High-power, very low threshold, GaInP/AlGaInP visible diode lasers

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Visible light (665 nm) laser diodes employing a strained-layer, single quantum well, graded index separate confinement heterostructure were fabricated from epitaxial wafers grown by metalorganic chemical vapor deposition. Threshold current densities for single element, uncoated, broad-area diodes operated cw as low as 425 A/cm^2, cw power outputs of 340 mW per facet, and pulsed outputs (100 μs pulse width) of slightly under 1 W per facet were achieved. These power output values are believed to be the highest reported to date for visible light diode lasers, and this cw threshold current density is believed to be, by far, the lowest.

Low-power visible light diode lasers operating in the 650–670 nm wavelength range are finding application in many areas such as barcode scanning and plastic fiber optics. However, high-power visible diode lasers are critically needed for such applications as optical pumping of tunable Cr-doped solid-state lasers including alexandrite[1] and lithium strontium aluminum fluoride (LiSAF).[2] This important application is analagous to the present, relatively widespread use of GaAs laser diodes for pumping longer wavelength Nd:YAG solid-state lasers. However the high threshold current densities (>800 A/cm^2) of visible diode lasers have, until now, severely limited their potential performance and utility. Specifically, the highest reported room-temperature cw and pulsed outputs from visible diode lasers are only 150 mW and 700 mW (per facet), respectively.[3,4] In this letter, we report the results of broad stripe, strained-layer, single quantum well, graded index separate confinement heterostructure (GRINSCH) visible lasers which have achieved output power levels, per facet, of over 300 mW cw and nearly 1 W pulsed at a heatsink temperature of 30 °C. This was accomplished by reducing the cw threshold current density to 425 A/cm^2, approximately half that of the previously reported lowest cw value.[5] As a result of these improvements, we anticipate significant advancement in diode pumping and other applications which require high output, high-efficiency visible diode lasers.

The high-power laser diodes reported here are of conventional oxide-defined, broad stripe design. The 60-μm-wide by 1200-μm-long GaInP/AlGaInP diodes rely on three key design features to achieve their record low threshold current density. First, 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.[6] Second, the utilization of a strained-layer quantum well in place of a lattice-matched well to reduce threshold current by lowering the valence-band effective mass has been both predicted theoretically in general[7] and demonstrated experimentally in the GaInP materials system.[8] Third, the incorporation of thin bounding layers immediately adjacent to the quantum well in longer wavelength, strained-layer InGaAs/AlGaAs GRINSCH lasers has also been shown to provide lowering of threshold current compared to diodes without such layers.[9] Figure 1 shows a schematic cross section of our laser structure grown by low-pressure metalorganic chemical vapor deposition (LP-MOCVD) in a single wafer, horizontal reactor[10] which incorporates these three design principles.

The compositions and thicknesses of the cladding, confinement, and bounding layers 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 composition of the cladding layers to a smaller 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.[11] 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 the band gap to shift to longer wavelengths compared to GaInP lattice matched to GaAs.[12] To offset this shift in order to keep the wavelength in the range possible with unstrained GaInP, appropriate adjustment must be made to the quantum well thickness. Our use of a 7 nm $Ga_yIn_{1-y}P$ ($y = 0.43$) quantum well resulted in a lasing wavelength of about 665 nm compared to 691 nm previously reported for a 10 nm quantum well of similar composition in a nongraded, separate confinement structure.[8]

The diode fabrication process consisted of chemically vapor depositing a SiO_2 oxide layer over the p-GaAs cap, photolithographically defining and etching 60-μm-wide stripes in the oxide, depositing a p-metallization layer over the oxide, thinning the wafer to approximately 100 μm, and depositing an n-metallization layer on the backside. Individual diodes were cleaved from the wafer and mounted p-side down on small copper blocks using indium solder. All testing was performed with the laser diode cop-

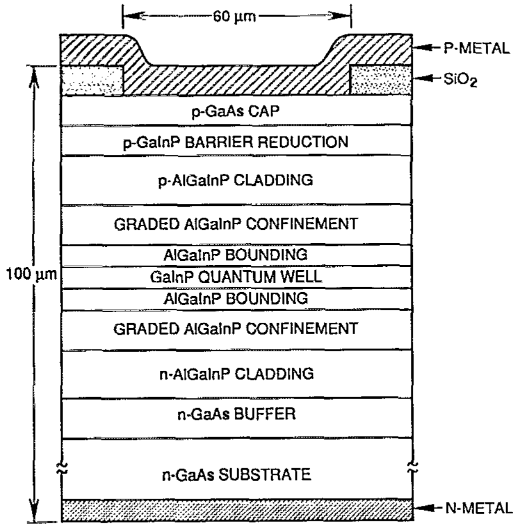

FIG. 1. Schematic cross section (not to scale) of the 60-μm-wide, oxide-stripe, strained-layer, single quantum well GRINSCH visible light laser.

per blocks attached to 30 °C temperature-controlled heatsinks.

Figure 2 shows the cw power-current (*P-I*) characteristic of a typical uncoated 60 μm by 1200 μm diode. The 306 mA threshold current corresponds to a cw threshold current density of 425 A/cm^2—a value never before even approached by a visible diode laser to the best of our knowledge. At low power, the *P-I* curve is linear and well-behaved; the slope efficiency for this diode is approximately 0.34 W/A which corresponds to an external quantum efficiency of 36% at the lasing wavelength of 665 nm. A maximum cw power output of 340 mW per facet (680 mW total output) limited only by thermal saturation was achieved which is, to our knowledge, the highest cw output ever reported for a visible laser diode operating at room temperature. At 300 mW/facet, the input dc power of 3.90

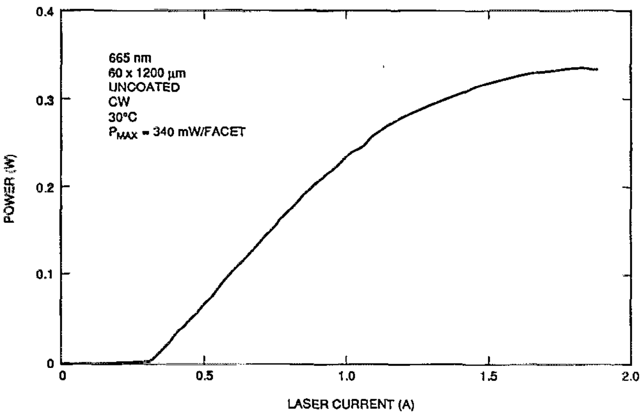

FIG. 2. Power output-current characteristic for an uncoated, *p*-side down, 1200-μm-long by 60-μm-wide, strained-layer, quantum well GRINSCH laser operating cw at 665 nm. Diode heatsink temperature is 30 °C. The 306 mA threshold current corresponds to a current density of 425 A/cm^2. A peak cw output of 340 mW/facet (680 mW total power output) occurs at approximately 1.8 A.

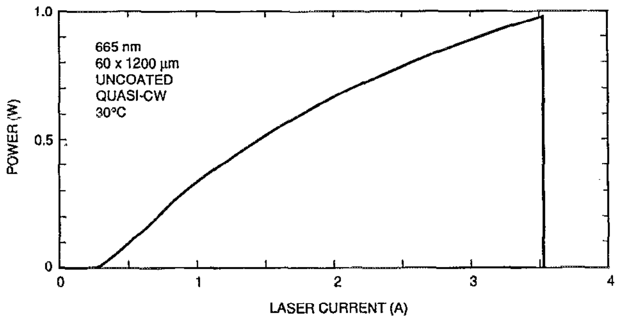

FIG. 3. Pulsed (quasi-cw) power-current characteristic for an uncoated, 1200-μm-long by 60-μm-wide, strained-layer, quantum well GRINSCH visible light laser mounted *p*-side down on a 30 °C heatsink. Pulse width is 100 μs, and duty cycle is 1%. A peak output of 0.98 W/facet (1.96 W total) was attained before the occurrence of catastrophic failure.

W (1.33 A at 2.92 V) corresponds to a net power conversion efficiency of 15.4%. The threshold current density of these 60 μm diodes is significantly better than our earlier results (650 A/cm^2) attained with 15 μm diodes.[13] Such an improvement with stripe width results from the combined effects of reduced lateral carrier diffusion, reduced absorption in the unpumped portions of the active region,[14] and lowered current spreading.

Shown in Fig. 3 are the results of pulsed testing of these diodes. Long pulses (100 μs, 1% duty factor) were utilized in order to simulate the operating conditions encountered in pulsed pumping of solid-state lasers such as alexandrite or LiSAF. Under such "quasi-cw" testing, catastrophic diode failure was observed at a power output of 0.98 W per facet (nearly 2 W total pulsed output). Again, to our knowledge, this is the highest pulsed output (for any pulse width) achieved by a single visible diode laser. When diodes were tested using short 0.4 μs pulses, the thermal saturation apparent in Fig. 3 disappeared, but the catastrophic power limit remained the same.

Measurements were also made to determine the characteristic temperature, T_0, of these visible diodes. Figure 4 shows the *P-I* characteristics for a 60 by 1200 μm diode at various heatsink temperatures between 10 and 40 °C. A value for T_0 of approximately 78 K was calculated for an

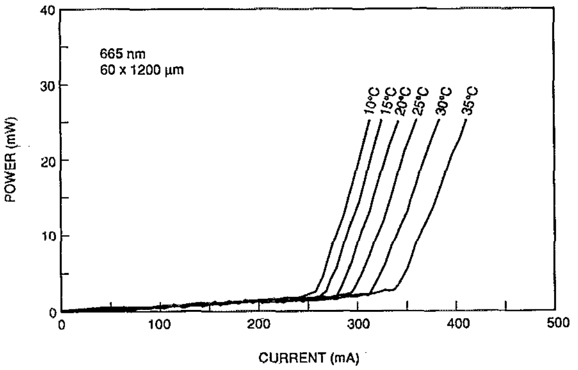

FIG. 4. Power-current characteristics for a 60 by 1200 μm laser diode at heatsink temperatures between 10 and 40 °C.

operating temperature around 30 °C. This value is in the same range as most other reported visible light diode lasers.[15]

In summary, we have fabricated high-output, low-threshold, strained-layer, single quantum well GaInP/AlGaInP GRINSCH visible light lasers. Room-temperature cw threshold current densities as low as 425 A/cm^2, cw power outputs as high as 320 mW per facet, and pulsed (quasi-cw) outputs of nearly 1.0 W per facet have been achieved. Work on improving the device structure in order to further increase the laser performance, as well as fabricating linear and two-dimensional arrays for practical solid-state laser pumping is in progress. Lifetesting of these diodes at high optical outputs is also an important task which is being addressed; initial results look extremely encouraging.

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