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cw operation of distributed-feedback GaAs-GaAlAs diode lasers at temperatures up to 300 K

M. Nakamura, K. Aiki, and J. Umeda

Central Research Laboratory, Hitachi Ltd., Kokubunji, Tokyo, Japan

A. Yariv

California Institute of Technology, Pasadena, California 91109

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Distributed-feedback GaAs-GaAlAs diode lasers with separate optical and carrier confinement have been successfully operated under dc bias up to room temperature. They lased in a single longitudinal mode with a threshold current density of 0.94 kA/cm^2 at 170 K and 3.5 kA/cm^2 at 300 K.

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Semiconductor diode lasers with distributed feedback (DFB) are expected to find application as future light sources because of their integration capability as well as their inherent spectral and modal control.[1-4] A remarkable reduction of the threshold current density of DFB GaAs-GaAlAs lasers has been achieved by adopting a separate confinement hetero (SCH) structure, as has been reported previously.[5] In these lasers, the active layer has been separated from the corrugated interface to avoid nonradiative recombination of the injected carriers. The lasers have been operated at ~300 K under pulsed bias with a threshold current density of ~3 kA/cm^2.

In this correspondence, we describe the study of the SCH structure DFB laser, which is aimed at the achievement of cw operation. The diodes are mounted on diamond heat sinks and are operated successfully under dc bias at temperatures up to 300 K. To our knowledge, this is the first report of cw operation of DFB semiconductor lasers.

The structure of the diode laser is shown in Fig. 1. It has a mesa-stripe geometry so that the injection is limited to a rectangular region.[6] The width of the stripe was 50 μm and the length of the excited region was ~700 μm. The output was obtained from the front surface. An unexcited waveguide with a length of 2–3 mm was continuous to the excited region. This blocked the optical feedback from the end surface. The photograph in Fig. 1 shows a crosssection of the corrugated waveguide. The grating with a period of 0.36–0.38 μm was made by chemical etching through a photoresist mask produced by holographic photolithography.[7] In this structure, the injected electrons are confined to the active layer by the p-$Ga_{0.83}Al_{0.17}As$ layer, while the light extends from the active layer to the p-$Ga_{0.93}Al_{0.07}As$ layer.[5]

A similar structure was recently reported by Casey *et al.*, where the diodes were prepared by a hybrid liquid-phase-epitaxy and molecular-beam-epitaxy growth process.[8] In our experiment, we were able to grow all the layers by liquid-phase epitaxy by introducing the p-$Ga_{0.93}Al_{0.07}As$ layer.

From a theoretical analysis of the SCH structure DFB laser,[9] it was found necessary to reduce the thickness of the waveguide in order to achieve low-threshold operation. In this experiment, the thickness of the active layer was chosen to be ~0.2 μm and that of the p-$Ga_{0.83}Al_{0.17}As$ layer to be ~0.1 μm. The thickness of

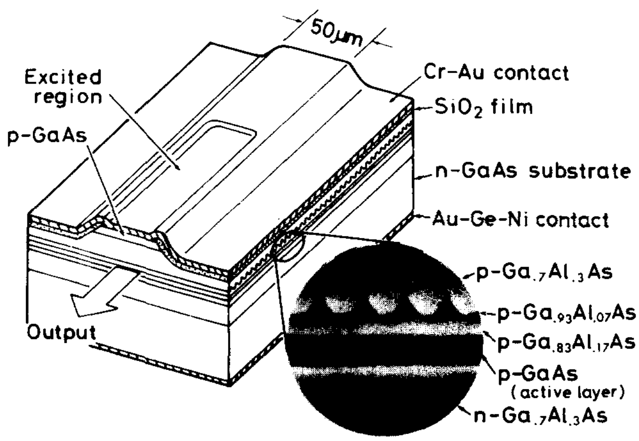

FIG. 1. Structure of the DFB laser with separate optical and carrier confinement.

the p-$Ga_{0.93}Al_{0.07}As$ layer was ~0.15 μm and about the same as the height of the corrugation.

Metallic contacts to the diode were made by evaporating Cr and Au on the p side and Au-Ge-Ni on the n side. The diode was bonded with the p side down onto a metallized diamond heat sink mounted on a copper block. The thermal resistance per unit area R_T was ~3×10^{-3} deg cm^2/W.

The dependence of the threshold current density and the lasing wavelength on the junction temperature was investigated under pulsed operation, and typical results are shown in Fig. 2. The length of the excited region was 730 μm, and the period Λ was 3814 Å in the diode. For comparison, the results obtained in a Fabry-Perot (FP) type cleaved laser which was made from the same wafer are also plotted in Fig. 2. The length of the cleaved laser was 570 μm. The DFB laser showed two transverse modes perpendicular to the junction plane. At junction temperatures between 300 and 350 K, the diode lased in the lowest mode ($m=0$) with a threshold current density of about 1.2 times that of the Fabry-Perot laser. The rapid increase of the threshold below 300 K and above 350 K was due to the mismatching between the period and the gain spectrum of GaAs. The intrinsic threshold gain of the $m=0$ mode is estimated to be ~25 cm^{-1} from the reflection loss of the cleaved laser.

Figure 3 shows the lasing spectra obtained under cw operation. In Fig. 3(a), the period Λ was 3648 Å and the length of the excited region was 690 μm. At heat-sink temperature $T_H=170$ K, the threshold current density J_{th} was 0.94 kA/cm^2. The junction temperature T_J was 182 K for the current density J of 0.96 kA/cm^2.

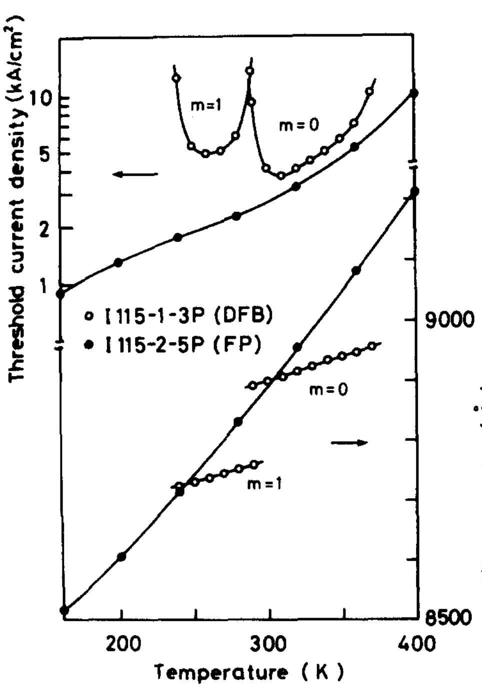

FIG. 2. Threshold current density and the lasing wavelength as a function of junction temperature. The period was 3814 Å in I115-1-3P. The results were obtained under pulsed operation.

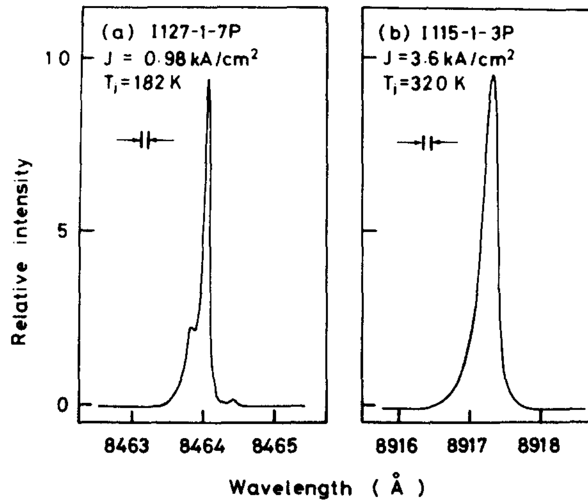

FIG. 3. Lasing spectra under cw operation. (a) Λ = 3648 Å, (b) Λ = 3814 Å.

Figure 3(b) shows the spectrum of the diode shown in Fig. 2, where $J_{th}=3.4$ kA/cm^2 at $T_H=280$ K. The junction temperature became 320 K for $J=3.6$ kA/cm^2. These threshold current densities were the same as those obtained at the above mentioned junction temperatures under pulsed operation.

The lasing spectra in Fig. 3 show that the diodes lased in a single longitudinal mode. From the study of the far-field pattern, the subpeaks in Fig. 3(a) and the broadening of the spectrum in Fig. 3(b) were attributed to the multitransverse-mode oscillation parallel to the junction plane.

The lasing characteristics were investigated up to twice the threshold current density. Spectra similar to those in Fig. 3 were obtained in this range of excitation, and no indication of multilongitudinal-mode oscillation was recognized.

For the operation at $T_H=300$ K, the junction temperature became ~340 K. In this case, the lowest threshold current density of 3.5 kA/cm^2 was obtained for Λ = 3820 Å. A dc output as high as 10 mW was obtained at 1.3 times the threshold current density. Further reduction of the threshold current density will be achieved by optimizing the structure parameters including the use of high-quality fundamental gratings. The thermal resistance will also be reduced by the reduction of the stripe width[10] and by the improvement of the bonding technique. Since the corrugation is separated from the active layer in the SCH structure, we expect that the life of the DFB laser is as long as that of conventional semiconductor lasers. Investigation on the degradation problem is being under way.

In conclusion, cw operation of DFB semiconductor lasers has been achieved at temperatures up to 300 K by a carefully designed SCH structure. The results obtained in this work are encouraging and prompt us to further explore the application of DFB lasers to optical communications and integrated optics.

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Embedded heterostructure epitaxy: A technique for two-dimensional thin-film definition*

I. Samid, C. P. Lee, A. Gover, and A. Yariv

California Institute of Technology, Pasadena, California 91125
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Selective multilayer epitaxial growth of GaAs-$Ga_{1-x}Al_xAs$ through stripe openings in Al_2O_3 mask is reported. The technique results in prismatic layers of GaAs and $Ga_{1-x}Al_xAs$ "embedded' in each other and leads to controllable uniform structures terminated by crystal faces. The crystal habit (shape) has features which are favorable for fabrication of cw injection lasers, laser arrays, and integrated optics components which require planar definition.

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Multilayer GaAs-GaAlAs thin-film structures grown by epitaxial techniques have been playing an increasingly important role in a variety of electro-optical applications. These include cw injection lasers, distributed-feedback lasers, light-emitting diodes, and a number of electro-optical components for integrated optics. The lateral definition often needed in these applications is achieved by techniques such as proton bombardment,[1,2] ion etching,[2] diffusion,[3,4] chemical etching,[5,6] chemical etching and regrowth.[7,8]

In the present paper we report on a new technique for growing multilayer GaAs-$Ga_{1-x}Al_xAs$ through openings in Al_2O_3 masks by liquid-phase epitaxy. Single-layer vapor-phase[9–12] and liquid-phase[13,14] epitaxial growth of GaAs and InGaAs through openings in SiO_2 masks have been reported previously. SiO_2 masks are probably not suitable for the growth of GaAlAs because the aluminum in the melt may react with the silicon oxide.[15] We found sputtered Al_2O_3 masks stable and adhering throughout the multilayer growing process. No growth was observed on the oxide away from the window openings.

The resulting structure consists of prisms of GaAs, or GaAlAs completely embedded epitaxially in outer crystalline layers of similar material. We thus propose the term embedded epitaxy for this growth technique.

The growth took place on [100]-oriented polished GaAs wafers with (n type) Si doping $n=3\times10^{18}$ cm^{-3}. The wafer's surfaces were sputtered with 3000 Å of Al_2O_3 and were cleaved into rectangles at the two perpendicular cleavage planes $(01\bar{1})$. Standard photolithographic techniques were used to define on a wafer photoresist stripe openings of widths 15, 25, and 100 μ on top of the Al_2O_3, and by etching in hot phosphoric acid very smoothly edged stripe openings were formed in the oxide. The stripes were oriented parallel to the cleavage plane (011) or $(01\bar{1})$ to within $\pm 0.05°$.

The wafers were briefly etched in Br_2-methanol and the growth performed by standard multilayer horizontal liquid-phase-epitaxy procedures.[16] The growth temperature was 818 °C and the cooling rate was as slow as 0.1°/min. The cooling cycle was up to an order of magnitude shorter than what is usually used in ordinary epitaxial growth. The first and third layer were $Ga_{0.6}Al_{0.4}As$ [dark layers in Figs. 1(a) and 2(a)]. The second and fourth layers were GaAs [white areas in Figs. 1(a) and 2(a)]. The samples were then cleaved perpendicular to the stripes and the multilayer structure revealed [Figs. 1(a) and 2(a)] using HF:HNO_3:H_2O (1:3:4) staining solution. The multilayer growth technique has the important advantage of indicating the growth history (by revealing the layers). This allowed us to achieve better understanding of the growth pattern in different orientations and conditions, and to improve our control of the growth cycle.

The first noteworthy characteristic is the considerably higher rate of growth through the openings in comparison with unmasked wafers. Furthermore, the thinner the stripe the higher the growth rate. This shows that the amount of growth is determined mainly by the

