Embedded epitaxial growth of low-threshold GaInAsP/InP injection lasers

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Single-growth liquid-phase embedded epitaxy in the GaInAsP/InP system is described, and a new heterostructure laser is grown using this technique. These lasers exhibit excellent current and optical confinement. Threshold currents as low as 45 mA are achieved for a laser with 4-μm-wide active region.

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The possibility of optical fiber communications in the long-wavelength range (1.2–1.6 μm) is gaining increasing attention owing to lower losses and dispersion of optical fibers in this range. The GaInAsP/InP double-heterostructure lasers and light-emitting diodes (LED's) are the favored light sources for this range.[1–4]

Many laser structures have been devised to obtain low-threshold currents in the GaInAsP/InP material system. Important considerations are good current confinement and good optical confinement, i.e., two-dimensional (2-D) definition of the active region. Most low-threshold devices such as the buried heterostructure lasers,[5] are achieved through a multistep processing involving regrowth and careful alignment in the photolithography. Embedded epitaxy,[6,7] by growth through a mask, has been demonstrated in the GaAs/GaAlAs system to be a good means of achieving 2-D definition. However, no such work has been reported on the quaternary GaInAsP/InP system. We show in this work that embedded epitaxy is an attractive technique in this material system and report on a new embedded heterostructure GaInAsP/InP laser grown using this technique.

Growths were made using two-phase liquid phase epitaxy [2,4] on (100) n^+ InP substrates. The growth mask was a thin ($\sim$ 1000 Å) layer of CVD or plasma-deposited silicon nitride. To characterize the growths, stripe openings 20 μm wide were etched in the mask photolithographically in the [011] direction. Growth occurred only within the 20-μm opening. Typical cross sections of a three-layer growth is shown in Fig. 1. As can be seen, the growth proceeds at a higher rate in the vertical [100] direction than in the [$\bar{1}$11] and [$\bar{1}$11] lateral directions. In the growth the active layer is almost completely embedded in the cladding layers, resulting in good 2-D definition. Laser structures grown by this technique should possess low-threshold current densities. To achieve low-threshold currents it is necessary to decrease the active region width as well as its height. The use of narrow stripes, say $\sim 5\,\mu$m, leads to a fast growth rate, since the excess solute crystallizes over a small area. This results in relatively thick active region ($\gtrsim 1\mu$m) and, hence, in relatively high-threshold lasers.

We have bypassed this limitation by opening the mask in other areas adjacent to the stripes so that a large "dummy" area is available to the growth solution, thereby slowing down the growth rate.

The mask we used consisted of sets of two narrow stripes that define the laser channel stripe typically 7 μm wide. In this way the growth rate within the channel was only slightly higher than that in a completely unmasked area.

The masked substrate was cleaned in organic solvents and etched slightly in dilute Br-methanol before loading into the boat. The furnace was heated to 675°C for 1 h and cooled at 0.7 °C/min. During this time the substrate was prevented from thermal damage by supplying a phosphorus overpressure.[8] Then, three layers, InP ($n \sim 5 \times 10^{17}$ cm^{-3}), GaInAsP (undoped), and InP ($p \sim 2 \times 10^{18}$ cm^{-3}) were consecutively grown. The quaternary active region was grown at 635 °C. The growth of the first layer was quite critical. It had to reach above the level of the mask in order for the GaInAsP active layer to be completely embedded in InP. A cross sec-

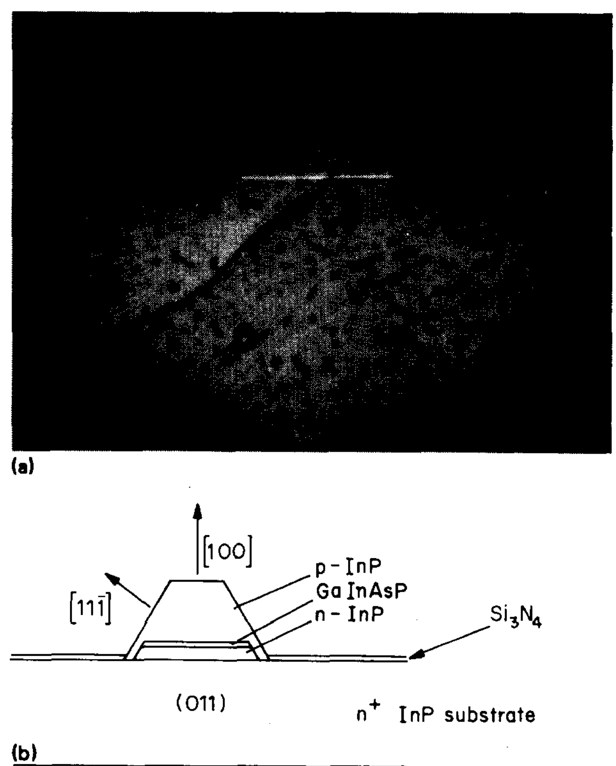

FIG. 1. (a) Cross section of growth on a 20-μm opening oriented in the [011] direction. (b) Schematic of growth.

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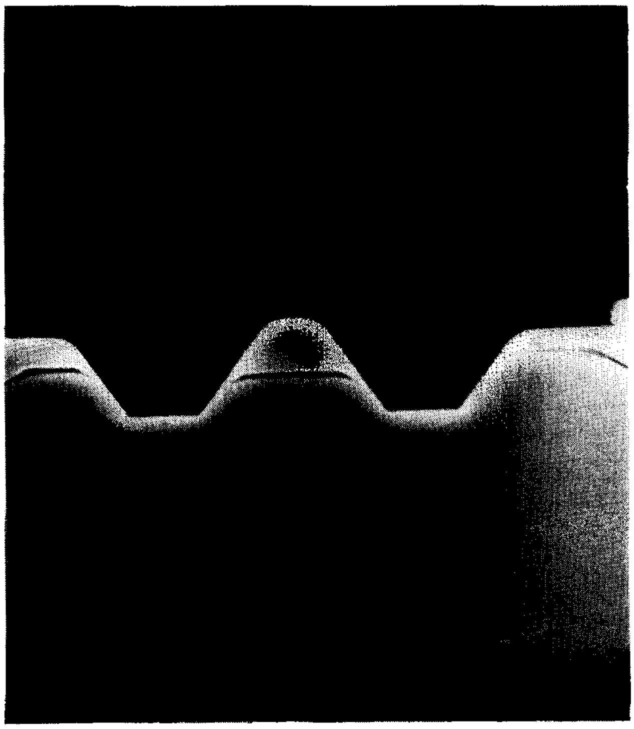

FIG. 2. SEM picture of low-threshold embedded GaInAsP/InP laser grown on [011] channel; the scale bar represents 1 μm.

tion of the growth on [011] channels is shown in Fig. 2.

After growth a layer of CVD silicon dioxide was deposited over the entire wafer and contact stripes were opened photolithographically. In this step it was important to make the openings only on the top of the ridge or the junctions would be shorted. This requirement was met in practice without undue difficulty, since the spun-on photoresist was thinner on top of the ridge and thicker in the two adjacent valleys. Au-Zn contact were evaporated and alloyed at 420 °C. The wafer was lapped down to 75 μm on the substrate side and Au-Ge was evaporated to form the n-contact. Bars of 200–300-μm-long lasers were cleaved and tested with 100-nsec current pulses.

For a laser shown in Fig. 2, with a 0.2-μm-thick and 4-μm-wide active layer, the pulsed threshold varied between 50 and 70 mA. The lowest achieved was 45 mA. A typical L-I characteristic is shown in Fig. 3. The external differential quantum efficiency including both facets was $\sim 40\%$. This is comparable to the value reported for the buried heterostructure lasers.[5] A far-field pattern taken parallel to the junction plane and a spectrum of such a laser is shown in Fig. 4.

It is possible to grow structures with even smaller active regions. At present, however, we are not able to reproducibly grow these structures. With modifications in the growth conditions and the mask dimensions, better control should be possible and produce lasers with even lower threshold currents.

In conclusion, we have demonstrated embedded epitaxy to be a simple means of obtaining 2-D definition in GaInAsP/InP double-heterostructure laser structures with only one growth step. This has resulted in lasers which are

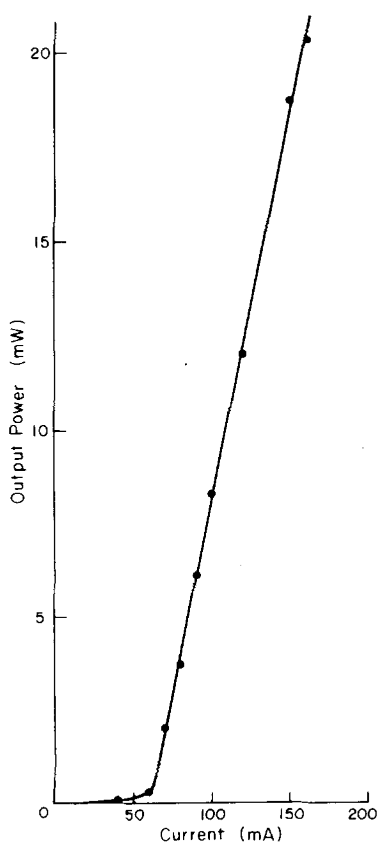

FIG. 3. Pulsed output power per facet vs input current for an embedded laser.

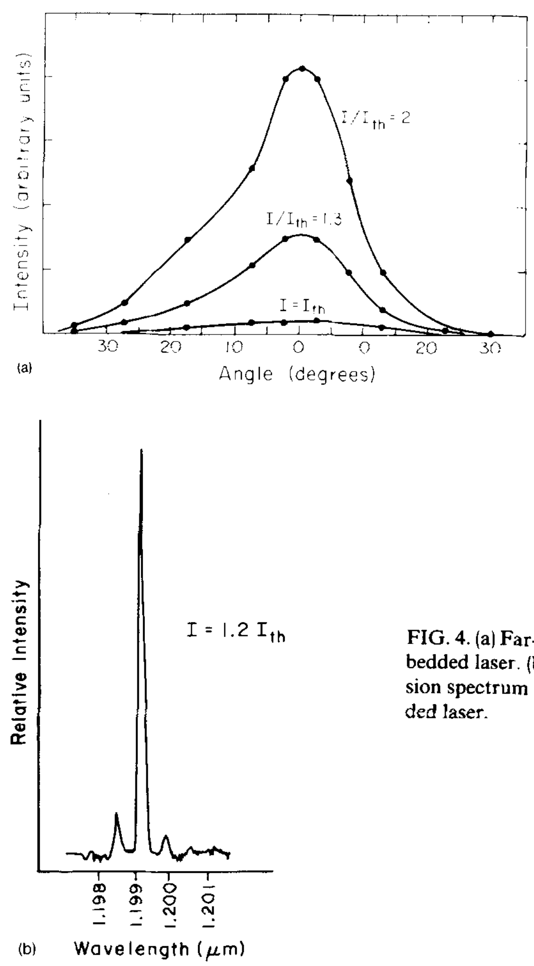

FIG. 4. (a) Far-field of an embedded laser. (b) Laser emission spectrum of an embedded laser.

comparable in threshold currents with buried heterostructure lasers.

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Double-heterojunction laser diodes with multiply segmented contacts

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Multiple segment stripe contact (MSSC) diode lasers, in which the pumping current density, and thus the gain or loss, can be varied and controlled along the length of the laser stripe, are reported. For different combinations and magnitudes of current density into the eight segments, self-pulsing, optical switching, bistability, hysteresis, and extremely high external differential quantum efficiencies can each be achieved. By simultaneously monitoring the voltage on the individual segments, changes in the carrier concentration and thereby changes in the gain and loss as a function of optical density and position along the stripe have also been observed. The use of MSSC lasers in the study of basic laser diode properties as well as novel devices of interest in their own right is suggested.

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In most analyses of cw semiconductor lasers, the current density, photon density, gain, and carrier concentration are treated as uniform in the axial direction. Recently, however, spatial nonuniformities in these quantities have been suggested as the explanation for the properties of some semiconductor lasers. A model proposed by Dixon and Joyce[1] to explain self-sustained pulsations, for example, relies upon the saturation of extra optical absorption at the end mirrors caused by the reduction in carrier concentration there due to surface recombination. In the experimental work of Hartman *et al.*[2] nearly all of the diode lasers which exhibited self-pulsing were also found to have darkening at the mirrors or dark-line defects which were modeled as extra saturable absorbing centers.

In this letter, we report early results of an experimental study of some of the effects of nonuniform current pumping in the axial direction on the performance of specially designed diode lasers. The pumping current density along the laser stripe is controlled through the use of an eight-segment contact to produce nonuniform carrier density and optical gain. For different combinations and magnitudes of current density into the segments, these lasers exhibit a variety of modes of operation, including self-pulsing, optical switching, bistability, hysteresis, and extremely high external differential quantum efficiencies. The segmented contact also permits a direct observation of the saturation of optical gain and absorption in the active region. The diode voltage measured at the contact pad of a segment is directly related to the carrier concentration under that segment, and any saturation of stimulated gain or absorption under a segment causes a change in the carrier concentration which can be determined by the change in the diode voltage.

There have been several publications on the dynamics of nonuniform current pumping of two section, homojunction lasers.[3–5] While those experiments demonstrated that the operation of lasers with one gain section and one absorber section leads to self-pulsing and nonlinearities in the output, the early lasers were limited by the need to operate at low temperatures and under pulsed excitation. The present work represents the first extension of this early work to incorporate state-of-the-art heterostructure geometries and multiple segments, and demonstrates the usefulness of this concept both to study fundamental features of device operation and to control the laser output. The study of multiple segment lasers should be helpful in understanding conven-

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