# GaAs–GaAlAs Double-Heterostructure Injection Lasers with Distributed Feedback

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***Abstract*—GaAs–GaAlAs double-heterostructure distributed-feedback injection lasers are investigated at temperatures between 80 and 150 K under pulsed operation. The optical feedback for laser oscillation is provided by a corrugated interface between the p-GaAs active layer and the p-GaAlAs layer. The corrugation is made by two methods, ion milling and chemical etching, and the latter method is found to give the lower threshold. The laser oscillation occurs in a single longitudinal mode, whose wavelength is stable against the change of the excitation level. The temperature dependence of the wavelength of the distributed-feedback laser is shown to be 0.5 Å/deg, which is about $\frac{1}{3}$ to $\frac{1}{4}$ that of the conventional Fabry–Perot (FP) laser.**

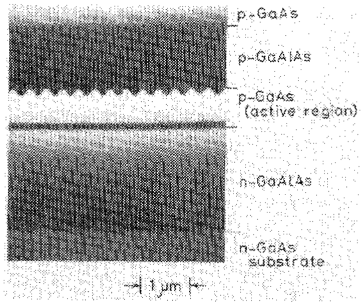

Fig. 1. A scanning electron microscope (SEM) photograph of the cross section of a distributed-feedback laser along the direction of light propagation. The corrugation period is 3470 Å.

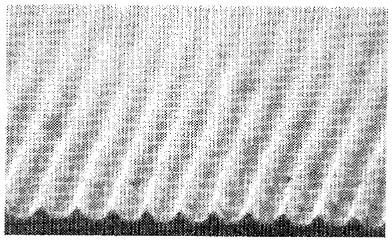

Fig. 2. A GaAs grating made by chemical etching. The period is 3470 Å.

## I. Introduction

SHORTLY after the demonstration of the laser oscillation in distributed-feedback dye lasers [1]-[4] and the subsequent theoretical analysis [5], the feasibility of distributed-feedback GaAs lasers was investigated at 77 K by optical pumping [6]-[9]. Following this the effort shifted toward the realization of injection-type distributed-feedback lasers, and laser oscillation has recently been demonstrated in homojunction [10], single-heterostructure [11], and double-heterostructure [12], [13] lasers.

In a previous paper [12] we have reported briefly the observation of laser oscillation in GaAs–GaAlAs double-heterostructure distributed-feedback lasers. The optical feedback for the laser oscillation was provided by a corrugated interface between the p-GaAs active layer and the p-GaAlAs layer. In this paper we describe a detailed study of the properties of these distributed-feedback lasers in the temperature range of 80–150 K.

## II. Experimental Method

Fig. 1 shows a typical cleaved cross section of the distributed-feedback lasers described in the following. The corrugation period is 3470 Å and the depth is 1800 Å. In the fabrication of such a structure, an n-$Ga_{0.7}Al_{0.3}As$ layer doped with Sn and a p-GaAs (active) layer doped with Ge were first grown on an n-GaAs substrate by conventional liquid phase epitaxy. The thickness of these layers was ~3 μm and ~1 μm, respectively.

The corrugation of the p-GaAs layer was achieved by ion milling [14] or by chemical etching [15]. In the case of ion milling, 5-keV Ar ions were incident on the p-GaAs layer through a photoresist mask produced by holographic photolithography. Fig. 2 shows the surface corrugation made by the chemical etching, where the grooves are composed of $\{111\}A$-side surfaces and a (100) bottom surface. The depth was 1500–1800 Å for the period of ~0.34 μm.

Next a p-$Ga_{0.7}Al_{0.3}As$ layer (~2 μm thick) and a p-GaAs layer (~1 μm thick), both doped with Ge, were grown on the corrugated surface of the p-GaAs layer by liquid phase epitaxy. The meltback of the corrugated surface during the epitaxial growth was avoided by growing the layers at relatively low temperatures (~700°C) with a cooling rate of 5°C/min as reported in [16].

Fig. 3 shows the schematic structure of the distributed-feedback laser. The laser has a mesa-stripe geometry [17] in order to limit the injection to a rectangular area. The width of the stripe is 50 μm. The metallic contacts of the laser were made by evaporating Cr and Au on the p-side, and Au–Ge–Ni on the n-side. The length of the Cr–Au contact in different lasers varied between 150 and 1100 μm. A lossy unexcited waveguide with a length of 2.5-3 mm was continuous to the current-excited section. This eliminated optical feedback from the end surface. The output was obtained through the front surface as shown in Fig. 3. The laser was pumped by applying current pulses with a duration of 50 ns and a repetition rate of 100 Hz.

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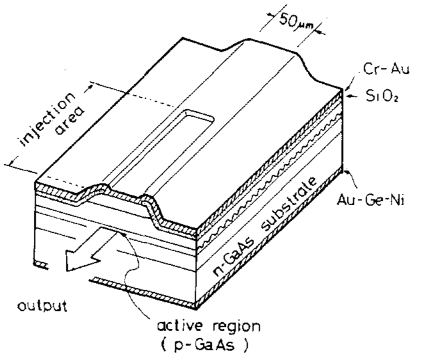

Fig. 3. The schematic structure of the distributed-feedback laser.

## III. RESULTS AND DISCUSSION

### *A. Spectral Characteristics*

The emission spectra of a typical injection laser is shown in Fig. 4, where the period of the corrugation is 3470 Å, the length of the active region is 1050 μm, and the threshold current density is 750 A/cm$^2$. In this figure the spontaneous emission has a broad peak centered at 8255 Å. Just above the threshold (390 mA), a narrow peak of stimulated emission appears at 8225 Å. The linewidth of the stimulated emission is 0.5 Å. The diode lased in a single longitudinal mode, whose wavelength was stable with respect to changes of excitation level from threshold to over four times the threshold. The lasing light was polarized with the electric-field vector parallel to the junction plane.

Lasers in which the length of the unexcited waveguide was less than 1 mm exhibited the coexistence of two oscillations: one due to the grating and the other to feedback involving the end surface. The oscillation by grating feedback was identified by the small temperature dependence of the lasing wavelength. When the unexcited waveguide is longer than 2 mm, which is the case in the following experiments, the influence of the end surface is not observed in the emission spectrum.

Fig. 5 shows the spectrum of a typical laser as a function of temperature. The laser, whose length was 630 μm, required a threshold current density of 1.8 kA/cm$^2$ at 80 K and of 8.6 kA/cm$^2$ at 145 K. The current was chosen to be about 1.05 times the threshold at each temperature. In this figure, the peak wavelength of the spontaneous emission at 80 K is shorter by 78 Å than that of the stimulated emission. As the temperature increases, the peak of the spontaneous emission shifts more rapidly than the peak of the stimulated emission does.. At 145 K, the peak wavelength of the spontaneous emission is longer by 17 Å than that of the stimulated emission.

A small auxiliary peak is seen in the spectrum of Fig. 5. We have no satisfactory explanation as to its origin, since its temperature dependence is inconsistent with either that of a normal Fabry-Perot (FP) mode or higher order DFB modes. It could, possibly, represent some hybrid combination. This peak is absent in lasers possessing longer unpumped corrugated end sections. Typical of the latter category is the laser whose spectrum is shown in Fig. 4.

Fig. 6 shows the wavelength of the stimulated-emission peak

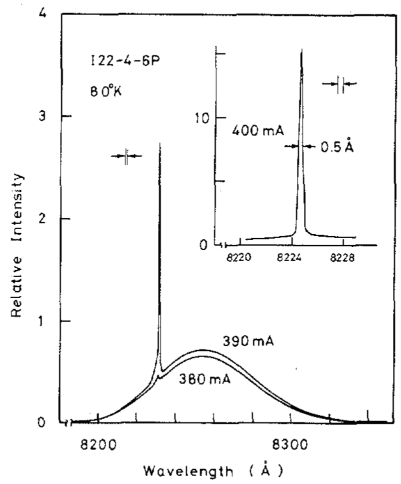

Fig. 4. The emission spectra of a typical laser. The period and the depth of the corrugation are 3470 Å and 1800 Å, respectively. The threshold current density is 750 A/cm$^2$ at 80 K.

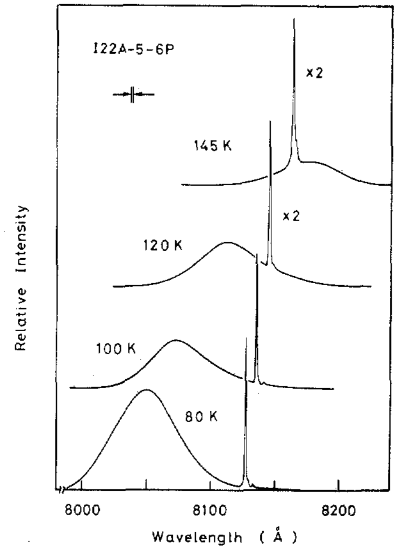

Fig. 5. Temperature dependence of the emission spectrum. The current is chosen to be ~1.05 times the threshold for each temperature.

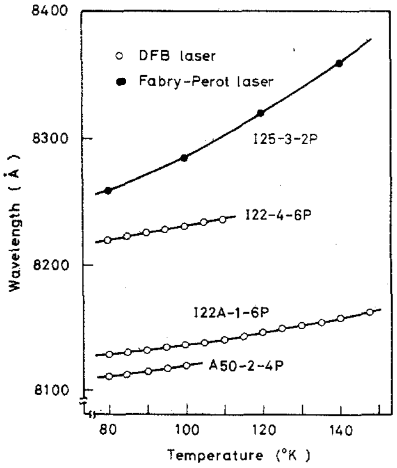

Fig. 6. The lasing wavelength as a function of temperature.

as a function of temperature. The temperature dependence of the main peak of a typical FP laser is also shown in this figure. It is seen from this figure that the wavelength of the distributed-feedback laser shifts at a rate of 0.5 Å/deg. Theoretically, the wavelength of the distributed feedback laser $\lambda$ is given approximately by [5]

$$\lambda \simeq \frac{2n_g\Lambda}{l} \tag{1}$$

where $n_g$ is the effective refractive index of the waveguide, $\Lambda$ is the period of the corrugation, and $l = 3$. By differentiating (1) with respect to the temperature $T$, one gets the relation

$$\frac{d\lambda}{dT} = \frac{\lambda}{\bar{n}_g}\frac{\partial n_g}{\partial T} \tag{2}$$

where

$$\bar{n}_g = n_g - \frac{\partial n_g}{\partial \lambda}\lambda. \tag{3}$$

With $\bar{n}_g \simeq 4.5$ and $\partial n_g/\partial T \simeq 3 \times 10^{-4}$/deg [18], we have $d\lambda/dT \simeq 0.57$ Å/deg, which agrees with the experimental result in Fig. 6.

On the other hand, the peak wavelength of the FP laser changes at a rate of 1.5-2 Å/deg, reflecting the shift of the band-gap energy with temperature.

### *B. The Threshold Current Density*

The threshold of the laser oscillation is a function of such structure parameters as the length and the thickness of the active region, and the depth of the corrugation. The dependence of the threshold current density on the length of the active region $L$ is shown in Fig. 7. The lasers were made from two wafers with chemically etched corrugations, I18 and I22. The thickness of the active region and the depth of the corrugation are 0.9 $\mu$m and 1600 Å in I18, and 0.8 $\mu$m and 1800 Å in I22, respectively. The period of the corrugation is 3470 Å and the lasing wavelength is 8249 ± 5 Å for all the lasers. In Fig. 7 the threshold current density $j_{th}$ decreases with the increase of $L$ as $j_{th} \propto L^{-0.8}$.

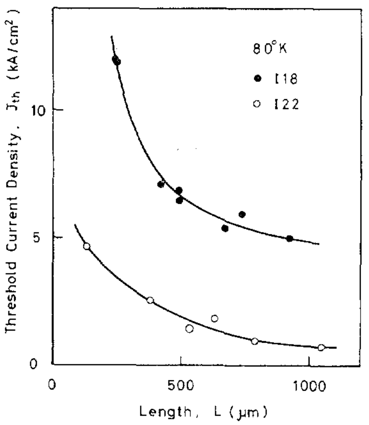

Fig. 7. The threshold current density as a function of the length of the active region.

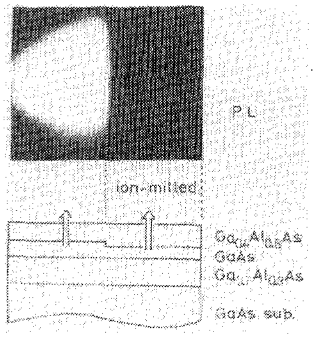

Fig. 8. Photoluminescence from a GaAs epitaxial layer. A part of the GaAs epitaxial layer was ion milled.

For $L = 400$ $\mu$m and $T = 80$ K, the threshold current density was typically 10 kA/cm$^2$ in the laser with the ion-milled grating, and 2 kA/cm$^2$ in the laser with the chemically etched grating. The lowest threshold current density of 750 A/cm$^2$ was obtained in a chemically etched laser with $L = 1050$ $\mu$m whose emission spectrum is shown in Fig. 4.

The higher threshold current density in the ion-milled lasers was found to be due to the nonradiative recombination of injected carriers near the interface. This is clearly demonstrated by the photoluminescence measurement as shown in Fig. 8. In this measurement, a part of the p-GaAs layer was ion milled by ~1000 Å, and then a p-$Ga_{0.4}Al_{0.6}As$ layer was grown by liquid phase epitaxy at 700-670°C. The p-GaAs layer was excited by a Kr laser (6471 Å) through the top p-$Ga_{0.4}Al_{0.6}As$ layer at room temperature, and the photoluminescence from the p-GaAs layer was monitored by a TV camera. In this figure, the intensity of the photoluminescence is about two orders of magnitude weaker in the ion-milled GaAs layer than in the original GaAs layer. This fact demonstrates that ion milling produces nonradiative recombination centers thus increasing the threshold current density.

In the laser with the chemically etched grating, the number of nonradiative recombination centers was much reduced, and the lower threshold operation became possible. Further reduction of the threshold current density may be achieved by adopting the separate-confinement heterostructure with a corrugated interface as was proposed elsewhere [19]. In this structure, the effect of the nonradiative centers should be greatly reduced since the corrugated interface is separated from the active layer. The use of the fundamental grating with a period of 0.12 $\mu$m should lead to further reduction in the threshold current density.

## IV. CONCLUSION

GaAs-GaAlAs double-heterostructure distributed-feedback injection lasers were investigated at temperatures between 80 and 150 K under pulsed operation. The grating was made by ion milling or by chemical etching. The laser oscillation occurred in a single longitudinal mode even at high current densities. The lasing wavelength was stable against the change of the excitation level. The temperature dependence of the lasing wavelength was found to be about 0.5 Å/deg and was explained by the temperature dependence of the refractive index of the waveguide. The lowest threshold current density of

750 A/cm$^2$ was obtained in a laser with a chemically etched grating. The threshold current densities of lasers with ion-milled gratings were found to be higher than those of chemically etched lasers because of the surface damage caused by the ion bombardment. Further reduction of the threshold current density is expected to result from the use of the separate-confinement heterostructure and a fundamental grating.

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# Single-Heterostructure Distributed-Feedback GaAs-Diode Lasers

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***Abstract*—This paper reports the fabrication, testing, and analysis of distributed-feedback (DFB) single-heterostructure (SH) electrically pumped GaAs lasers. The techniques of fabricating the DFB grating and diode using interferometric exposure of photoresist, development, ion milling, liquid-phase-epitaxial growth, and diffusion are described in detail. Next, experimental results on a variety of diodes operating at 77 K are presented. It is shown that narrow laser linewidth (< 0.15 Å) and low threshold operation (775 A/cm$^2$) can be obtained. Also reported is output coupling from the grating which results in highly collimated laser beams with divergence of approximately 0.35°. Coupling coefficients, which determine laser threshold, are computed as a function of device parameters including physical dimensions, refractive indices, grating size and shape, and Bragg order for single- and double-heterostructure geometries. Calculated and measured thresholds are shown to be in good agreement.**

## I. INTRODUCTION

IN A RECENT LETTER we reported the first observation of laser operation in an electrically pumped distributed-feedback (DFB) diode [1]. Since this laser requires no discrete end mirrors as is the case with a conventional diode laser it is potentially useful as a source for integrated optical circuits. In addition, DFB injection lasers have several other unique features which make them potentially useful even as discrete devices. First, the feedback is frequency selective so that various laser wavelengths within the gain line may be obtained. Second, DFB lasers enhance the possibility of mode control [2]-[4] and, finally, the periodic DFB structure may be used as an output coupler to obtain a polarized low-divergence laser beam [5]. These attributes may make DFB injection lasers useful in point-to-point communications as well as enhancing their utility in fiber optic systems.

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