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Surface-emitting laser diode with vertical GaAs/GaAlAs quarter-wavelength multilayers and lateral buried heterostructure

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Threshold current of 2 mA at room temperature cw operation is realized in a vertical distributed feedback surface-emitting laser diode with lateral buried heterostructure (LBH). In this LBH structure, the vertical distributed feedback active region (AlGaAs/GaAs multilayer) is entirely surrounded with *n*- and *p*-type AlGaAs cladding layers for minority-carrier confinement. The far-field angle is 7°. The beam shape is nearly circular. However, the lasing spectrum is broad (2–3 nm) compared with the conventional edge-emitting laser. Major differences between the surface-emitting laser diode presented here and the conventional edge-emitting laser diode are discussed.

The vertical distributed feedback surface-emitting laser diode (DFB-SELD) is very advantageous for optoelectronic integration because it does not need cleavage nor a backside substrate etching process to form a vertical cavity.[1–3] High reflectivity of the cavity mirrors and high efficiency in the carrier confinement structure are important to realize low threshold current operation of the vertical DFB-SELD. High reflectivity of the cavity mirrors was already realized by the use of a quarter-wavelength stack of AlGaAs and GaAs thin layers[4]; however, carrier confinement was not adequate in the previous structures.[1–3] In this letter, we realized a novel lateral buried heterostructure (LBH) by selective liquid phase epitaxy (LPE) and selective zinc diffusion, and achieved a room-temperature, low-threshold current, cw operation of the vertical DFB-SELD.

Figure 1 depicts the DFB-SELD with LBH structure. The active layer is made of a quarter-wavelength stack of $Al_{0.3}Ga_{0.7}As$ and GaAs thin layers prepared by metalorganic chemical vapor deposition (MOCVD). This multilayer is etched by a wet etching solution leaving mesas with different dimensions ranging from 2×8 to 3×17 μm on the top surface and 10 μm in height with the DFB type active region. The *n*-type $Al_{0.4}Ga_{0.6}As$ cladding layer is formed by LPE using silicon nitride on top of the island as a selective epitaxial mask. The lateral *pn* junction is formed by selective zinc diffusion through an opening in the silicon nitride film at a distance of 3 to 4 μm away from the edge of the mesa. Due to lateral diffusion, the zinc diffusion front is inside the multilayer. In this structure, the GaAs/AlGaAs part of the multilayer is completely surrounded by the *n*- or *p*-type AlGaAs. Therefore, carrier confinement should be comparable with that of buried heterostructures used with the edge-emitting laser diode.[5] The zinc diffusion front spreads along the cladding region as well as along the AlGaAs/GaAs multilayer. However, carriers are injected predominantly into the GaAs part of the multilayer because the turn-on voltage for an AlGaAs *pn* junction is higher than for a GaAs *pn* junction. This mechanism is also utilized in the transverse junction stripe (TJS) type edge-emitting laser diode,[6] which has low threshold current comparable with that of the BH laser diode.

Figure 2 shows the cross-sectional picture of the LBH structure observed by the scanning electron microscope (SEM). The white and black stripes at the center of the picture are the alternating thin layers of $Al_{0.3}Ga_{0.7}As$ and GaAs, respectively, prepared by the MOCVD technique. The thickness of each pair of the AlGaAs/GaAs layers is adjusted so that the reflectivity is peaked at the gain maximum of GaAs. The optical cavity, formed by these AlGaAs/GaAs multilayers, consists of 20 pairs at the top, 60 pairs at the bottom, and a phase shifter GaAs layer in between. The thickness of the GaAs phase shifting layer is about half wavelength of the gain maximum, which allows the laser to lase at the Bragg wavelength of the multilayer. The multilayer is surrounded by the *n*- and *p*-type $Al_{0.4}Ga_{0.6}As$ cladding layers formed by the selective LPE and selective zinc diffusion. The *p*-type region is seen brighter in the SEM picture. The intermixing effect[7] of zinc diffusion in the multilayer interface is negligible because zinc concentration is already low at the diffusion front.

Figure 3 shows the light output versus dc current (*L-I*) characteristics of the DFB-SELD. The laser is operated cw

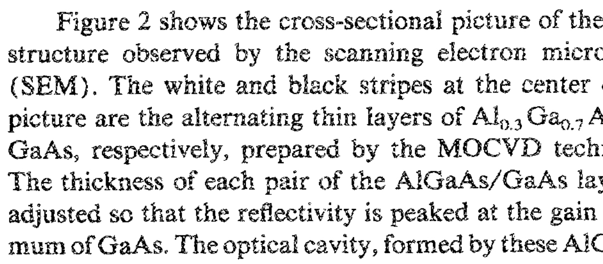

FIG. 1. Schematic diagram of the DFB-SELD with LBH structure.

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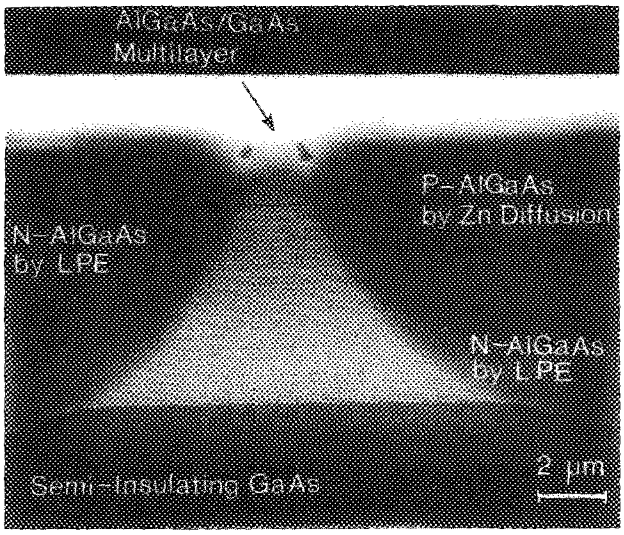

FIG. 2. Cross-sectional SEM picture of the DFB-SELD with LBH structure, after the selective etching of GaAs layers by 100:1 (H_2O_2:NH_4OH) for 15 s. The white contrast region at the right side of the multilayer is a zinc-diffused p-type AlGaAs cladding layer.

at room temperature. The threshold current is 2 mA as seen in the inset of this figure. The total light output increases linearly up to 25 mA. The output power is 28 μW at 10 mA and 87 μW at 25 mA.

Figure 4(a) shows the near-field pattern of the DFB-SELD. The light-emitting region is tightly confined within the rectangular top emission surface. Therefore, carrier confinement by the LBH structure is very effective. Figure 4(b) shows the far-field pattern at an operating current of 20 mA. The far-field pattern is taken from a screen placed at a distance of about 16 mm from the emission facet using the RCA vidicon TV camera, an image profiler, and a monitor. The result shows a nearly circular pattern with a Gaussian-like intensity profile. The estimated beam divergent angle from this measurement is about 7° for both directions. This indicates a good spatial coherence in this device. However, the circular emission pattern is not expected from a trapezoidal mesa cavity with a rectangular emission surface. We think that the curved boundary between the AlGaAs/GaAs multilayer active region and AlGaAs cladding region may affect the emission beam pattern in the plane along line AA' in Fig. 1. This is currently under investigation.

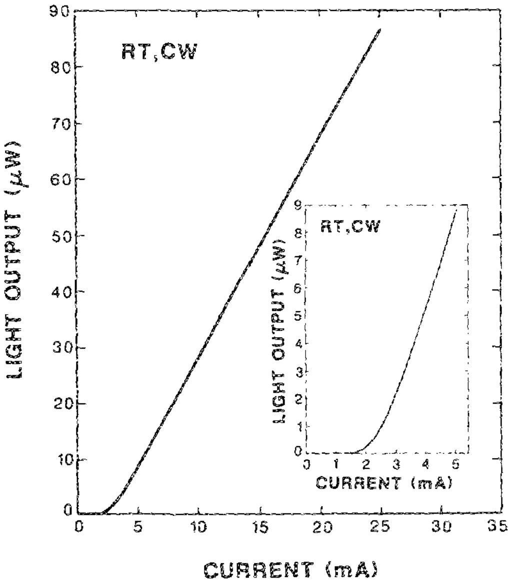

FIG. 3. Light output vs dc drive current of the DFB-SELD with LBH structure.

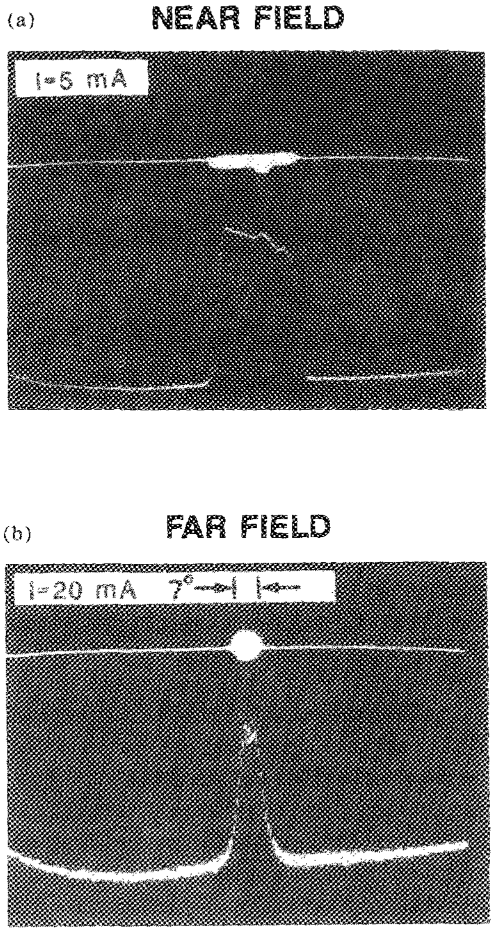

FIG. 4. (a) Near-field pattern of the DFB-SELD. Also shows the line profile of the field intensity across the long edge of the rectangular emission region. (b) Far-field pattern and its intensity line profile across the beam center of the DFB-SELD.

Figure 5 shows the electroluminescence spectra of the DFB-SELD with LBH structure. As is seen in the inset of the figure, the onset of sharp emission line becomes obvious at the drive current of 1.6 mA. This current level is consistent with the threshold current deduced from the L-I characteristics. At higher operation current, two peaks become dominant at 884 and 859 nm. Both of the peaks increase superlinearly up to 10 mA. The shorter wavelength peak saturates at higher operation current, while the longer wavelength peak keeps on growing superlinearly. Therefore, stimulated emission is taking place.

The half-width of the lasing spectrum is rather wide (2 to 3 nm) compared with an edge-emitting (EE) laser diode and there is a large satellite peak at the shorter wavelength side. However, there are fundamental differences between the short-cavity SE and long-cavity EE lasers. First, the

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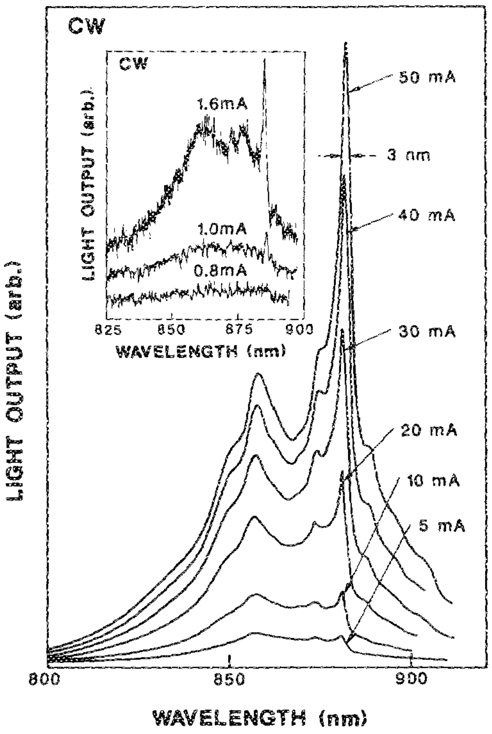

FIG. 5. Electroluminescence spectra of the DFB-SELD.

mode spacing in the SE laser is much larger than the 0.3 nm in the EE laser. For such wide spectral separation, the mode broadening mechanism will be different from that of the EE laser. Second, the spontaneous emission factor in the short-cavity SE laser is expected to be much larger than in the long-cavity EE laser.[8] We believe that both these factors will affect the behavior of the two types of lasers in terms of lasing spectrum and *L-I* characteristic. The effects are currently under investigation. In addition, further improvement in the spectrum is expected by the modification of the optical cavity. Perpendicular sidewalls in the multilayer mesa will eliminate a parasitic light emission from the oblique region in current structure which will not couple with the vertical optical cavity. The distributed Bragg reflector type optical cavity with thicker center GaAs region will concentrate the carrier injection at the center of the cavity where lasing electric field is maximum.

In conclusion, the DFB-SELD with LBH structure is realized with the combination of MOCVD, selective LPE, and zinc diffusion techniques. In this structure, a MOCVD-grown AlGaAs/GaAs multilayer is surrounded completely by *p*- and *n*-type AlGaAs cladding layers, such that lateral carrier injection and carrier confinement are achieved. Nominal threshold current for cw operation is 2 mA. The radiation region is well confined within the active region. The far-field pattern is circular and well defined. However, the lasing spectrum is broad (2 to 3 nm) and there is large satellite emission at shorter wavelengths. Further improvement can be realized by proper modifications of the optical cavity. We also believe that there are major differences between the surface- and edge-emitting lasers and further studies are needed to fully understand the physics of the surface-emitting laser.

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