GaAs quantum well distributed Bragg reflection laser with AlGaAs/GaAs superlattice gratings fabricated by focused ion beam mixing

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GaAs quantum well (QW) lasers with distributed Bragg reflection (DBR) $Al_{0.3}Ga_{0.7}As$/GaAs superlattice gratings have been fabricated by the single-step, maskless focused ion beam (FIB) mixing. 200 keV Si^{++} FIB implantation with a beam diameter of ~60–70 nm and a dose of 10^{14} cm^{-2} was used to obtain localized compositional mixing. The DBR grating period was 350 nm, corresponding to a third order grating matched to the emission from the 30 nm wide QW. Lasing operation was examined by optical pumping. With a pumping power 1.6× the threshold value, lasing modes were observed near 827 nm, with a spacing of 3 Å and a linewidth of 1.5 Å.

Distributed Bragg reflection (DBR) lasers are attractive candidates for light sources in monolithic photonic and optoelectronic integrated circuits (PICs and OEICs) because the absence of cleaved facets allows for direct connection to other optical elements. The DBR laser[1,2] utilizes a diffraction grating built into the structure in the vicinity of the active region to provide a strong wavelength selectivity. Techniques commonly used[3] to fabricate the grating corrugations have combined high resolution lithography and wet chemical etching or ion milling to achieve the submicrometer periods required. Most DBR laser fabrication schemes require extreme care in completing the device structure after grating formation (including a particularly sensitive second epilayer growth) in order not to affect the grating geometry.

In this letter, we report on the operation of a GaAs laser structure with twin DBR gratings fabricated by impurity-induced reordering (IIR) with a single-step focused ion beam (FIB) maskless implantation. IIR converts individual GaAs–AlGaAs multiple quantum well (MQW) or superlattice (SL) layers by compositional mixing[4] to form a homogeneous AlGaAs alloy. The IIR process as employed herein involves impurity introduction by FIB implantation followed by rapid thermal annealing (RTA) designed to induce Al interdiffusion while also removing the implantation damage. In general, IIR can be used[5] to provide effective local confinement of charge carriers and photons, as well as periodic variations in refractive index required for grating fabrication, while preserving a planar topology. A GaAs/AlGaAs single quantum well (SQW) DBR laser with gratings fabricated by Si implantation IIR in conjunction with electron beam lithography has been reported[6] by Hirata *et al.* However, a rather complex process was necessary, with postgrating growth of the top cladding contact layers.

FIB technology[7,8] provides energetic ion beams (with diameters of 50–100 nm) which can produce spatially localized confinement regions through IIR of MQW and SL structures in a simple, maskless process. Ishida *et al.* have reported[9] a stripe geometry AlGaAs MQW laser, wherein the optical confinement was provided by 40 keV Be^{+} FIB implantation in the stripe region with a dose of 5×10^{14} cm^{-2}, which suppressed IIR in the Si-doped MQW. Submicron grating fabrication, with a period of 0.4 μm, but no laser operation, was also reported[10] by Ishida *et al.* in an AlGaAs/GaAs SL using 80 keV Si^{+} FIB with a dose of $\sim9\times10^{13}$ cm^{-2}. Finally, 100 keV Si^{+} FIB implantation with a dose of $\sim4-8\times10^{14}$ cm^{-2} has been used by Wu *et al.*[11] to produce a second order grating in an AlGaAs/GaAs laser structure with one cleaved facet and one DBR grating. In this case, the FIB implantation generated a periodic change in refractive index due to changes in the free carrier concentration, which is significantly less effective[11] than the changes in composition produced by IIR mixing.

A cross section of the structure used in our experiments is shown in Fig. 1. The starting sample consists of several layers grown by molecular beam epitaxy[12] on an undoped (100) GaAs substrate: (a) GaAs buffer layer; (b) 1 μm $Al_xGa_{1-x}As$ cladding layer; (c) 30 nm GaAs SQW active layer; (d) GaAs/$Al_xGa_{1-x}As$ SL stack with 29 GaAs and AlGaAs layers of 3.5 nm each for the DBR gratings; (e) 50 nm $Al_xGa_{1-x}As$ cap layer. The Al composition x was 30%. The SQW and the SL were designed such that emission from the active layer is not absorbed in the grating. A third order grating was chosen for our first attempt at fabricating a DBR laser by IIR since the grating period should be readily accommodated by the FIB process. The two DBR sections are separated by 140 μm. Each third order grating consists of

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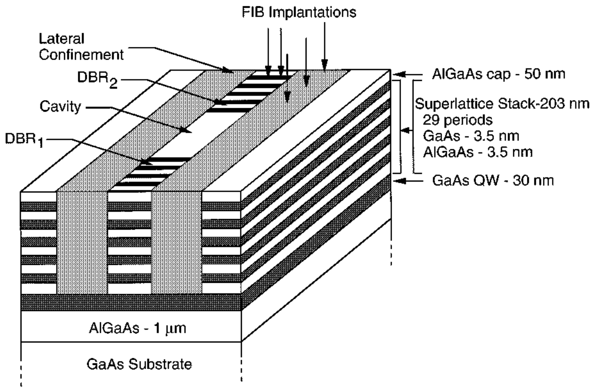

FIG. 1. DBR laser structure cross section, indicating the FIB implanted region which provides both the gratings and the waveguide.

1000 equally spaced lines, with a period of 350 nm. Two implanted stripes of 10 μm width are designed to provide lateral confinement within a 25 μm waveguide. Both the gratings and the waveguide were produced by FIB-induced IIR mixing.

FIB implantation was performed with 200 keV Si^{++} ions at a dose of 1×10^{14} cm^{-2}. The Si^{++} beam had a current of 25 pA and a beam diameter of ~60–70 nm. Postimplantation RTA was carried out at 950 °C for 10 s, conditions previously established[13] to provide suitable mixing in the implanted region, while preserving the layer structure of the unimplanted superlattice region. This grating fabrication by FIB mixing was obtained at a lower dose than that reported[11] for gratings fabricated by FIB-implanted periodic variations in doping concentration. Even lower doses for IIR gratings may be possible through the careful design of the laser structure and of the implantation and annealing conditions.[14] An essentially identical DBR laser structure was previously shown[15] to exhibit a significant photoluminescence enhancement from the active region, as compared to those from either the grating regions or from sample locations distant from the laser. In addition, similar FIB implantation and annealing conditions were previously reported to lead to the formation of relatively low-loss MQW AlGaAs channel waveguides.[16]

To observe and characterize the emitted DBR laser signal, the samples were cleaved on one end only, in the vicinity of the grating. To exclude any possible Fabry–Pérot modes, the other end of the samples, located 1–2 mm from the DBR structure, was left rough and uncleaved. The laser structures were pumped with a *Q*-switched, frequency doubled YAG laser operating at a wavelength of 532 nm, with a spot size of ~350 μm, a pulse duration of ~250 ns and a repetition time of 1 ms. The DBR laser samples were pumped from the top surface, while the output signal was collected from the cleaved sidewall through a microscope coupled to a spectrometer with a resolution of 0.2 cm^{-1}. The measurements reported were performed at 77 K.

The optical emission spectrum is shown in Fig. 2 for different levels of optical pumping power. As the pumping power increases, the spontaneous emission at the SL wavelength first increases and then begins to broaden. At a peak power density of approximately 10 kW/cm^2, a series of very

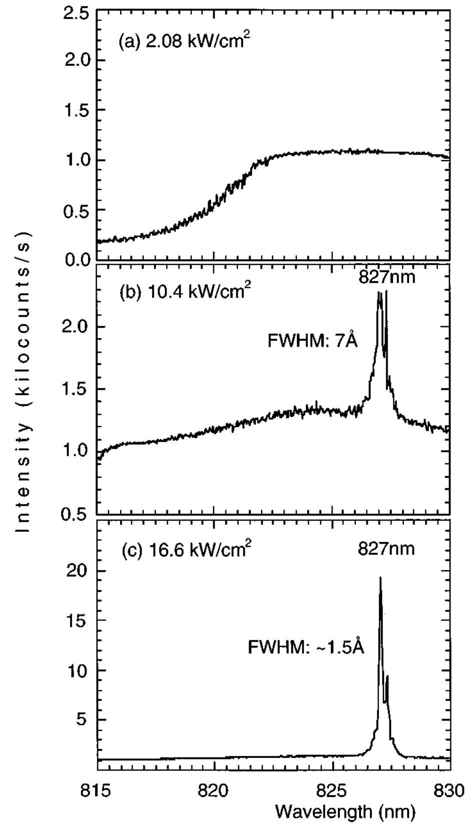

FIG. 2. Spectra at various optical pumping power levels; note the different scale for part (c).

sharp, closely spaced emission lines appear at 827 nm, indicating the threshold for stimulated emission. An average value of the refractive index of 3.54 for the SL is calculated from the emission wavelength and grating period. For a pump power density ~60% above threshold, the laser emission at 827 nm increases by more than 20×. Under this pumping power, the emission spectrum is shown in Fig. 3 over a larger wavelength range. The laser emission at 827 nm is observed in addition to a much lower and broad emission from the QW and the SL (peaked at ~740 nm). The insert in

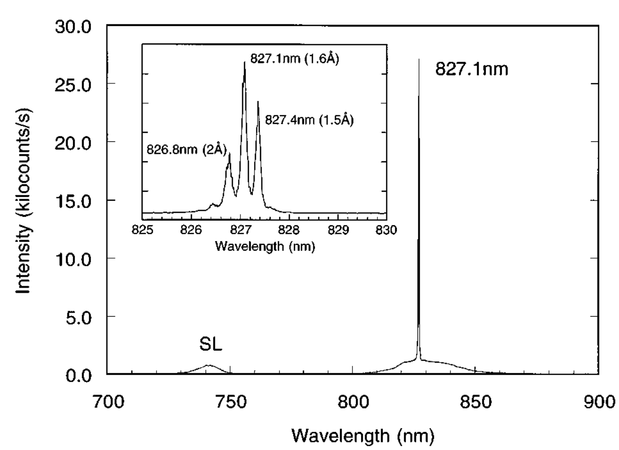

FIG. 3. Spectrum emitted from DBR structure showing broad PL from SL and QW, and lasing at ~827 nm; insert: high resolution spectrum of 827 nm region.

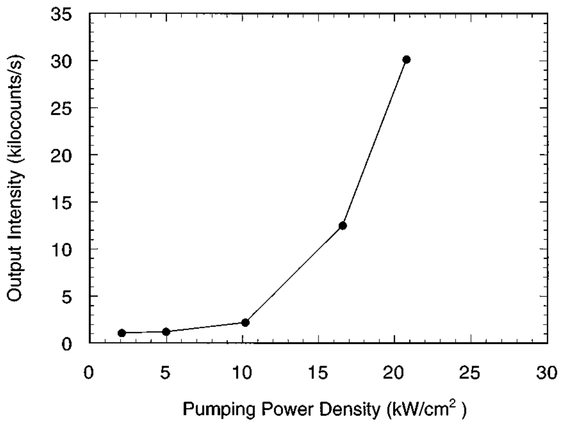

FIG. 4. DBR laser emission intensity at 827 nm as a function of pump power.

Fig. 3 shows a high resolution scan in the vicinity of the laser emission wavelength. Three main emission modes are observed, with a linewidth of ~1.5 Å and a separation of ~3 Å. The optical input/output relation of the DBR laser is shown in Fig. 4.

The observed mode spacing corresponds[17] to an effective cavity length of ~322 μm, implying an effective DBR grating length ($L_{\rm eff}$) of ~91 μm. The DBR coupling coefficient (κ) is a measure of the effectiveness of the grating in providing a high reflectivity.[16] κ can be calculated from either the spectral emission bandwidth[18] or from $L_{\rm eff}$.[19] We first estimated the radiation loss due to coupling into out-of-plane modes to be ~4 cm^{-1}, using the calculations of Streifer *et al.*[20] for a third order grating. Then we have calculated the reflectivity[17] as a function of wavelength for several κ values. The best fit between the reflectivity curve and the experimental spectral emission envelope is obtained for $\kappa \approx 80$ cm^{-1}. Using the reflectivity corresponding to the same loss value in the $L_{\rm eff}$ approach, we calculate $\kappa \approx 50$ cm^{-1}. The discrepancy between the two values calculated for κ is not currently understood. However, the κ values obtained by these methods overlap the range reported by Namizaki *et al.*[21] for a third order DBR corrugated grating with a period of 373 nm fabricated by conventional techniques in an AlGaAs guide layer. The product of the coupling coefficient and the grating length (κL) determines the maximum grating reflectivity, obtained under phase-matched conditions. Based on the above two methods, we estimate a $\kappa L \approx 1.75$–2.8 and an $R_{\rm max} \approx 80\%$–90%.

In summary, the operation of a DBR GaAs QW laser with AlGaAs/GaAs SL grating reflectors has been reported. The entire laser has been fabricated by the single maskless step of Si^{++} FIB implantation IIR mixing with the relatively low dose of 10^{14} cm^{-2}. Multiple mode laser emission has been observed at ~827 nm, with emission linewidths of ~1.5 Å. Future improvements in laser characteristics are anticipated with this technique by optimizing the laser design and the FIB implantation parameters. In addition, it is important to explore the FIB fabrication of first and second order DBR gratings. The ability to fabricate these narrower period (~115 and 230 nm) gratings is a function not only of beam diameter, but also ion-solid scattering (i.e., lateral straggle) and postimplantation diffusion during anneal. The FIB IIR technique thus appears very promising for producing DBR lasers which can be readily integrated in OEICs.

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[1] S. Wang, IEEE J. Quantum Electron. **QE-10**, 413 (1974).
[2] F. K. Reinhart, R. A. Logan, and C. V. Shank, Appl. Phys. Lett. **27**, 45 (1975).
[3] For a selection of papers (up to 1989) on DFB/DBR and other semiconductor lasers see *Semiconductor Diode Lasers*, edited by W. Streifer and M. Ettenberg (IEEE, New York, 1991), Vol. I.
[4] W. D. Laidig, N. Holonyak, Jr., M. D. Camras, K. Hess, J. J. Coleman, P. D. Dapkus, and J. Bardeen, Appl. Phys. Lett. **38**, 776 (1981).
[5] For a useful review of the IID process and its applications see D. G. Deppe and N. Holonyak, Jr., J. Appl. Phys. **64**, R93 (1988).
[6] T. Hirata, M. Maeda, M. Suehiro, and H. Hosomatsu, Jpn. J. Appl. Phys. **29**, L961 (1990).
[7] For a comparison of FIB and other particle beam fabrication techniques see A. J. Steckl, Proc. IEEE **74**, 1753 (1986).
[8] For a review of FIB technology see J. Melngailis, J. Vac. Sci. Technol. B **5**, 469 (1987).
[9] K. Ishida, T. Takamori, K. Matsui, T. Fukunaga, T. Morita, E. Miyauchi, H. Hashimoto, and H. Nakashima, Jpn. J. Appl. Phys. **25**, L783 (1986).
[10] K. Ishida, E. Miyauchi, T. Morita, T. Takamori, T. Fukunaga, H. Hashimoto, and H. Nakashima, Jpn. J. Appl. Phys. **26**, L285 (1987).
[11] M. C. Wu, M. M. Boenke, S. Wang, W. M. Clark, Jr., E. H. Stevens, and M. W. Utlaut, Appl. Phys. Lett. **53**, 265 (1988).
[12] B. Frank, M.S. dissertation, North Carolina State University, Raleigh, NC, 1989.
[13] A. J. Steckl, P. Chen, A. G. Choo, H. E. Jackson, J. T. Boyd, P. P. Pronko, A. Ezis, and R. M. Kolbas, Mater. Res. Soc. Symp. Proc. **240**, 703 (1992).
[14] P. Chen and A. J. Steckl, J. Appl. Phys. **77**, 5616 (1995).
[15] A. J. Steckl, P. Chen, A. G. Choo, H. E. Jackson, J. T. Boyd, A. Ezis, P. P. Pronko, S. W. Novak, and R. M. Kolbas, Mater. Res. Soc. Symp. Proc. **281**, 319 (1993).
[16] M. Kumar, V. Gupta, G. N. DeBrabander, P. Chen, J. T. Boyd, A. J. Steckl, A. G. Choo, H. E. Jackson, R. D. Burnham, and S. C. Smith, IEEE Photonics Technol. Lett. **4**, 435 (1993).
[17] H. M. Stoll, IEEE Trans. Circuits Syst. **CAS-26**, 1065 (1979).
[18] A. Yariv and P. Yeh, *Optical Waves in Crystals* (Wiley, New York, 1983).
[19] F. Koyama, Y. Suematsu, S. Arai, and T. Tawee, IEEE J. Quantum Electron. **QE-19**, 1042 (1983).
[20] W. Streifer, D. R. Scifres, and R. D. Burnham, IEEE J. Quantum Electron. **QE-12**, 422 (1976).
[21] H. Namizaki, M. K. Shams, and S. Wang, Appl. Phys. Lett. **31**, 122 (1977).