Very low threshold InGaAs/InGaAsP graded index separate confinement heterostructure quantum well lasers grown by atmospheric pressure metalorganic vapor phase epitaxy

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Record low threshold current densities have been achieved in InGaAs/InGaAsP step graded index separate confinement (GRIN SCH) quantum well lasers emitting close to 1.50 μm. Single (SQW) and multiple (MQW) quantum well lasers with 300–500 μm long cavities had threshold current densities as low as 1.9 and 0.9 kA/cm^2, respectively. In longer cavity devices, threshold current densities as low as 750 and 450 A/cm^2 have been measured in SQW and MQW lasers, respectively. These lasers show no significant change in threshold current density with well thicknesses varying from 5 to 25 nm which demonstrate the effectiveness of the graded index in the carrier capture process. Buried-heterostructure GRIN SCH SQW and MQW with active layer widths of ~ 2 μm show threshold currents of 15 and 9 mA, respectively.

Quantum well lasers have a number of advantages over conventional double-heterostructure devices and their preparation and properties have been intensively studied.[1–5] Their principal advantage is the very low internal waveguide loss giving rise to lasers with low threshold and high quantum efficiency only weakly dependent on the laser length. These features are extremely attractive for optoelectronics integration. The simplest quantum well structure, demonstrated already in the GaAlAs/GaAs[6–8] system, is the single quantum well laser. This type of laser is also most demanding in terms of material perfection. In order to improve the confinement factor of such a laser, the active quantum well is placed in a separate waveguide layer. The separate confinement heterostructure (SCH) typically consists of a number of steps, each with a different index of refraction, or a continuously graded index (GRIN) waveguide. While the design principles of such lasers are fairly well understood, their implementation in the near-infrared materials such as GaInAs/InP or GaInAs/InAlAs has turned out to be quite difficult. High quality single quantum well lasers of GaInAs/InP have been reported only very recently.[9]

In this letter, we report a record low threshold current density operation of step graded index SCH single (SQW) and multiple quantum well (MQW) lasers with well dimensions as narrow as 5 nm. The SCH confining layers are formed by a series of four lattice-matched step-like changes in composition in order to approximate the GRIN waveguide. The quaternary steps are 15–30 nm thick and several composition sequences were explored in the range 1.0–1.4 μm. The atmospheric pressure metalorganic vapor phase epitaxy (MOVPE) apparatus and the source materials had been described elsewhere.[9]

Figure 1(a) shows the schematic diagram of the GRIN SCH QW laser. The number of wells was varied from 1 to 5. The epitaxial layers were grown on a (100) n-InP substrate using the following growth steps: an n-InP buffer layer (1 μm thick, S doped to 3×10^{18} cm^{-3}), a lower part of GRIN SCH confining layers with step-like decreasing band gap of 1.14, 1.25, 1.33, and 1.40 μm (15–30 nm each, undoped), a single ternary quantum well (thickness varying from 5–25 nm) for SQW, or multilayers of GaInAs cladded by GaInAsP (band-gap wavelength of 1.40 μm, 15–30 nm thick) barriers, an upper part of the undoped GRIN SCH GaInAsP confining layers similar to the lower ones but increasing in band gap (15–30 nm each), an InP setback layer to minimize effects of Zn diffusion from the upper cladding (50 nm thick, undoped), a p-InP cladding layer (Zn doped to 3×10^{17} cm^{-3}, 1–2 μm thick), and finally a p-InGaAsP contact layer (Zn doped to 4×10^{18} cm^{-3}, 120 nm thick). After each layer was grown, and before the growth of the subsequent layer of different composition, the reactor was flushed by the hydride gases characteristic of the first layer and then preflushed with gases characteristic of the second layer to achieve sharp interfaces, as described in some detail previously.[9] We also tested other composition sequences of GRIN confining layers such as 1.0, 1.1, 1.2, and 1.25 μm and found an improvement in quantum efficiency as well as less threshold current variation with the laser length by using GRIN terminated at the larger band-gap composition (1.25 μm as compared to 1.40 μm). Further studies of the optimization of the GRIN composition and dimensions are in progress. Samples both with and without thin InP interfacial layers between the quantum well(s) and barrier(s) were grown for this study.[9]

Figure 1(b) shows the transmission electron micrograph (TEM) cross-sectional picture of the as-grown GRIN SCH SQW laser with a well width of 5 nm. In this TEM photograph, composition changes are identified by the changes in contrast in which a layer with a narrower band gap appears to be darker. The layer thicknesses are very uniform and in excellent agreement with the growth times. The interfaces between various quaternary compositions are very sharp and free from defects. Such sharp and well-defined heterostructures are obtained reproducibly.

Figure 2 shows the relationship between the broad-area threshold current density (J_{th}) and the number of well(s). The SQW devices contained a GRIN SCH waveguide terminating with a 1.4 μm composition quaternary layer grown

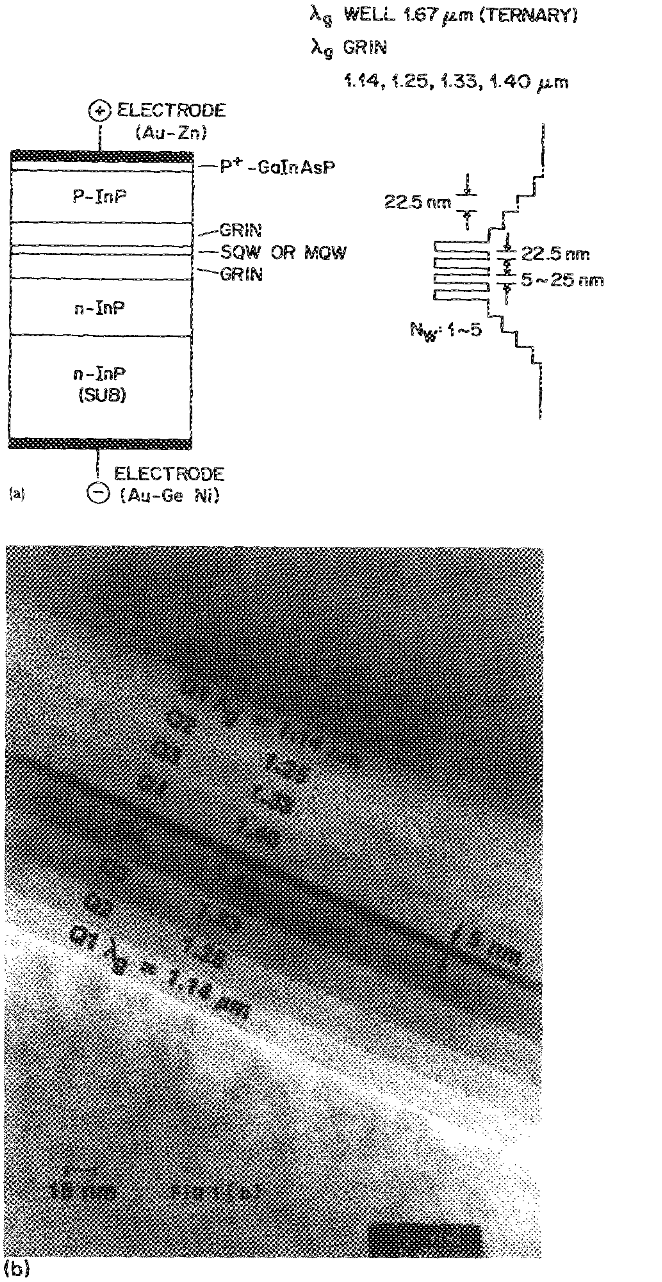

FIG. 1. (a) Schematic diagram of the GRIN SCH QW laser structure. (b) TEM cross section of a step-graded single quantum well laser structure.

adjacent to the quantum well. The MQW lasers with the GRIN structures terminating at 1.4 and 1.25 μm are included. The cavity length was 300–500 μm. Although a small decrease in threshold current density was observed as the number of wells increased, no significant change was observed even in the single quantum well in contrast to the results of Kasukawa *et al.*[10] where the threshold current density increased sharply with the reduced number of wells. The lowest threshold current density was ~ 1.9 kA/cm^2 for a SQW laser as compared to 0.9 kA/cm^2 for four quantum wells. With a cavity of 1000 and 2110 μm, the four quantum well laser showed threshold current densities of 560 and 450 A/cm^2, respectively. For SQW lasers with similar cavity lengths, the threshold current densities of 1.13 and 0.75 kA/cm^2 had been observed. This value is believed to be the lowest ever reported in a quantum well laser operating close to 1.5 μm.

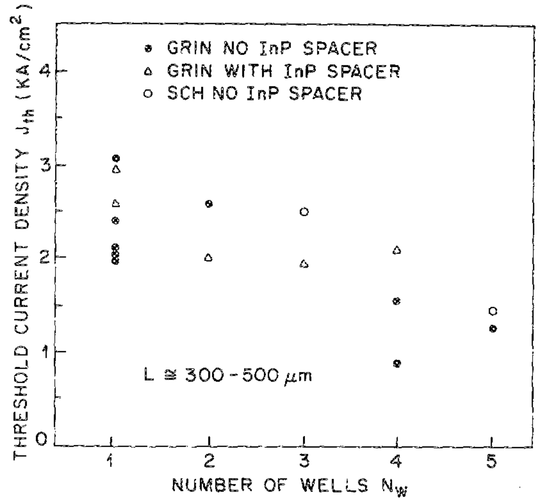

FIG. 2. Broad-area threshold current density plotted as a function of the number of quantum wells. No significant increase in the threshold current density is observed for the single quantum well.

In order to demonstrate that the structures discussed here indeed act as quantum well lasers, we have carefully measured the lasing wavelength dependence on the thickness of the quantum well. The measured changes in the lasing wavelength with decreases in the well sizes from 25 to 5 nm are plotted in Fig. 3. We also compare the experimental data with the calculated energy level of the structure assuming a 40/60 split in the band-gap discontinuity between the conduction and valence bands. Effective electron and hole masses of the quaternary layers comprising the GRIN struc-

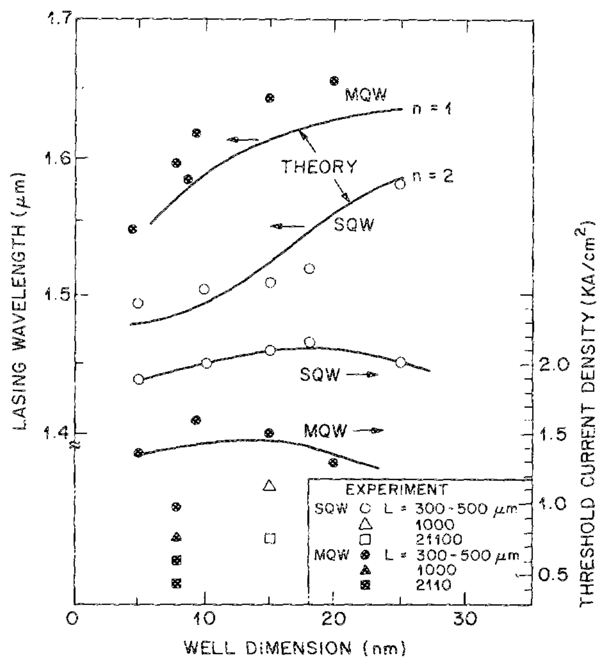

FIG. 3. Laser wavelength and threshold current density plotted as a function of the well thickness. The calculated lines represent the $n = 1$ and $n = 2$ confined particle state of the entire quantum well GRIN structure.

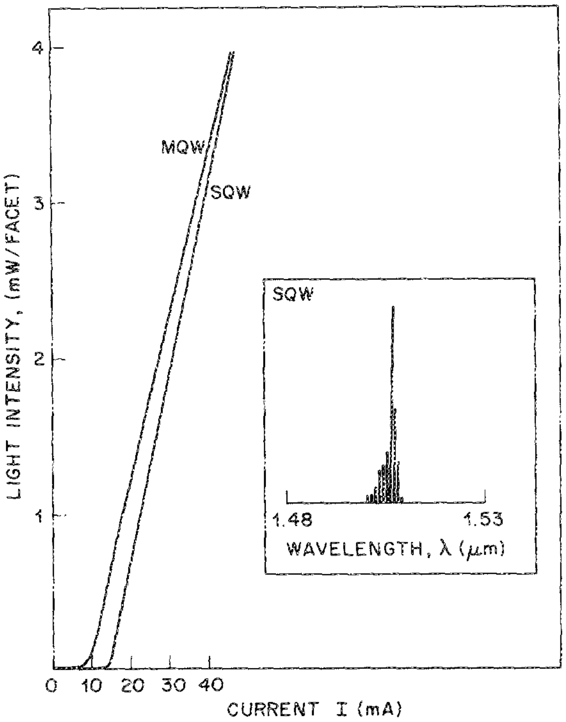

FIG. 4. Light-current characteristics and lasing spectrum of a buried-heterostructure laser based on a single and multiple quantum well GRIN SCH structure.

tures were obtained using extrapolation procedures of Adachi.[11] It is important to include in the calculation at least the lowest energy part of the GRIN structure since the $n = 2$ electron level is not confined to a simple square well thinner than 10 nm. The lasing wavelength of the multiquantum well lasers (four wells) follows the $n = 1$ transition, independent of the composition of the waveguide structure. The lasing wavelength shifts from 1.66 to 1.53 μm as the well dimensions decrease from 20 to 5 nm. The optical spectra taken below and slightly above threshold show that the lasing occurs between 5 and 20 meV below the electroluminescence peak energy. The behavior of single quantum well lasers, terminated here with a 1.4 μm GRIN composition, is markedly different and the lasing wavelength is in excellent agreement with the $n = 2$ exciton transition energy. Indeed the detailed optical spectra show lasing at an energy of up to 25 meV higher than the electroluminescence peak, depending on the quantum well width. This accounts well for the slight increase in the lasing threshold of the single quantum well structures. The single quantum well structures thinner than 5 nm tend to lase at 1.42 μm, corresponding to the lowest band-gap cladding layer. The demarcation line between the lasers operating at $n = 1$ and $n = 2$ excitons typically lies in the structures with 2–3 wells. Further lowering of the threshold current density is expected if single quantum well structures operating at a lower loss $n = 1$ level could be prepared. It is noteworthy that only a weak dependence of threshold current densities on well dimensions was again observed for both SQW and MQW. This indicates the effectiveness of graded barrier structure in carrier trapping processes, thus reducing the threshold current density of the quantum well lasers. Lowest threshold current density of 450 A/cm^2 was obtained in four quantum wells with a cavity length of 2110 μm and 7.5 nm well thickness.

Buried-heterostructure lasers grown entirely by metal-organic vapor phase epitaxy were realized in a two-growth step procedure.[12] Light output versus current at room temperature of a SQW (well size of 16 nm) and MQW laser together with lasing spectrum of the SQW laser are shown in Fig. 4. Threshold currents as low as 15 and 9 mA with quantum efficiency of 15%/facet were obtained at room temperature for SQW and MQW lasers, respectively. A preliminary measurement of the temperature dependence of the light output against current yielded a T_0 of 76–80 K with no break point above room temperature.

In summary, we have demonstrated the effectiveness of GRIN SCH in lowering the threshold current in single and multiple quantum well lasers, with well dimensions as narrow as 5 nm. A record low threshold current density of 450 A/cm^2 was measured in MQW lasers. Buried-heterostructure SQW and MQW lasers had threshold currents of 15 and 9 mA, respectively.

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