# GaAs-$Ga_{1-x}Al_xAs$ double-heterostructure distributed-feedback diode lasers

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We report laser oscillation at 80–100 °K in electrically pumped GaAs-$Ga_{1-x}Al_xAs$ double-heterostructure distributed-feedback diode lasers. The feedback for laser oscillation was provided by a corrugated interface between the active GaAs layer and the $p$-$Ga_{1-x}Al_xAs$ layer. The lowest threshold current density was 2.5 kA/cm$^2$ in pulsed operation. The wavelength of laser emission was 8112 Å at 82 °K with a half-width of less than 0.3 Å. The temperature dependence of the laser wavelength was found to be smaller than that of the conventional Fabry-Perot laser.

An analysis of the performance of semiconductor injection lasers with a corrugated interface indicates the possibility of low-threshold operation as well as frequency and mode discrimination.[1] Such a laser is also expected to facilitate the problem of coupling to other monolithic integrated optical circuit components because of the freedom from cleaved mirrors.

Several workers, including the present authors, have reported on optically pumped GaAs and GaAs-GaAlAs waveguide lasers in which the feedback was provided by corrugating the GaAs surface.[2–5] In the present work, we have fabricated GaAs-$Ga_{1-x}Al_xAs$ double-heterostructure *diode* lasers with a corrugated interface and examined their lasing characteristics under injection pumping.[6]

The diode laser is illustrated schematically in Fig. 1. A $n$-$Ga_{0.7}Al_{0.3}As$ layer doped with Sn and a $p$-GaAs (active) layer doped with Ge were grown on a $n$-GaAs substrate by conventional liquid-phase epitaxy. The thickness of the layers was ~4 and ~1.5 $\mu$m, respectively. After reducing the thickness of the $p$-GaAs layer by chemical etching down to 0.5–1.3 $\mu$m, we fabricated surface corrugations on the $p$-GaAs layer by ion milling through a photoresist mask which was produced by holographic photolithography.[7] The period of the corrugation was ~0.34 $\mu$m so that the third-order coupling was used for laser oscillation. The depth of the corrugation was ~900 Å. Next a $p$-$Ga_{0.7}Al_{0.3}As$ layer (~3 $\mu$m thick) and a $p$-GaAs layer (~1 $\mu$m thick), both doped with Ge, were grown on the corrugated surface of the $p$-GaAs layer by liquid-phase epitaxy. Meltback of the corrugated surface during the epitaxial growth was avoided by growing the layers at relatively low temperatures (~700 °C) at a cooling rate of 5 °C/min. The details of the liquid-phase epitaxy were reported in Ref. 8.

The diode had a mesa-stripe geometry[9] so that the injection was limited to a rectangular region. The width of the stripe was ~50 $\mu$m. The 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 length of the Cr-Au contact varied between 150 and 700 $\mu$m. A lossy unexcited waveguide with a length of 2.5–3 mm was contiguous to the current-excited section. This prevented optical feedback from the end surface. The output was obtained through the front cleaved surface as shown in Fig. 1.

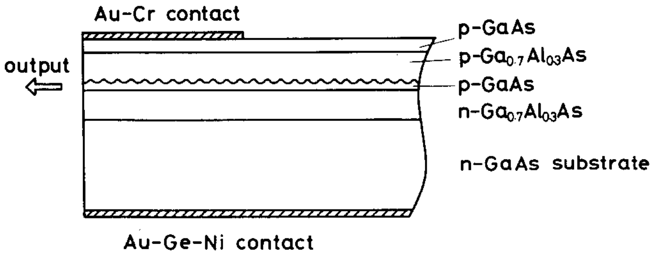

FIG. 1. Schematic cross section of the double-heterostructure distributed-feedback laser.

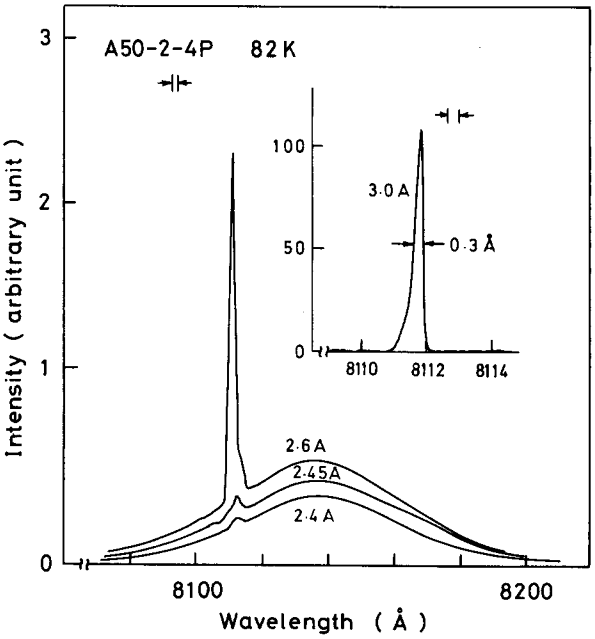

FIG. 2. Emission spectra of a double-heterostructure distributed-feedback laser. The length and the thickness of the active region were 630 and 1.3 $\mu$m, respectively. The depth of the corrugation was 900 Å, and the period was 3416 Å.

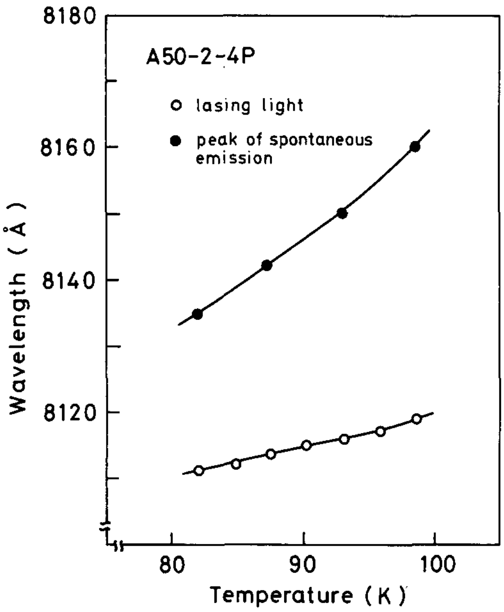

FIG. 3. Temperature dependence of the wavelength of the laser emission and the spontaneous emission.

Current pulses with a duration of 50 ns were applied to the diode, and the lasing characteristics were measured at 80–100 °K.

Figure 2 shows the emission spectra of a typical diode laser, where the corrugation period was 3416 Å and the threshold current density was 9 kA/cm$^2$. In this figure, the spontaneous emission has a broad peak centered at 8135 Å. Just above threshold (2.6 A), a narrow peak of stimulated emission appears at 8112 Å. The linewidth of the stimulated emission is 0.3 Å and is within the resolution of the spectrometer. The lasing light was polarized with the electric field vector parallel to the junction plane. The wavelength $\lambda$ of the laser emission and the corrugation period $\Lambda$ are related theoretically by

$$\Lambda = 3\lambda/2n_g \tag{1}$$

for the third-order coupling, where $n_g$ is the effective refractive index of the waveguide. From Eq. (1) and Fig. 2, the effective refractive index $n_g$ is estimated to be 3.56, which is a reasonable value for the thin-slab waveguide structure.

The temperature dependence of the emission spectrum was investigated in the range 82–98 °K. In Fig. 3, the wavelength of the laser emission and the wavelength of the spontaneous emission peak are plotted as a function of temperature. The temperature dependence $d\lambda/dT$ of the wavelength of the stimulated emission is 0.5 Å/°K. This result is predicted from Eq. (1) if one accounts for the temperature dependence of the refractive index of GaAs.[10] The wavelength of the spontaneous emission peak, on the other hand, changes at a rate of 1.5 Å/°K, which reflects the shift of the band-gap energy with temperature. Cleaved Fabry-Perot lasers made from the same epitaxial wafer lased at wavelengths near the peak of the spontaneous emission, and had the same temperature dependence as that of the spontaneous emission peak. This clearly demonstrates the fact that the laser feedback is due predominantly to the periodic corrugation. The smaller temperature dependence of the wavelength of the laser emission may be attractive in the practical application of semiconductor lasers.

The lowest threshold current density of 2.5 kA/cm$^2$ was obtained at 80 °K in a sample with an excitation length of 480 μm, a corrugation depth of 850 Å, and an active layer thickness of 0.6 μm. The surface damage caused by the ion milling was found to severely reduce the recombination efficiency, thus increasing the threshold current density. This may be reduced by adopting a SCH structure with a corrugated interface as was proposed elsewhere.[11] The use of fundamental corrugations with a period of 0.12 μm will also reduce the threshold current density.

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[1] M. Nakamura and A. Yariv, Opt. Commun. **11**, 18 (1974).

[2] M. Nakamura, A Yariv, H.W. Yen, S. Somekh, and H.L. Garvin, Appl. Phys. Lett. **22**, 515 (1973).

[3] M. Nakamura, H.W. Yen, A Yariv, E. Garmire, S. Somekh, and H.L. Garvin, Appl. Phys. Lett. **23**, 224 (1973).

[4] H.W. Yen, M. Nakamura, E. Garmire, S. Somekh, A. Yariv, and H.L. Garvin, Opt. Commun. **9**, 35 (1973).

[5] C.V. Shank and R. Schmidt, Digest of Technical Papers, Topical Meeting on Integrated Optics, New Orleans, 1974, Paper No. MB1-1 (unpublished). This paper discusses the results of optically pumped double-heterostructure GaAs-Ga$_{1-x}$Al$_x$As lasers.

[6] D.R. Scifres, R.D. Burnham, and W. Streifer, VIII International Quantum Electronics Conference, San Francisco, 1974, Paper No. R1 (unpublished). This is the first DFB injection laser reported in the literature.

[7] H. L. Garvin, E. Garmire, S. Somekh, H. Stoll, and A. Yariv, Appl. Opt. **12**, 455 (1973).

[8] M. Nakamura, K. Aiki, J. Umeda, A. Yariv, H.W. Yen, and T. Morikawa, Appl. Phys. Lett. **24**, 466 (1974).

[9] T. Tsukada, H. Nakashima, J. Umeda, S. Nakamura, N. Chinone, R. Ito, and O. Nakada, Appl. Phys. Lett. **20**, 344 (1972).

[10] J. Zoroofchi and J.K. Butler, J. Appl. Phys. **44**, 3697 (1973). (1973).

[11] M. Nakamura and A. Yariv, Digest of the 1974 Topical Meeting on Integrated Optics, Paper No. TuB9 (unpublished).