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Semiconductor distributed feedback lasers with quantum well or superlattice gratings for index or gain-coupled optical feedback

W. T. Tsang, F. S. Choa, M. C. Wu, Y. K. Chen, R. A. Logan, S. N. G. Chu, and A. M. Sergent
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

C. A. Burrus
AT&T Bell Laboratories, Crawford Hill, New Jersey 07733

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We introduce a semiconductor distributed feedback (DFB) in which the grating is fabricated out of quantum well (QW) or superlattice multilayers. This approach provides a very simple and effective scheme for achieving gain (loss)-coupled DFB lasers. The present idea was successfully demonstrated with a 1.55-μm wavelength 6-QW $In_{0.6}Ga_{0.4}As$ (5 nm)/InGaAsP (band-gap wavelength = 1.25 μm, 18.6 nm) separate confinement heterostructure DFB laser utilizing only a 2-QW $In_{0.62}Ga_{0.38}As$ (4 nm)/InP (9.3 nm) as the grating.

The control of the optical feedback coupling coefficient κ is very important in distributed feedback (DFB) lasers.[1] It has a very significant effect on the device characteristics, e.g., spectral linewidths, harmonic distortions, and relative intensity noise, etc. The oscillation wavelength degeneracy at the edges of the Bragg reflection band is a major problem in index-coupled DFB[2–7] lasers. It can cause unacceptable mode partitions under pulse-code modulation. One solution to this problem is the use of antireflection/high reflection (AR/HR)-coated facets. This, however, results in a yield problem associated with the uncertainty of the facet phases.[2] Another solution is the incorporation of a $\lambda/4$ or corrugation-pitch modulated phase shift during growth.[3,4,8] For perfect AR coatings, such lasers show a high yield, but the yield deteriorates rapidly for reflectivities of only a few percent.[3] Other drawbacks include the fact that half of the power is wasted from the back facet and high spatial hole burning is caused by the $1/4\lambda$ phase shift[4] (although this is reduced by the corrugation-pitch modulation scheme[8]). The high spatial hole burning gives rise to optical nonlinearity in the light-current (*L-I*) curves, increased spectral linewidth, and a less flat frequency-modulation response.

An alternative approach is the introduction of gain coupling.[7,9,10] Purely gain-coupled lasers theoretically should have one lasing mode exactly at the Bragg wavelength for AR-coated facets, thereby solving the degeneracy problem.[7] It has been shown theoretically[11,12] that even a small degree of gain coupling enhances the performance considerably in terms of threshold gain difference (side-mode-suppression ratio) and removes the degeneracy of an Ar-coated DFB laser. Moreover, a complete elimination of spatial hole burning is possible.[12] This, in turn, will further increase the laser yield. For non-AR-coated lasers, it has been shown[13,14] that there is a relevant improvement in yield for even a small amount of gain coupling. In addition, results also show a potential for lower feedback sensitivity compared to other DFB lasers.[15] The validity of the gain-coupled approach for semiconductor DFB lasers has been demonstrated recently in GaAs/AlGaAs lasers.[9,10]

In Fig. 1 we schematically show the proposed new DFB laser structure with a quantum well (or superlattice) grating for optical feedback. As an illustrative example, a 1.5-μm $In_xGa_{1-x}As$/InGaAsP multiquantum well (MQW) active-layer laser with a 2-QW $In_yGa_{1-y}As$/InP grating is shown. In this structure, a QW structure is used for the grating. The coupling coefficient κ is conveniently controlled by the number, the composition, or the thickness of the QWs. Since the index of refraction of InGaAsP quaternary material increases as the band gap of the material becomes narrower, the QW thickness can be further reduced by using narrower band-gap material for the grating quantum wells. Furthermore, because of the quantum-size effect, the absorption edge of the QW grating can be designed to be above the lasing wavelength even if the same material composition as that of the active layer is used in the grating QWs. On the other hand, if a gain (loss)-coupled grating is desired, the thickness or composition of the grating QWs can be designed so that its absorption edge is below the lasing wavelength. Since the grating QWs can be made very thin, the gain-coupling effect can be made to dominate the index-coupling effect. If necessary, the grating QWs can have a composition with narrower bulk band gap than the active QW material. Figure 1 illustrates such possibilities with $In_xGa_{1-x}As$/InGaAsP active QWs and a $In_yGa_{1-y}As$/InP QW grating. The QW grating can also be composed of strained layers, which are either in tension or compression. This can further modify the coupling coefficient of TE and TM modes of the DFB lasers.

Figure 2 shows a transmission electron microscope photograph (the cross-sectional view) of a 6-QW active-layer DFB laser with a 2-QW grating. The fuzzy outline of the InP/InP grating interface is due to nonexact perpendicular orientation of the sample with respect to the incident electron beam during viewing and the rough, uneven etched grating surface. Nevertheless, it is seen that the regrowth is defect-free.

To fabricate this, a uniform stack of *n*-type InGaAs/InP QWs (or superlattices) of the desired number, composition, and thickness, and having a thin InP cap layer for grating fabrication, was grown first over a 2-in. diam

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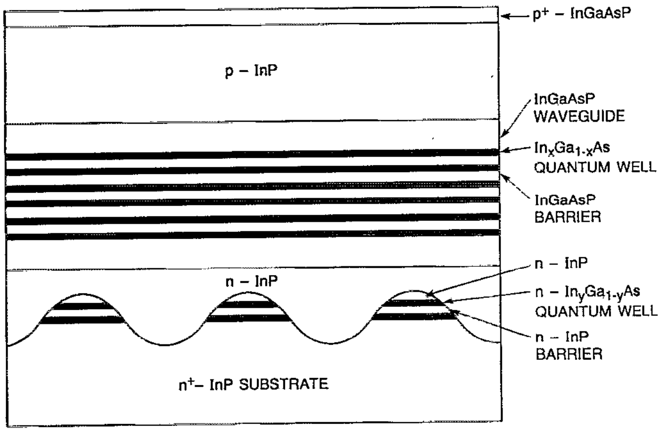

FIG. 1. Shows schematically the proposed DFB laser structure with quantum well (or superlattice) grating for optical feedback. As an illustrative example, a 1.5-μm $In_xGa_{1-x}As$/InGaAsP/InP 6-QW active-layer laser with a 2-QW $In_yGa_{1-y}As$ grating is shown.

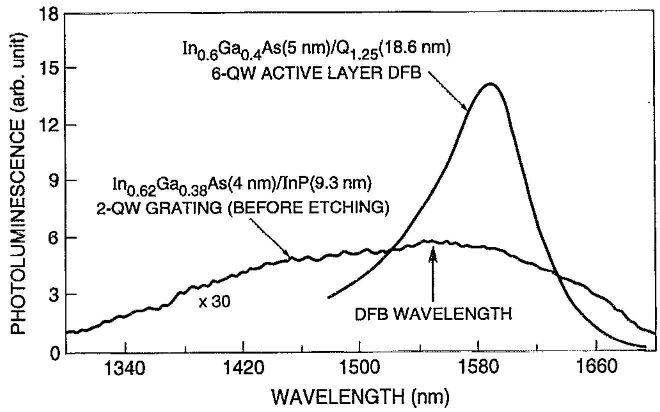

FIG. 3. The photoluminescence spectra from the two grating QWs before grating etching, and from the 6-QW active-layer DFB laser wafer after regrowth over the grating. The optical absorption by the 2-QW grating has extended well beyond the intended DFB lasing wavelength at 1.55 μm.

(100)-oriented n-InP substrate. It has been shown previously that the present CBE system is capable of producing layers with a thickness uniformity of $\lesssim \pm 1\%$ and a photoluminescence (PL) peak wavelength uniformity of $\lesssim \pm 5$ nm (as good as ± 1.5 nm).[16,17] Recent results from other research groups also have demonstrated thickness variations $\lesssim 0.75\%$ and band-gap wavelength variations of InGaAsP quaternaries $\lesssim \pm 1$ nm over 3-in. diam wafers with CBE.[18] We have have fabricated such DFB laser wafers with the number of grating QWs varied from 1 to 8. For wafers with a large number of QWs, thinner QWs and InP barriers were used in order to maintain a total thickness $\lesssim 50$ nm. In these cases, they behave more as superlattices than independent QW gratings. In the example shown by the TEM photograph in Fig. 2, two $In_{0.62}Ga_{0.35}As$ (slightly In-richer than the $In_{0.6}Ga_{0.4}As$ active QWs) QWs of 4 nm and InP barrier of 9.3 nm were grown. The top InP cap layer was 9.3 nm. First order gratings were prepared by standard holographic techniques and wet etching that had an amplitude of ~48 nm, as shown in Fig. 2. No precise grating depth control was exercised as long as the QWs were completely etched through. After cleaning, the sample was reintroduced into the CBE system for MQW laser regrowth. The substrate was heated to ~545 °C under phosphorus overpressure from precracked phosphine (PH_3). Under such low-temperature conditions, no grating erosion was observed. The detailed shape of the grating was well preserved, as shown by the TEM photograph. An n-type InP spacer layer of the desired thickness (65 nm in the present laser) was grown. (The thickness of this layer will also affect the value of κ.) This was then followed by the standard strained-layer 6-QW separate confinement heterostructure (SCH). The quaternary, $Q_{1.25}$, waveguide layer thicknesses were 52.2 nm each. The $In_{0.6}Ga_{0.4}As$ QWs and $Q_{1.25}$ barriers were 5 and 18.6 nm, respectively. In these experiments, all-vapor sources were used, including those for the p- and n-type dopants. Diethylzinc and tetraethyltin were employed as the p- and n-type doping sources, respectively.

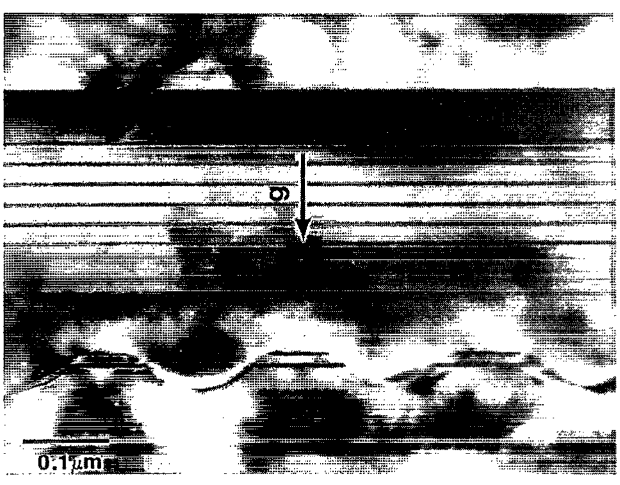

FIG. 2. A TEM photograph of the cross-sectional view of a 6-QW $In_{0.6}Ga_{0.4}As$ (5 nm)/$Q_{1.25}$ (18.6 nm) active-layer DFB laser with a 2-QW $In_{0.62}Ga_{0.38}As$ (4 nm)/InP (9.3 nm) grating.

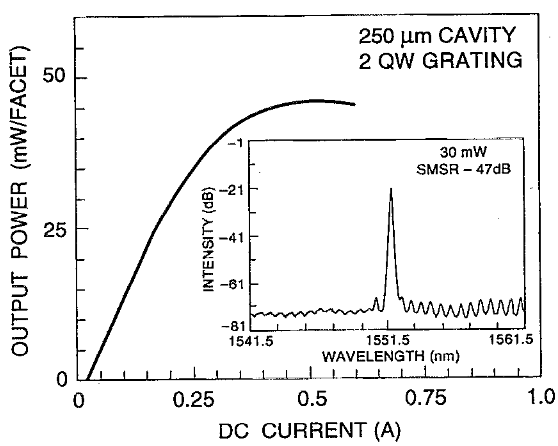

FIG. 4. The light-current characteristic of a typical 500-μm long laser with both facets AR-coated (~5%). The inset shows the lasing spectrum at ~30 mW.

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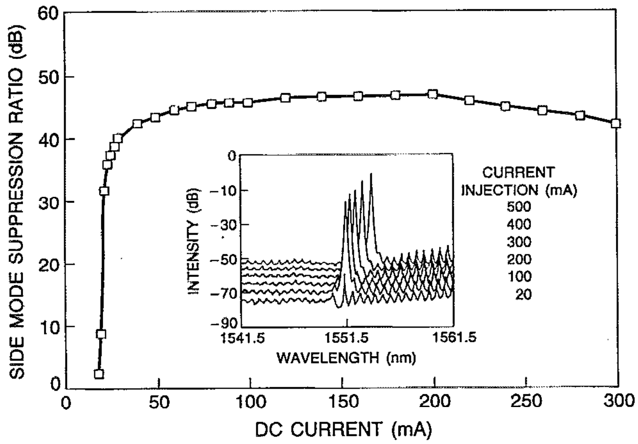

FIG. 5. The SMSR as a function of injection current. The inset shows the spectra at different injection currents. Near threshold the DFB mode is relatively well centered with a small Bragg stop band.

These laser wafers were further processed into buried heterostructure devices employing MOVPE regrowth of Fe-doped InP at 630 °C.

We have studied the device performance of DFB lasers with various QW grating designs. The details will be reported elsewhere. Here, we will report the results obtained from a wafer with a 2-QW $In_{0.62}Ga_{0.38}As$ grating (sample shown in Fig. 2). In this particular wafer, because the gain peak is located sufficiently (38 nm) longer in wavelength (see Fig. 3) than the DFB peak designed at 1550 nm, antireflection (AR) facet coatings ($\sim$5% on both facets) were employed to push the gain peak towards the shorter wavelength. When the gain peak was located closer to the DFB peak in the other wafers, even as-cleaved lasers showed high side-mode-suppression ratios (SMSR). However, we choose to present the results from this particular wafer because the total thickness of the two QWs was only 8 nm and they were of $In_{0.62}Ga_{0.38}As$ material. This combination serves well to demonstrate the present proposed idea. The photoluminescence (PL) spectrum of this grating QW structure was measured before grating etching, and it is shown in Fig. 3, together with the PL spectrum from the 6-QW $In_{0.6}Ga_{0.4}As$ (5 nm)/$Q_{1.25}$ (18.6 nm) active-layer DFB laser wafer after regrowth over the 2-QW grating. It is seen that optical absorption has extended well beyond 1550 nm. This suggests that the present QW grating will also produce a significant gain (loss)-coupled component.

In Fig. 4 we show the *L-I* characteristic of a typical 500-μm long laser. Output power of 46 mW/facet was obtained with a slope efficiency of $\sim$0.2 mW/mA/facet. The inset shows the lasing spectrum at $\sim$30 mW output. A SMSR of 47 dB was obtained. It is important to point out that, even though the $In_{0.62}$ $Ga_{0.38}As$ QW grating may introduce some additional loss, we have not observed any unacceptable increase in threshold currents. For example, in the present case, the CW threshold currents were 13–18 mA even when the cavity length was 500 μm, both facets AR coated, and the DFB mode was far away from the gain peak. Figure 5 shows the SMSR as a function of injection current. A SMSR of $\sim$45 dB was maintained throughout the entire current range once lasing started. The inset shows the actual spectra up to 500 mA. Near threshold the DFB mode is relatively well centered with a small Bragg stop band. This indicates that the κ is small and there is the presence of a gain-coupled component.

In summary, a DFB (or DBR) laser is designed with the grained fabricated out of QWs or superlattices. This approach greatly facilitates the reproducible regrowth (defect-free) over the grating and the control of the coupling coefficient. It also provides a very simple and effect scheme for achieving gain (loss)-coupled DFB lasers. The present idea was successfully demonstrated with a 1.55-μm wavelength 6-QW $In_{0.6}Ga_{0.4}As$ (5 nm)/$Q_{1.25}$(18.6 nm) SCH 2-QW $In_{0.62}Ga_{0.38}As$ (4 nm)/InP (9.3 nm) grating.

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