed Bragg reflector (DBR) pairs. The oxidant-supply layer is an 83 nm thick AlAs layer. The tuning is provided by a 237 nm thick $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ layer, positioned one DBR period away from the active region. The tuning layer is designed so that the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ and the oxide form $\lambda/2$ and $\lambda/4$ layers (at $\lambda = 951 \text{ nm}$) respectively, when the $\text{Al}_{0.7}\text{Ga}_{0.3}\text{As}$ is vertically oxidized by 95 nm. The tuning range is therefore centered at

FIG. 1. Schematics (not to scale) of wavelength tuning in a VCSEL by using lateral-vertical oxidation. The water vapor is supplied to the tuning layer inside the cavity by the lateral oxidation of the supply layer.

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FIG. 2. Calculated wavelength shift and threshold gain, as a function of the vertically oxidized thickness, in a VCSEL with two oxidized DBR periods. The squares represent experimental lasing wavelength shifts, with the corresponding stripe width number.

951 nm. The active region consists of three 80 nm $\text{In}_{0.18}\text{Ga}_{0.82}\text{As}/\text{GaAs}$ quantum wells at the center of an $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ 1 λ cavity. The room-temperature photoluminescence peak is centered at 976 nm. The electrical pumping is provided by two intracavity contacts, realized on a bottom Si-doped ($2 \times 10^{18} \text{ cm}^{-3}$) $3/4 \lambda$ GaAs n -contact layer and a top Be-doped ($2 \times 10^{18} \text{ cm}^{-3}$) $3/4 \lambda$ p -GaAs contact layer. The lateral current confinement is provided by the oxidation of a 27 nm thick $\text{Al}_{0.98}\text{Ga}_{0.02}\text{As}$ aperture layer between the active region and the top p -contact. In our simulations, the uniformity of threshold current density is limited by the bandwidth of the top DBR mirror if a semiconductor mirror is used. To achieve a large lasing wavelength span, we use a top mirror composed of two periods of GaAs/(Al oxide) Bragg pairs, next to the cavity, and 8 periods of GaAs/ $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}$ Bragg pairs. The high index contrast GaAs/(Al oxide) periods increase the total tuning range¹⁰ and the mirror bandwidth¹¹ to a point where the uniformity of threshold current density is likely to be limited by the gain bandwidth. Figure 2 shows the calculated wavelength shift (with respect to $\lambda = 951$ nm) and corresponding threshold gain, as a function of the vertically oxidized thickness t_{oxide} ($t_{\text{oxide}} = 0$ corresponds to the situation where only the 83 nm thick AlAs supply layer is oxidized). We assume a 12% contraction of both AlGaAs and AlAs upon oxidation. For $t_{\text{oxide}} > 150$ nm, two modes in the cavity compete for threshold (upper and lower branch of the continuous line). The resulting lasing wavelength will be determined by the optical loss of the modes and their spatial overlap with the gain region (i.e., the enhancement factor) and by their spectral overlap with the gain spectrum.

Device fabrication comprises multiple etching steps to expose the intracavity contacts and the layers to be oxidized, two separate oxidation steps, and finally, contact deposition. Etches are realized by Cl_2 reactive ion etching. First, circular mesas of varying diameters on a 250 μm pitch are defined by etching through the top DBR down to the p -contact layer. Larger mesas, aligned to the existing ones, are then etched down to the n -contact layer. A 240 nm thick layer of SiN_x is then deposited by plasma-enhanced chemical vapor deposition at 350 $^\circ\text{C}$. This is needed to prevent oxidation of the

FIG. 3. Measured spectra of lasing VCSELs. The peaks are numbered corresponding to the stripe width number. Inset: Threshold current as a function of wavelength. Filled dots represent top-emitting lasers, empty squares represent bottom-emitting lasers.

aperture layer during the oxidation of the tuning layer. Stripes with varying widths ($W = 60, 65, 70, 76, 83, 91, 100, 111, 123, 139, 164, 200 \mu\text{m}$), centered on the mesas, are defined by etching into the bottom DBR. These stripes are used as a pattern for lateral oxidation of the AlAs supply layer. The oxidation is performed at 465 $^\circ\text{C}$ for 40 min in a water-vapor atmosphere obtained by bubbling N_2 through water at 80 $^\circ\text{C}$. SiN_x is then removed by CF_4 plasma etching and the sample is oxidized again at 435 $^\circ\text{C}$ for 16 min. During this time, the two AlAs layers in the top DBR are completely oxidized, whereas oxidation of the aperture leaves a channel (6–8 μm diameter) for current flow into the active region. p -metal (Au–Zn–Au) and n -metal (Ni–Ge–Au–Ni–Au) are then evaporated on the corresponding contact layers. In order to avoid thermal stress in thick oxide layers, the contacts were not annealed.

The devices were tested at room temperature under dc electrical pumping. Figure 3 shows lasing spectra from devices having different stripe widths. The peaks are numbered corresponding to the stripe width, No. 1 being the smallest ($W = 60 \mu\text{m}$), No. 12 the largest ($W = 200 \mu\text{m}$). Figure 4 shows the net wavelength shift (filled dots, with respect to the central wavelength, $\lambda = 951$ nm), as a function of the stripe width. A small gradient in resonant wavelength (1 nm/

FIG. 4. Measured net wavelength shift (filled dots, left axis) and corresponding oxidized thickness (empty squares, right axis), as a function of stripe width. Inset: Schematics of stripe patterning for wavelength tuning. Circles and gray regions represent lasers and etched stripes, respectively.

device), due to a gradient in growth rate, has been subtracted to give the net tuning due to oxidation. On the right axis the corresponding oxidized thickness t_{oxide} is shown (empty squares), as deduced from the wavelength shift using the tuning curve on Fig. 2. Moving from larger to smaller stripe widths, the tuning layer becomes more and more oxidized, and the lasing wavelength decreases accordingly. For $t_{\text{oxide}} > 130$ nm, the devices start lasing on the longer wavelength mode, which is closer to the gain peak. A net 48 nm span is obtained by exploiting the two lasing modes. An even larger lasing span can be obtained by placing the gain peak at the center of the tuning range. Figure 4 shows that the oxidized thickness t_{oxide} varies nonlinearly with the stripe width. This nonlinear dependence is related to the spatial distribution of the oxidizing species in the supply and tuning layers and will be the object of further investigation. The nonlinear stripe width sequence used in the experiment partially compensates for this nonlinearity and allows to exploit all the available wavelength span.

The inset in Fig. 3 shows the threshold current as a function of the wavelength. All devices have 8 μm diameter current apertures, except those emitting at 959, 984, and 990 nm, which have 6 μm diameters. Due to processing problems, a gold layer was left on the top of the pillar on some of the devices. Although still lasing (with output from the bottom DBR), these devices present higher threshold currents (empty squares). The other, top-emitting lasers (filled dots) have sub-mA threshold currents in the 960–990 nm range. The corresponding threshold voltages are in the 4–6 V range and differential efficiencies vary between 10 and 30%. We attribute these high voltages to the voltage drop in the nonannealed contacts. The variation in threshold currents and differential efficiencies is likely to be due to non-optimized device processing.

In conclusion, we have demonstrated a new approach to multiple-wavelength VCSEL arrays. It is based on post-growth lateral-vertical oxidation of an intracavity AlGaAs layer. Contrary to techniques based on anodic oxidation or growth on patterned substrates, this technique uses a single epitaxial growth on conventional substrates, which results in easier device fabrication. We have measured a 48 nm lasing wavelength span. This method is very flexible and should lead to low-cost fabrication of densely-packed WDM arrays of lasers and detectors.

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