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Citation: Applied Physics Letters **50**, 705 (1987); doi: 10.1063/1.98073
View online: http://dx.doi.org/10.1063/1.98073
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Surface emitting laser diode with bent waveguide

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(Received 8 December 1986; accepted for publication 22 January 1987)

A surface emitting laser diode (SELD) with a bent double heterostructure is fabricated on a grooved substrate. This SELD has a facet angle of 20° and lased at a threshold current of 120 mA. The external quantum efficiency is 33%. The far-field pattern has sharp peaks at 10° and 18° and wider emission bands between 25° and 45°. Radiation loss by the bent waveguide is also estimated by the equivalent current source model.

A surface emitting laser diode (SELD) has advantages of electro-optic integration because a cleaving process is unnecessary. There are two approaches for the surface emitting laser diode. One is to incorporate a vertical optical cavity with high reflectivity mirrors[1,2] and the other is to combine an edge emitting laser and an isolated output mirror to reflect the beam upward.[3,4] There are intrinsic advantages in the first approach in terms of high speed and integration density. However, the second approach is easier to realize since we start with the edge emitting laser, for which the technology is well established. Although light output is not perpendicular to the substrate, it may be taken at an angle. An angle of 20°–45° from the substrate should allow most of the light output to be taken from the surface. Being analogous to an optical fiber, a bent double-hetero (DH) structure can guide a laser beam without significant loss. In this letter, we estimate the radiation loss caused by bending and report the realization of the first surface emitting laser diode with the bent waveguide.

Radiation loss from the bent waveguide can be estimated from coordinate transformation[5–7] or, more simply, from antenna theory by finding radiation from a distributed current source embedded inside the infinite cladding region.[8] In this approach, the electric field $\mathbf{E}$ in the active region is replaced by an effective current source J_z with the amplitude

$$J_z = i\sqrt{\epsilon_0/\mu_0}\,k_0(\bar{n}^2 - n^2)\mathbf{E}\,, \tag{1}$$

where k_0 is the free-space wave number, and $\bar{n}$ and n are the refractive indices of the cladding and active layer, respectively. When the double heterostructure is bent with a radius R_c and assumed to be infinite across the bending, the radiation power per unit angle (radian) $P_{\rm rad}$ from this cylindrical waveguide[9] is found to be

$$P_{\rm rad} = (\pi/4)k_0\sqrt{\mu_0/\epsilon_0}\,J_z^2 R_c^2 J_\nu(k_0 R_c \bar{n})^2, \quad \nu = k_0 R_c \bar{n}_{\rm eff}\,, \tag{2}$$

where J_ν is the Bessel function of the order of ν and $n_{\rm eff}$ is the effective refractive index of the guided mode. Because the order ν is larger than 100 in our case, the above Bessel function can be well approximated by

$$J_\nu \simeq \frac{\exp(-R_c/2R_0)}{\sqrt{2\pi k_0 R_c}\,(\Delta n^2)^{1/2}}, \quad R_0 = \frac{3n_{\rm eff}^2}{2k_0(\Delta n^2)^{3/2}}, \quad \Delta n^2 = (n_{\rm eff}^2 - \bar{n}^2)\,, \tag{3}$$

where R_0 is a characteristic radius mainly determined by Δn^2, the difference between square of effective refractive index $n_{\rm eff}^2$ and that of the cladding region $\bar{n}^2$. The expression R_0 is similar to the one obtained by the method of coordinate transformation.[5–7] The value of Δn^2 is a good measure for optical confinement because field intensity in the cladding region attenuates in proportion to $\exp(-k_0\sqrt{\Delta n^2}\,l)$, where l is the distance from the heterointerface. Characteristic radius R_0 decreases superlinearly with Δn^2. So, radiation loss is dependent on the optical mode confinement as well as on the curvature of bending R_c. When the Bessel function in Eq. (2) is substituted by Eq. (3), the radiation loss per radian is proportional to

$$P_{\rm rad} \propto R_c \exp(-R_c/R_0)\,. \tag{4}$$

The first term R_c comes from the fact that the length of waveguide to produce a certain degree of bending is proportional to the bending radius R_c. If we assume an $Al_{0.3}Ga_{0.7}As$/GaAs DH structure with an active layer thickness of 0.15 μm, the characteristic length R_0 is 10 μm.

Figures 1(a) and 1(b) show the radiation loss as a function of the radius of bending R_c to produce the bent angle of 20°. The loss is normalized by the total transmitted power which is carried by the fundamental mode in the planar DH structure. The radiation loss is sensitive to the aluminum concentration in the cladding layers [Fig. 1(a)] or active layer thickness [Fig. 1(b)] because the characteristic radius R_0 in Eq. (3) is related to the degree of optical confinement. If we assume an $Al_{0.3}Ga_{0.7}As$/GaAs DH structure with an active layer thickness of 0.15 μm [the second curve in Fig. 1(a)], the radiation loss is estimated to be 25% at the bending radius of 40 μm. When a laser length of 250 μm is assumed, the radiation loss of 25% at both ends of the cavity is equivalent to an additional internal loss of 20 cm^{-1}. If we suppose the material loss of 20 cm^{-1} and mirror loss of 50 cm^{-1}, the threshold gain will increase by 30%. So, the radiation loss of 25% will be the maximum feasible value for the bent waveguide laser. As seen in the figures, radiation loss can be reduced substantially either by increasing the aluminum concentration of the cladding layer or the active layer thickness. The radiation loss is porportional to the bending angle when the amount of loss is relatively small. It is apparent that a bending angle of more than 45° is feasible by selecting the appropriate values for the bending radius and the physical parameters of the DH structure.

The curved DH structure which satisfies the foremen-

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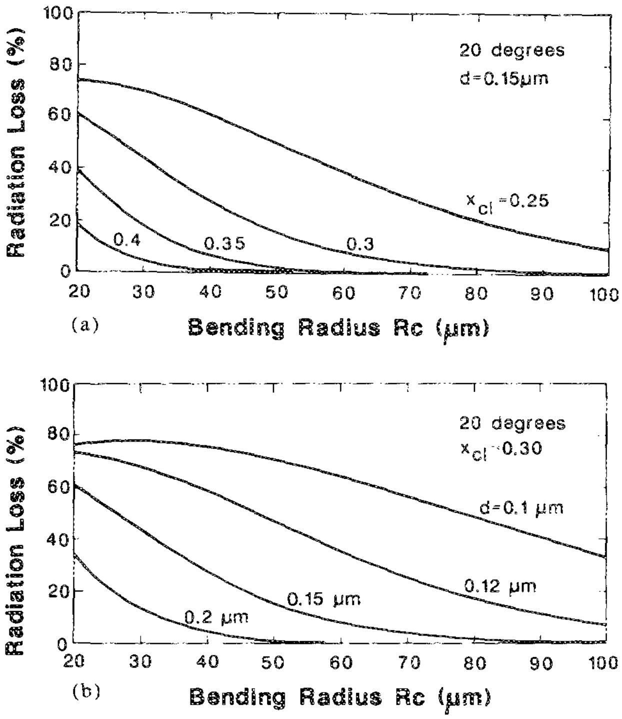

FIG. 1. Radiation loss in the bent AlGaAs/GaAs DH structure calculated by the current source model. The bent angle is 20°. (a) With different aluminum concentration in the cladding layer, (b) with different active layer thickness.

tioned condition is made by liquid phase epitaxy (LPE) on a grooved substrate [Fig. 2(a)]. Forward mesa slope across the $\langle 01\bar{1}\rangle$ direction is utilized to achieve the bending. The etched grooves have a depth of 10 μm and a width of 250 μm.

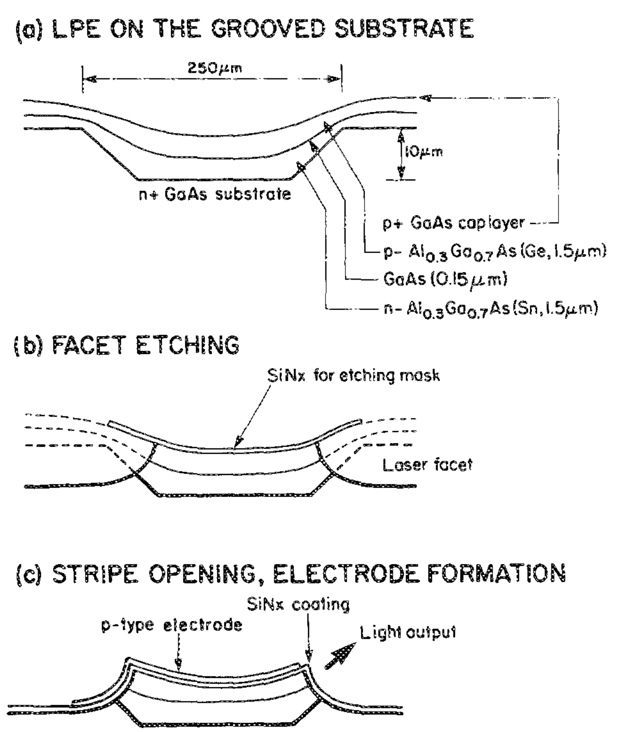

FIG. 2. Processing steps and schematic structures for the SELD with bent waveguide.

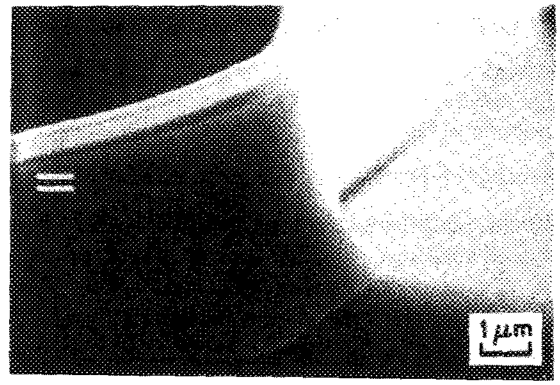

FIG. 3. Cross-sectional SEM picture of the bent DH structure. The active layer is bent at 20°.

After the DH structure is formed by LPE, selective etching is performed from the upper boundary of the groove to make a facet opening [Fig. 2(b)]. The etching condition is NH_3:H_2O_2:H_2O = 1:1:20 for 10 min ($\approx 10\,\mu$m). The etched facet and active layer intersect nearly at the right angle as shown in the cross-sectional secondary electron microscope (SEM) picture (Fig. 3). In this picture, the active layer is bent upward by 20° with a curvature around 40 μm. The bent angle of the active layer can be determined by the thickness of the epitaxial layer and position of the etching facet. A shallow ridge with a depth of 1 μm is incorporated to reduce the current spreading. After the whole region is coated by SiN_x, contact stripes with a width of 4 μm are opened. Au(3000 Å)/Cr(150 Å) is evaporated for the p-side electrode. One of the laser facets is coated by the p electrode to reduce the cavity loss.

Figure 4 shows the typical light versus current characteristic of the surface emitting laser with bending. The threshold current is around 120 mA in a pulsed condition. Differential quantum efficiency is 33% from one facet. The maximum light output in this curve is 40 mW at 220 mA.

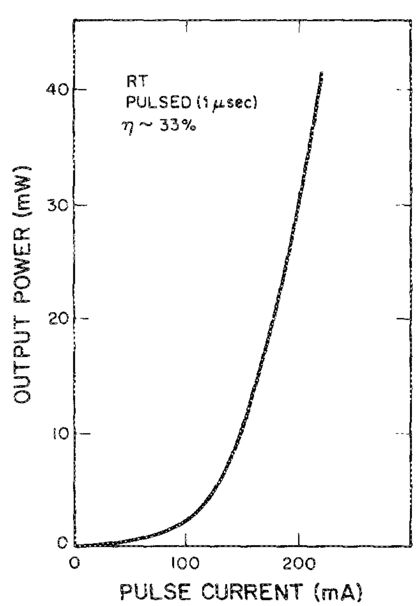

FIG. 4. *I-L* characteristic of the SELD with bent waveguide.

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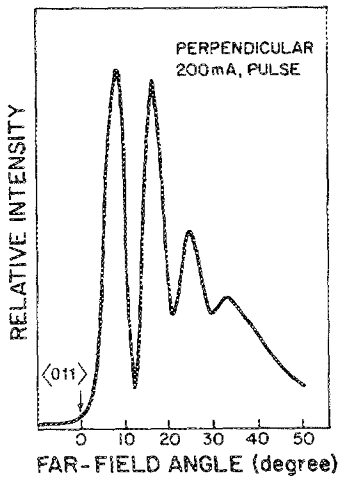

FIG. 5. Far-field pattern of the SELD with bent waveguide.

The threshold current is about 50% higher than the edge emitting laser diode with the same stripe width. The increase in the threshold current is due partly to the mirror loss of the etched facet, in addition to the bending loss. The relatively high quantum efficiency of 33% is due to the partial antireflection coating of the output facet with SiN_x and high reflective metallization covering the other facet.

Figure 5 shows the vertical far-field pattern of the bent waveguide laser. The diode was cleaved just in front of the etched facet so that the light output is not blocked by the substrate or sample package. The far-field pattern has sharp peaks at 10° and 18° and wider emission bands between 25° and 45°. Two distinct features are to be noted. First, the angle of the active layer at the facet is observed around 20° in the SEM picture (Fig. 3), whereas the actual emission peaks begin to show up at shallower angles. This is because higher order modes in a curved waveguide are excited at the joint of straight and curved sections. High-order modes penetrate more deeply into the upper cladding layer and have larger phase velocity. Therefore, the radiation angle is pushed towards the lower cladding layer. Similar behavior of the radiation angle is also observed in Ref. 7 (pp. 98–104). Second, several peaks are observed in the far-field pattern. The multiple peak characteristics of the far-field pattern can be explained by the slight difference of the facet angles between upper and lower cladding layers caused by wet etching (Fig. 3). This problem can be overcome by reactive ion beam etching technique.[10]

In conclusion, a SELD with bent waveguide is fabricated by LPE technique on a grooved substrate. This SELD has a facet angle of 20° at both ends and lased at a threshold current of 120 mA. One of the facets is completely covered by a *p*-type electrode to improve the external quantum efficiency. The far-field pattern has sharp peaks at 10° and 18° and wider emission bands between 25° and 45°. Theoretical calculation indicates that a bending angle of more than 45° is possible by either increasing the curvature of bending or modifying the DH structure for better optical field confinement.

The authors acknowledge contributions of Professor A. Dienes of the University of California, Davis, and Professor J. S. Smith and J. Fang of the University of California, Berkeley, for helpful discussions. They also appreciate the technical assistance of R. Hamilton, P. Guillory, D. Chan, and J. Rivera of the Microfabrication Laboratory, University of California, Berkeley. This work is supported in part by NSF No. ECE-8410838, JSEP No. F49620-84-C-0057 and Lockheed Missiles and Space Company.

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