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Invited

Patterning of Quantum Wells by Growth on Nonplanar Substrates: Application to Quantum Wire Lasers

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Epitaxial growth of quantum wells (QWLs) on nonplanar substrates results in lateral bandgap patterning due to lateral QWL thickness variations. We have used this effect to fabricate GaAs/AlGaAs single- and multiple-quantum wire (QWR) semiconductor lasers by organometallic chemical vapor deposition on V-grooved substrates. The QWR lasers exhibit threshold currents as low as 1mA and show spectral features which are attributed to the QWR subbands. Lasing from lower subbands is achieved with multiple QWR structures due to reduced carrier density (per wire) at threshold.

The realization of one- and zero-dimensional (1D and 0D) semiconductors relies on fabrication techniques which can produce lateral bandgap variations without introducing excess damage onto the interfaces defining these quantum structures. Such damage-free interfaces are of particular importance in the case of optical studies of quantum structures, in which nonradiative recombination at defects can significantly reduce the radiative carrier lifetime. Recently, a number of techniques for producing quantum wires (QWRs) and dots with damage-free interfaces have been proposed, including epitaxial growth on vicinal substrates[1] and strained-induced bandgap patterning[2]. Here, we review our recent progress in developing a new technique for lateral bandgap patterning, and describe its application to semiconductor QWR lasers.

Our patterning technique utilizes lateral thickness variations and quantum size effects in QWL heterostructures grown on nonplanar substrates to achieve lateral bandgap patterning with damage-free interfaces[3]. This approach has been useful for obtaining controlled lateral bandgap variations using a single step of molecular beam epitaxy (MBE)[4] or organometallic chemical vapor deposition (OMCVD)[5] on nonplanar substrates, as supported by transmission electron microscopy (TEM) and low temperature cathodoluminescence imaging studies. Furthermore, with this technique, record-low threshold currents of patterned QWL lasers[6] and laser-passive waveguide integrated structures[7] (both grown by MBE) have been demonstrated.

Single and multiple QWR lasers were grown by OMCVD on V-grooved substrates. The cross section of a GaAs/AlGaAs single QWR laser is shown in Fig. 1. The growth of the AlGaAs cladding layers results in the formation of a sharp V-groove, on which corner the GaAs crescent-shaped QWR grows[8,9]. The QWR is ~ 10nm thick and <100nm wide and is located at the center of a two-dimensional (2D) optical waveguide. The threshold current for these single QWR lasers is as low as 18mA for $x=0.5$ Al mole fraction in the cladding layers[8], and is reduced to 3.5mA by increasing x to 0.7 and reducing the optical waveguide width to increase the power filling factor[9] (room temperature, uncoated facets). Fig. 2 shows the light-current characteristic of a single QWR laser (x=0.7); the inset shows the near field pattern which indicates operation in the fundamental spatial mode.

Spectra of single QWR lasers of various cavity lengths L and facet reflectivities are shown in Fig. 3. Below threshold, the amplified spontaneous emission spectra exhibit peaks with separations (~10meV) which correspond to the QWR subband spacings, as determined by a model based on the TEM data[8]. Shorter cavity lasers lased at higher QWR subbands due to band filling[8,9]. Reduction in the threshold current to ~1mA and lasing from lower QWR subbands were achieved by employing high reflection (HR) mirror coatings (~95%).

The threshold current of QWR lasers can be reduced also by inserting several QWRs into the optical mode volume in order to increase the optical filling factor[10]. Figure 4 shows a TEM cross section of a 3-QWR laser structure, in which the 2D optical waveguide and each wire's cross section are similar to those in the case of the single QWR structure of Fig. 1. For these 3-QWR lasers, a minimum threshold current of 2.5mA was obtained at L=100μm, compared to 3.5mA at L=350μm for the single QWR structure (uncoated facets). The QWR subband structure is evident in the laser spectra (see Fig.5) indicating that the variations in subband positions from wire to wire are relatively small. The lower carrier density (per wire) resulted in lasing from lower QWR subbands. The dependence of I_{th}/L on the mirror loss parameter for lasers with one, two and three QWRs (Fig.6) agrees with a model accounting for gain saturation in the QWR active region[10]. This provides further evidence that the wires contribute collectively to stimulated emission in these structures.

In conclusion, we have applied the technique of lateral bandgap patterning by QWL growth on nonplanar substrates to the fabrication of single- and multiple-QWR laser structures. These lasers exhibit lasing from 2D quantum confined states with threshold currents as low as ~1mA, at room temperature. Further optimization of these devices is required in order to achieve lasing from the fundamental QWR subband and to reduce threshold currents to the sub-mA regime.

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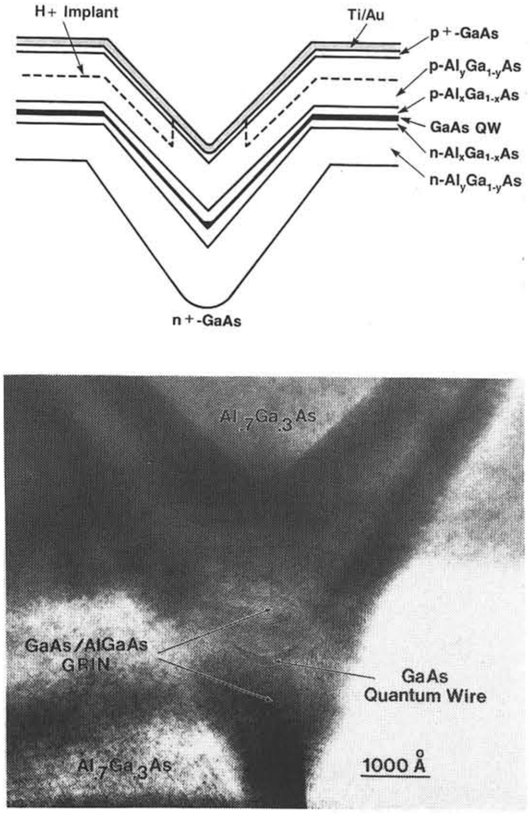

Fig.1: Schematic and TEM cross sections of a single-QWR laser

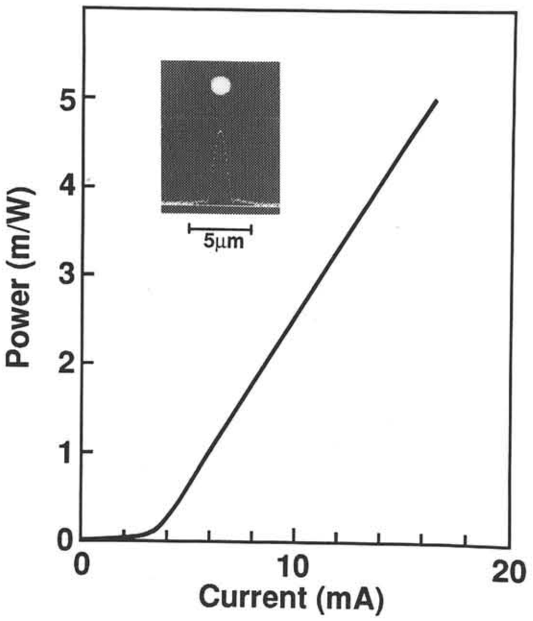

Fig.2: Light-current characteristic of a 350µm long single QWR laser (uncoated facet, pulsed operation). The inset shows the near field pattern.

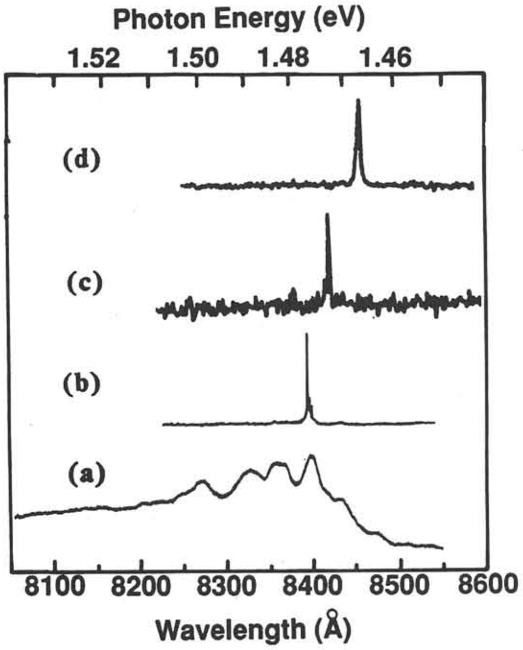

Fig.3: Spectra of single QWR lasers. (a)uncoated facets, L=3.48mm, I=22mA (I_{th}=23mA); (b) same as (a), except I=25mA; (c) HR coated facets, L=180μm, I=1.3mA (I_{th}=1.05A); (d) HR coated facets, L=350μm, I=2mA(I_{th}=1.7mA).

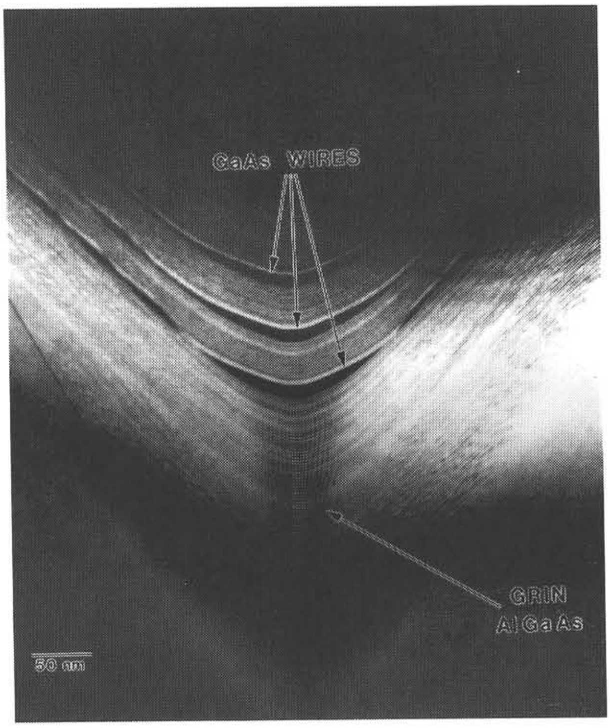

Fig.4: TEM cross section of a 3-QWR laser.

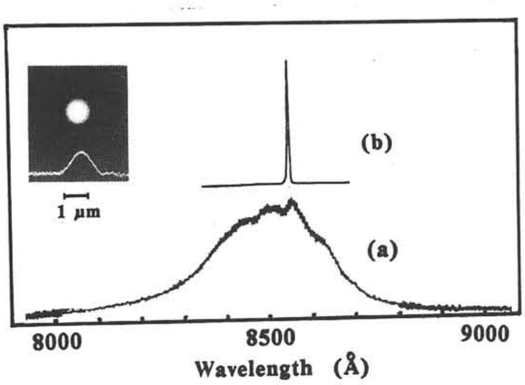

Fig.5: Spectra of a 3-QWR laser; L=1.29mm, I_{th}=10mA, uncoated facets (a) I=8mA (b) I=12mA. Inset shows the near field pattern.

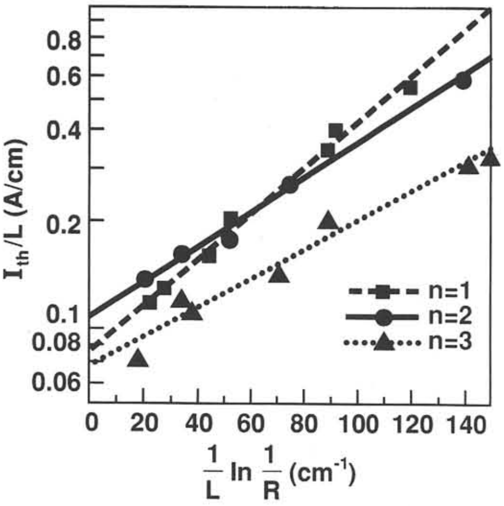

Fig.6: Log(I_{th}/L) vs mirror loss parameter for 1-, 2- and 3-QWR lasers.