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Low-Threshold, Strained-Layer, GaInP/AlGaInP GRINSCH Visible Diode Lasers

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Abstract—**Graded-index, separate-confinement heterostructure (GRINSCH) semiconductor diode visible lasers employing a strained-layer GaInP single quantum well were fabricated from metalorganic chemical-vapor deposition (MOCVD)-grown epitaxial material. CW threshold current densities as low as 650 A/cm^2 were measured for uncoated, 1200-μm-long, 15-μm-wide ridge structures operating at 30°C and emitting at 655–670 nm. A maximum output under quasi-CW conditions (100 μs pulse length, 1% duty factor) as high as 320 mW/facet was achieved before catastrophic failure. This CW threshold current density is believed to be the lowest reported to date for visible light diode lasers.**

HIGH-EFFICIENCY, low-threshold-current semiconductor diode lasers emitting in the red portion of the spectrum (650–670 nm) are needed for a variety of applications such as diode pumping of Cr-doped solid-state lasers [1], optical recording, high-definition television (HDTV), and plastic fiber optics. Over the past several years, AlGaInP has evolved as the semiconductor material of choice. However, in spite of advancements in materials and device technology, threshold current densities have always been high. Only recently have CW thresholds been reduced below 1000 A/cm^2 [2]–[4], and values approaching those achievable for GaAs lasers (< 100 A/cm^2) have always seemed out of reach. In this letter, we report the first graded-index, separate-confinement heterostructure (GRINSCH) visible light laser which utilizes a strained-layer GaInP single-quantum-well active region. CW threshold current densities as low as 650 A/cm^2 were measured on 15 × 1200 μm, uncoated ridge structures. These CW threshold values, to our knowledge, are the lowest ever reported for any diode laser emitting in the 660–670 nm wavelength range. Further improvements are expected as the device structure and material parameters become optimized.

It is well established from GaAs/AlGaAs laser technology that the use of a GRINSCH quantum-well structure can lead to improved performance and low threshold current [5]. Furthermore, the utilization of a strained-layer quantum well in place of a lattice-matched well to reduce the threshold current as a consequence of a smaller valence-band effective mass has been both predicted theoretically [6] and demonstrated experimentally in the GaInP materials system [3]. Finally, the incorporation of thin bounding layers immediately adjacent to the quantum well of longer wavelength, strained-layer InGaAs/AlGaAs GRINSCH lasers has also been shown to provide a lowering of the threshold current compared to diodes without such layers [7]. In order to produce a visible light laser diode with low-threshold characteristics, we adopted all three of these principles in our design. Fig. 1 shows a schematic cross section of our laser structure which was grown by low-pressure metalorganic chemical-vapor deposition (LP-MOCVD) in a single-wafer horizontal reactor [8].

The compositions and thicknesses of the cladding, confinement, and bounding layers of the device shown in Fig. 1 were optimized to first order for both carrier and optical confinement using a finite-element computer analysis which calculates the TE modes in the planar waveguide defined by the various epitaxial layers. The n- and p-$(Al_xGa_{1-x})_{0.51}In_{0.49}P$ cladding layers were doped with Si and Zn, respectively. Confinement layers linearly graded from the cladding layer composition to a lower x-value composition surround the two bounding layers, which are of still lower, but nonzero, x-value AlGaInP. A thin, Zn-doped p-GaInP layer was incorporated between the p-AlGaInP cladding layer and the p-GaAs contact layer to reduce the high barrier which can be present at such an interface [9]. The calculated confinement factor for our final structure was 2.04%.

The use of biaxial compressive strain in GaInP to lower the valence-band effective mass by increasing the In mole fraction causes a shrinkage of the bandgap compared to GaInP lattice-matched to GaAs [10]. To offset this shift in order to keep the wavelength in the range possible with unstrained GaInP, an adjustment must be made to the quantum-well thickness. Our use of a nominal 7-nm $Ga_{0.43}In_{0.57}P$ quantum well resulted in lasing wavelengths from 664 to 672 nm, depending upon the location within the wafer and cavity length, compared to 691 nm previously reported for a 10-nm well of similar composition in a nongraded structure [3]. We attribute our shorter wavelengths to a combination of the narrower well (3 nm smaller) and also a higher barrier height (estimated to be 160 meV larger). No specific attempts were made to shorten the wavelength by either adjusting the growth conditions [11] or using off-angle substrates [12].

Laser diodes were fabricated from the epitaxial wafers by

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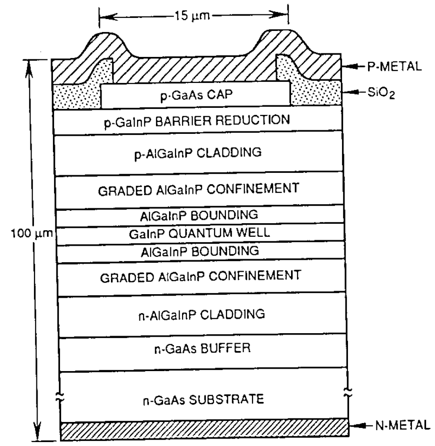

Fig. 1. Schematic cross section (not to scale) of an etched-ridge, strained-layer, single-quantum-well GRINSCH visible light laser with bounding layers.

defining 15-μm-wide mesa ridges in the 0.15-μm-thick, p-GaAs cap layer using an $NH_4OH:H_2O_2:H_2O$ selective etchant [13], coating the resultant surface with CVD-deposited SiO_2, and etching 11-μm-wide stripes in the oxide for a subsequent p metallization. The wafer was thinned to 100 μm, an n metallization was deposited, and diodes were cleaved and mounted p side down onto copper heat sinks using indium solder.

Shown in Fig. 2 is the CW power-current ($P-I$) characteristic for a 1200-μm-long, uncoated device mounted on a 30°C heat sink. Near-field measurements above threshold confirmed an emitting width in the 15-16 μm range. The 117 mA CW threshold current evident from Fig. 2 corresponds to a threshold current density of 650 A/cm^2 for the 15 × 1200 μm geometry, a value never before attained to the best of our knowledge. The differential (external) quantum efficiency for this diode is approximately 47%, and the characteristic temperature (T_0) is approximately 75 K, a value typical of previously reported diodes operating in this wavelength range.

The results of quasi-CW testing (100 μs pulse length, 1% duty factor) for a similar diode are shown in Fig. 3. A maximum power output of 320 mW/facet was achieved before the occurrence of catastrophic failure. The noticeable kinks in the $P-I$ characteristic were accompanied by visually observed changes in the lateral far-field optical pattern due to the lateral-mode instability of this 15-μm-wide diode. Very recent results on 60-μm-wide broad stripe visible diodes confirm the association of these kinks with cavity width; linear $P-I$ characteristics typical of well-behaved, broad-stripe, GaAs laser diodes are observed for the 60-μm-wide visible diodes.

Measurements of slope efficiency and threshold current were performed as a function of cavity length (300-1200 μm) in order to estimate the internal laser parameters. Fig. 4 shows preliminary data, together with results of a least squares analysis. While there is some scatter in the data, the relative insensitivity of the quantum efficiency to length would tend to indicate a low absorption coefficient (< 5 cm^{-1}). Of more significance, however, is the apparent low internal quantum efficiency (~ 50%). From the threshold current dependence on length, we can also extract initial estimates of the transparency current density (< 150 A/cm^2) and the differential gain coefficient (> 2 cm/A). Both of these values appear quite acceptable.

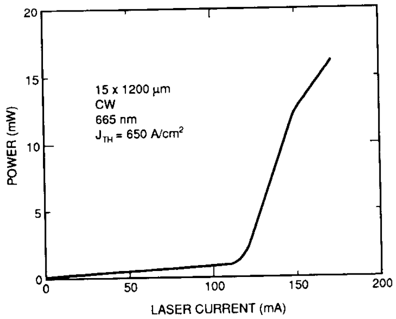

Fig. 2. Power output-current characteristic for an uncoated, p side down, 1200-μm-long × 15-μm-wide, strained-layer, quantum-well GRINSCH laser operating CW at 665 nm. Diode heat sink temperature is 30°C. The 117 mA threshold current corresponds to a current density of 650 A/cm^2.

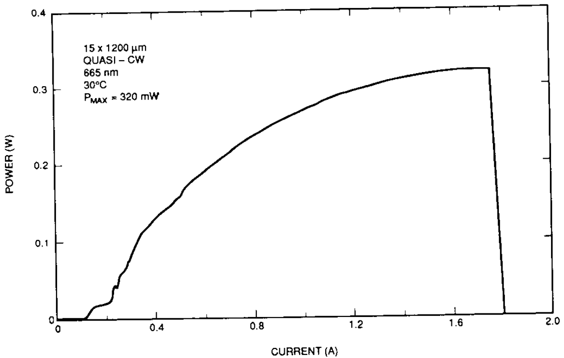

Fig. 3. Pulsed (quasi-CW) power-current characteristic for an uncoated, 1200-μm-long × 15-μm-wide, strained-layer, quantum-well GRINSCH visible light laser mounted p side down on a 30°C heat sink. The pulsewidth is 100 μs and the duty cycle is 1%.

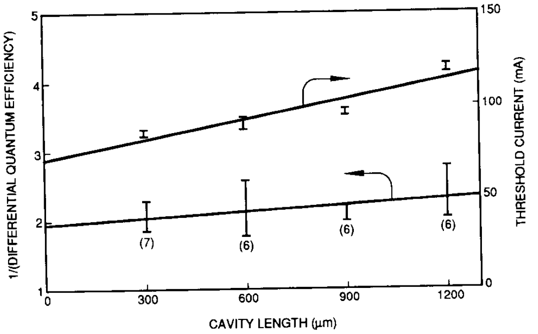

Fig. 4. Reciprocal differential quantum efficiency and threshold current dependence on cavity length for a number of 15-μm-wide lasers operating at 30°C. Least squares fit to the data is shown by the solid lines. Numbers in parentheses indicate the number of diodes of each length. Error bars indicate plus or minus one standard deviation about the mean.

In summary, we have fabricated strained-layer, single-quantum-well GaInP/AlGaInP GRINSCH visible light lasers with room-temperature, CW threshold current densities as low as 650 A/cm^2 and quasi-CW power outputs as high as 320 mW/facet. Work on modifying the device structure in order to further increase the laser performance, as well as fabricating linear and two-dimensional arrays, is in progress.

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