measurements made with these couplers are reported elsewhere.[11] Each prism is less than 1 cm long. Although the prism has an inherent bandwidth limitation for fixed input angles, this characteristic can be improved by special transducer design.

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Single-growth embedded epitaxy AlGaAs injection lasers with extremely low threshold currents

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A new type of strip-geometry AlGaAs double-heterostructure laser with an embedded optical waveguide has been developed. The new structure is fabricated using a single step of epitaxial growth. Lasers with threshold currents as low as 9.5 mA (150 μm long) were obtained. These lasers exhibit operation in a single spatial and longitudinal mode, have differential quantum efficiencies exceeding 45%, and a characteristic temperature of 175° C. They emit more than 12 mW/facet of optical power without any kinks.

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It is widely appreciated that a prerequisite for a double-heterostructure (DH) laser with low threshold current and a well-behaved optical mode is the existence of a built-in optical waveguide and carrier confinement in the plane of the active layer as well as at right angles to it. The buried-heterostructure (BH) laser(1) is proably the best-known example of such a laser structure. In this letter we report a new embedded stripe-geometry AlGaAs DH laser which possesses a two-dimensional electrical and optical confinement. Unlike the BH laser, this laser, to which we refer as ESL(embedded stripe laser) is fabricated by a one-step liquid phase epitaxial growth. This growth is performed on a GaAs substrate through openings in Si_3N_4 masks.

Other types of selective, or embedded, epitaxial growth have been reported recently.(2–4) However, in these cases the substrate area was covered completely by the oxide or nitride, except for the relatively narrow stripes where the laser mesa was grown. Since the area available in these earlier cases to the excess solute is limited, large and poorly controlled growth rates result, even at slow cooling rates. This leads to devices with large dimensions (stripe width $\simeq 25\mu$m) and hence high threshold currents ($>$ 200mA).

In the growth method employed in our new laser, illustrated in Fig. 1, the Si_3N_4 mask, which delineates the area of selective growth, is deposited as two narrow stripes–one on each side of what is to become the laser mesa. Large "dummy" areas of the substrate adjacent to the stripe are thus available to receive most of the solute and thus moderate the growth rate. This results in embedded lasers with active regions whose width as well as height can be controlled within the submicron range. An example of the small structure di-

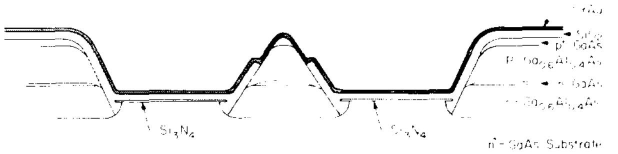

FIG. 1. Schematic cross section of the device.

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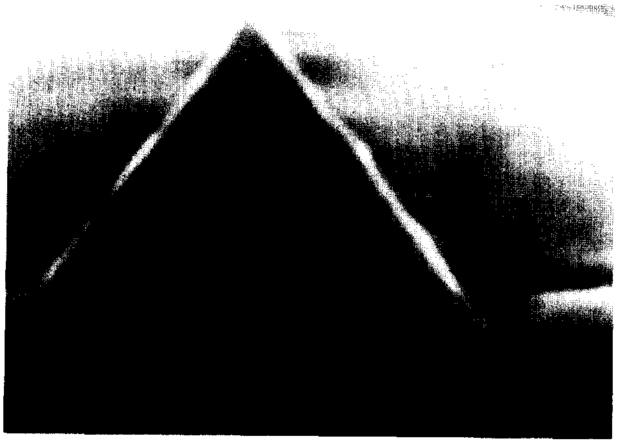

FIG. 2. Example of small structure dimensions obtainable with the new growth technique. (The length mark is 0.1 μm.)

mensions that can be obtained reproducibly under normal growth conditions is shown in Fig. 2. It should be noted that the total height of the mesa is 2 μm, and the width of the center layer is 1.4 μm, and its thickness in the center is about 0.3 μm.

Fabrication of the device starts with deposition of Si_3N_4 film on a (100) oriented n^+-GaAs substrate. Most of the nitride area, except for two 5-μm stripes 5 μm apart, is etched away. This pattern is repeated every 250 μm. Typical epitaxial layer composition is as follows: n (S_n doped)-$Al_{0.4}Ga_{0.6}As$; undoped ($n \simeq 10^{16}$ cm^{-3}) GaAs active region–the active region is crescent shaped, with ~ 0.3 μm thickness in the center;p (Ge doped)-$Al_{0.4}Ga_{0.6}As$; and p^+ (Ge doped)- GaAs contact layer. A SiO_2 film is deposited on the growth, and stripes are opened along the center of the lasers mesas. Because the thickness of the photoresist around the laser mesa is larger than in other places, the accuracy of the registration in this photolithographic step is not critical. Cr-Au is evaporated as the p-type ohmic contact. The wafer is then lapped and AuGe/Au is evaporated as the n-type contact, followed by alloying at 360° C. The last step is cleaving the wafer to devices with lengths in the 125–325-μm range.

edges grow at an angle of about 55° to the (100) face. These are the (111) surfaces, in agreement with the results reported in Ref 2. The laser mesa grows at the nominal rate until the triangle shape is completed. After that the growth rate on the mesa is much smaller, while at the sides it remains the same. If the growth is continued, we get intolerably large differences in height between the mesa and its surroundings. This makes it difficult to apply the p contact to the device. The exact shape of the grown structure also depends on the orientation of the stripes We found, in accordance to the results of Ref. 2, that if the stripes are perpendicular to the $(01\bar{1})$ cleavage plane, the growth rate is higher than in the case where the stripes are perpendicular to the (011) cleavage plane. This causes the lasers grown using the first orientation to have thicker active regions.

Scanning electron microscope pictures of a cross section of typical devices grown in both orientations are shown in Fig. 3. The active region of a device grown with the stripes perpendicular to the (011) direction has a crescent shape. It was found recently that lasers with curved active layers give better results in terms of spatial mode stability.[5]

The dependence of the room temperature pulsed threshold current on the laser length is shown in Fig. 4. Typical values of threshold currents are 15–20 mA for 200-μm lasers and 25–30 mA for 300 μm lasers. The light versus current curve of a typical device is linear and kink free up to

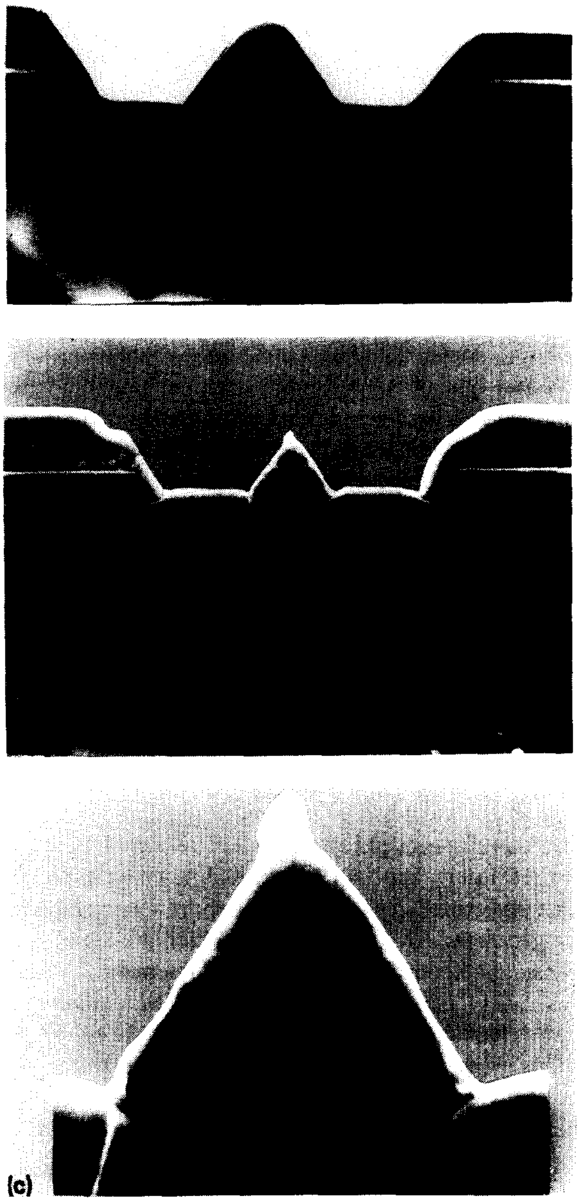

FIG. 3. SEM photographs of (a) device grown with mesa perpendicular to (011) orientation (b) device grown with mesa perpendicular to the $(01\bar{1})$ orientation, and (c) enlarged photograph of (b). The length mark is 1 μm.)

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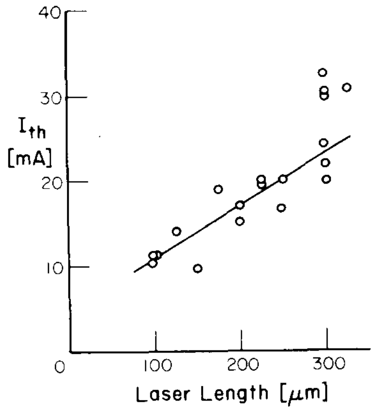

FIG. 4. Dependence of lasers threshold current I_{th} on the laser length L.

power levels of about 12 mW/facet. Differential quantum efficiencies exceeding 45% were obtained (for lasers with cavity length of 225 μm).

cw operation has been demonstrated with cw threshold currents higher by about 15–20% than the pulsed threshold currents. The exponential characteristic temperature T_0 is about 175°C in the temperature range of 20–90 °C and 160 °C in the 20–135 °C range.

Measurements of the near- and far-field patterns show that the devices operate in the fundamental spatial mode up to more than three times the threshold currents (devices with thicker active region $\sim 0.4\,\mu$m develop the higher-order mode at $\sim 1.4 I_{th}$). A far-field pattern in the direction parallel to the junction plane is shown in Fig. 5. The half beam angle of the mode is about 30°. These new lasers also operate in a single longitudinal mode, as can be seen in Fig. 6. The devices maintained this single-mode behavior up to $4I_{th}$. At this higher current there is a small shift ($\sim +20$ Å) in the oscillation wavelength.

In conclusion, we have demonstrated a single-step epitaxial growth fabrication of a new type of laser with an embedded optical guide. Lasers with very low threshold currents good T_0, stable spatial and longitudinal mode pattern, and kink-free operation up to high power levels were obtained.

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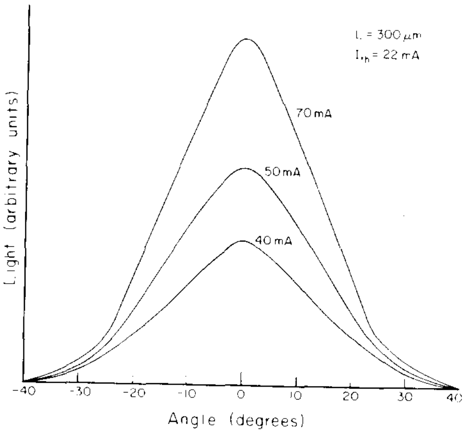

FIG. 5. Far-field pattern of a laser.

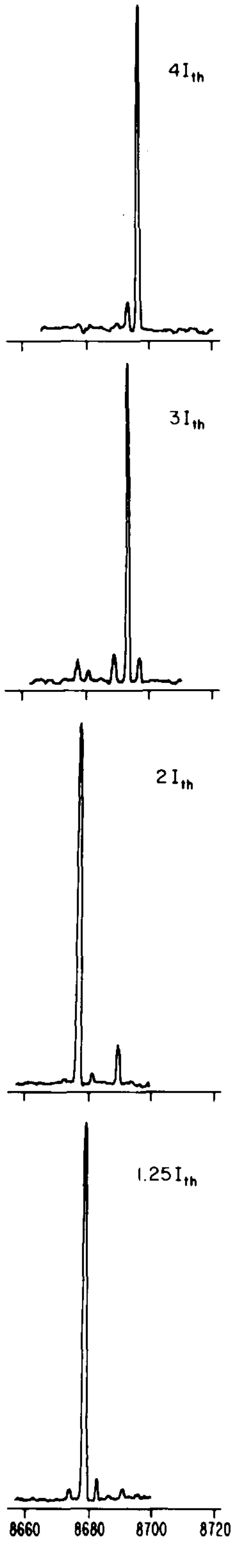

FIG. 6. Spectrum of a laser (The horizontal scale depicts wavelength in Å.)

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