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Highly-Efficient Buried-Oxide-Waveguide Laser by Selective Oxidation

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An edge-emitting buried-oxide waveguide (BOW) laser structure employing lateral selective oxidation of AlGaAs layers above and below the active region for waveguiding and current confinement is presented. This laser configuration has the potential for very small lateral optical mode size and high current confinement and is well suited for integrated optics applications where threshold current and overall efficiency are paramount. Optimization of the waveguide design, oxide layer placement, and bi-parabolic grading of the heterointerfaces on both sides of the AlGaAs oxidation layers has yielded 95% external differential quantum efficiency and 40% wall-plug efficiency from a laser that is very simple to fabricate and does not require epitaxial regrowth of any kind.

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Waveguide-based photonic integrated circuits (PICs) offer many attractive features, such as single-mode waveguides, couplers, and switches making them useful for optical computing and signal processing. However, the most highly capable circuits will take advantage of the best of electronics and photonics while avoiding the drawbacks of each technology. In this scenario, the electrical-to-optical interface will be high-speed, high-efficiency lasers diodes. Future realization of high-density or low-power opto-electronic integrated circuits (OEICs) will require extremely efficient light sources in order to reduce overall circuit power consumption. We report highly efficient, low-threshold-current edge-emitting lasers where both the optical waveguide and lateral current confinement are achieved by lateral selective oxidation of AlGaAs. This buried-oxide waveguide (BOW) laser structure employs lateral oxidation of AlGaAs layers above and below the active region resulting in an easily manufactured laser with a very small lateral optical mode size and high current confinement. Such highly confined lasers are well suited for OEIC applications where threshold current and overall efficiency are paramount. External differential quantum efficiency in excess of 95% and 40% wall-plug efficiency are demonstrated in devices without facet coatings.

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Selective wet oxidation of Al[1] offers a powerful capability to simultaneously create both an optical waveguide and current aperture within a heterostructure of Al-containing compound semiconductors. Since the initial development of wet AlGaAs oxidation methods,[2] a number of oxidized edge-emitting laser concepts have been tried.[3] The most successful of these have used lateral selective oxidation of AlGaAs layers between 100 and 300 nm thickness. These layers have been used as current restricting apertures[4, 5] or for both current restriction and lateral waveguiding.[6-8] Use of an oxide layer above and below the laser active region offers the ability to create a self-aligned waveguide with current apertures on both sides of the pn-junction in a process requiring only one epitaxial growth step. The high refractive-index contrast between AlGaAs and its oxide permits fairly thin selectively-oxidized layers to form a very highly-confining optical waveguide. Such highly-confined waveguides with self-aligned current apertures are expected to give very low threshold currents and very high overall efficiency in an optimized laser design. Previous use of apertures for these dual purposes resulted in multi-moded lasers with reduced efficiency and elevated threshold current density due to non-ideal formation of the waveguide and possibly excess stress caused by the thick (300 nm) oxide layer.[6]

The BOW laser structure is shown in Fig. 1(a). Four oxide layers are shown extending laterally from the edges of a deeply-etched mesa. The optical mode of the laser cavity is pinched between the tips of the oxide layers and current injected from a large-area contact above the laser is funneled through the narrow oxide aperture. The BOW laser design has high optical and current confinement resulting from optimized placement of the oxide layers and selection of the aperture width. Fig. 1(b) is a numerical simulation of the optical mode overlaid onto the layer structure of the guide showing the strong lateral guiding effect of the oxide layers. This design supports only one guided TE mode for laser widths less than 2 μm. Oxidation-induced stress is reduced by the use of thin, 40 nm, $Al_{0.98}Ga_{0.02}As$[1] oxidation layers. The minimum layer thickness was chosen in order to achieve a reproducible oxidation rate. Thinner oxidation layers may be used while maintaining the strong waveguiding effect although a reduced and oxidation rate may occur.

A key aspect of design of a BOW laser for high efficiency is the potential barrier created by the heterojunction offset between the oxidation layer, having as much as 98% Al content, and the surrounding waveguide cladding, where Al content does not usually exceed 60%. Reduction of these barriers through engineered grading and doping of the heterojunction has improved vertical-cavity surface-emitting laser (VCSEL) performance[9] but these techniques have not been used in edge-emitters prior to this work. In fact, since the composition grades are not constrained by optical resonance conditions, edge-emitters present a much larger design space for use of graded interfaces allowing for greater reductions in barrier height. Using one-dimensional simulations of the heterojunction band structure, the potential barrier height of oxidation-layer interfaces within BOW lasers has been reduced to less than 15 meV for both the p-type and n-type high-Al-content layers. This low barrier is a consequence of using fully bi-parabolic graded interfaces and is smaller than barriers typically built into uni-parabolic graded VCSEL interfaces.

Lasers were fabricated using metal-organic chemical-vapor deposition of (Al,Ga)As on n-type-doped GaAs substrates. Waveguide material is 60% Al with 175 nm thick grade between 60% and 30% Al forming a graded-index separate confinement heterostructure (GRINSCH) waveguide around a 10 nm GaAs single quantum well (SQW) active region. 40-nm-thick 98%-Al AlGaAs layers for selective oxidation are located on both sides of the graded waveguide.

Mesas between 20 and 40 μm wide were etched through to the substrate and steam oxidized at 420° C to create oxide layers with apertures between 2.3 μm and 25 μm in width. SiO_2 was deposited between the mesas to insulate the n-type material from the top ohmic contact and the entire mesa surface was used to form the upper p-type ohmic contact with Pt/Ti/Pt/Au metalization. After completion of the p-side, the wafer was thinned, Pd/Ge/Au ohmic contact metalization applied and the entire structure heat-treated at 175°C. Fig. (2) is a SEM cross section image of a completed laser. The gap between the darkest gray laterally oxidized regions, corresponding to the optical waveguide, is clearly seen. The upper and lower oxide apertures are slightly different in width due to a 14% difference in oxidation rate of the n- and p-type AlGaAs oxidation layers in this configuration.

Lasers were tested p-side up without heat sinking or facet coatings using 1 μs pulses at 10 kHz repetition rate. Fig. (3) shows pulsed light-versus-current data for 300-μm-long BOW lasers with 4-μm-wide waveguide apertures. The 300 μm laser has a threshold current, I_{th}, of <6 mA and a threshold density, J_{th}, of 486 A/cm^2. The slope efficiency is constant at 1.15 W/A (assuming equal power from rear facet) for all tested currents. Longer, 600-μm lasers (Fig. 4) has I_{th} = 8.7 mA, J_{th} = 307 A/cm^2, and slope efficiency of 1.48 W/A. At the operating wavelength these devices have external differential quantum efficiencies of 0.79 (short laser) and >0.95 (long laser). Wall-plug efficiency of the long laser peaks at 40%. Wall-plug efficiency of both lasers is limited by the ~2.3 V threshold voltage. Examination of current-voltage characteristics suggests.that this high threshold voltage is due to excessive series resistance, possibly due to high specific contact resistance.

Ensemble average data for threshold current and external differential quantum efficiency from 70 tested lasers is presented in Fig. 5. Threshold current of 300-μm-long lasers decreases monotonically with width suggesting that narrower lasers with lower threshold are possible. The longest (900 μm) lasers are more sensitive to internal loss and show a minimum threshold current at 4 μm width. External differential quantum efficiency is only weakly varying with laser width (except for the 25-μm-wide devices where filamentation may dominate) indicating that losses attributable to the BOW waveguide are quite low even for very narrow guides with significant overlap of the optical mode and the oxidized material. Calculation of overall internal losses from the measured data for laser widths between 2.3 μm and 12 μm gives losses between 2.9 cm^{-1} and 4.4 cm^{-1} including all scattering and self-absorption effects. Little, if any, correlation with width exists in the loss values suggesting that, within the uncertainty of the experiment, narrow BOW lasers do not introduce additional internal waveguide loss due to scattering or absorption by the oxide or oxide interfaces.

In summary, we have demonstrated a highly efficient BOW laser using dual selectively-oxidized AlGaAs layers to form both the optical waveguide and the current confinement regions. Optimization of the waveguide design, oxide layer placement, and bi-parabolic grading of the heterointerfaces on both sides of the AlGaAs layers for oxidation has yielded 95% external differential quantum efficiency and 40% wall-plug efficiency from a laser that is very simple to fabricate and does not require epitaxial regrowth of any kind. Further improvments in wall-plug efficiency and threshold are anticipated through the use of narrower waveguides, facet coating, and reduced threshold voltage.

Acknowledgement

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Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

Figure Captions:

Figure 1: (a) Cross-section schematic of BOW laser showing location of laterally-oxidized regions above and below the GRINSCH-SQW layers. (b) Simulated contours of constant optical field overlayed onto the epitaxial structure of the BOW laser. Confinement of the optical (TE) mode by the GRINSCH structure in the vertical direction and the oxide layers in the horizontal direction is evident.

Figure 2: Scanning electron micrograph of completed BOW laser. Selectively oxidized regions are the dark lines extending in from the sides of the image.

Figure 3: Light output (solid line) and wall-plug efficiency (diamonds) versus injection current of a 300-μm-long by 4 μm wide BOW laser.

Figure 4: Light output (solid line) and wall-plug efficiency (diamonds) versus injection current of a 600-μm-long by 4 μm wide BOW laser.

Figure 5: Threshold current and external differential quantum efficiency of BOW lasers as a function of laser width.

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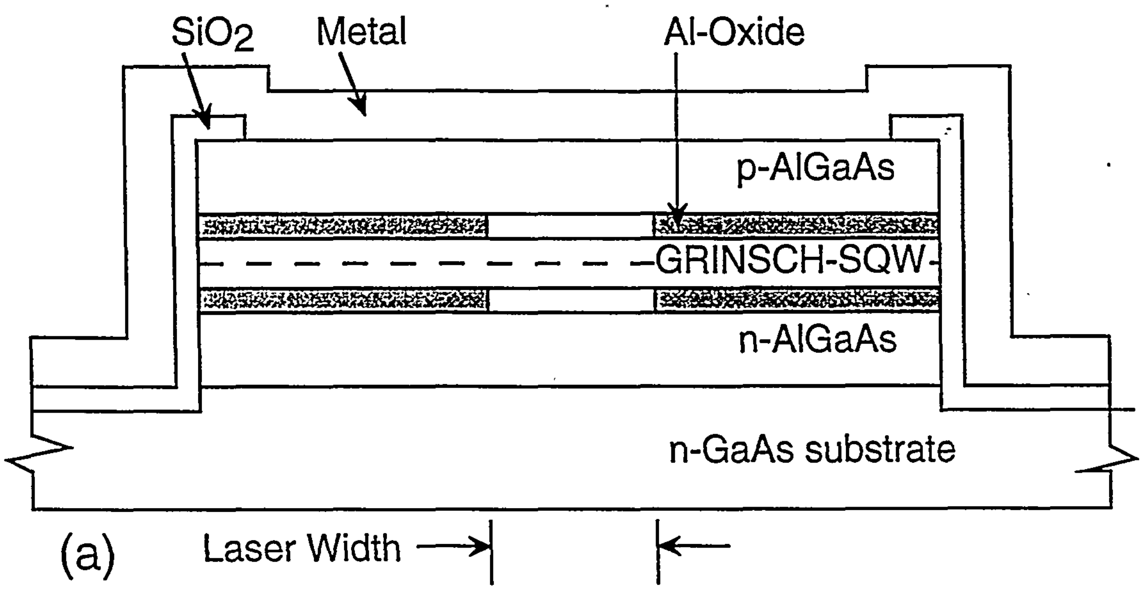


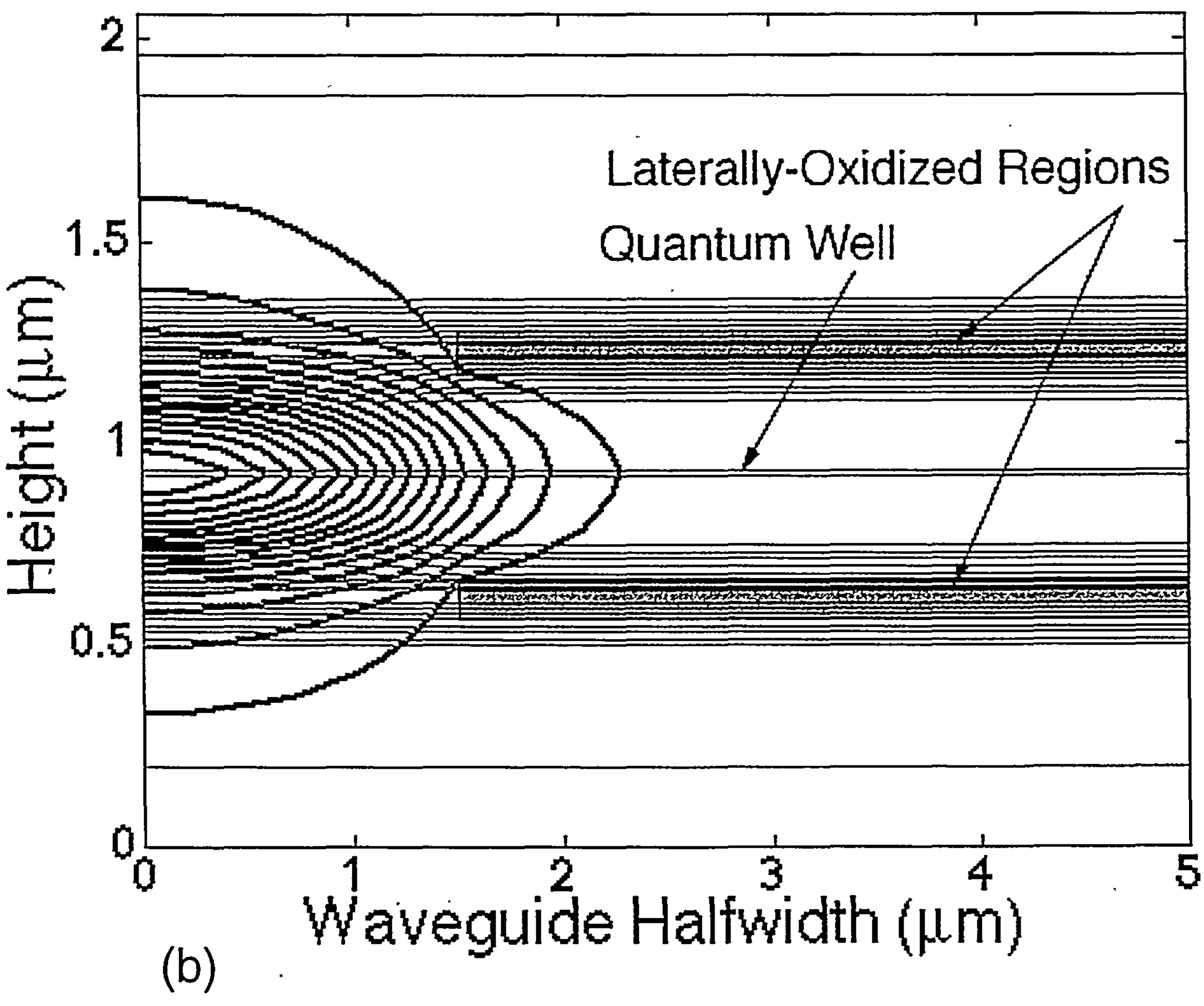


figure 1

VAWTER

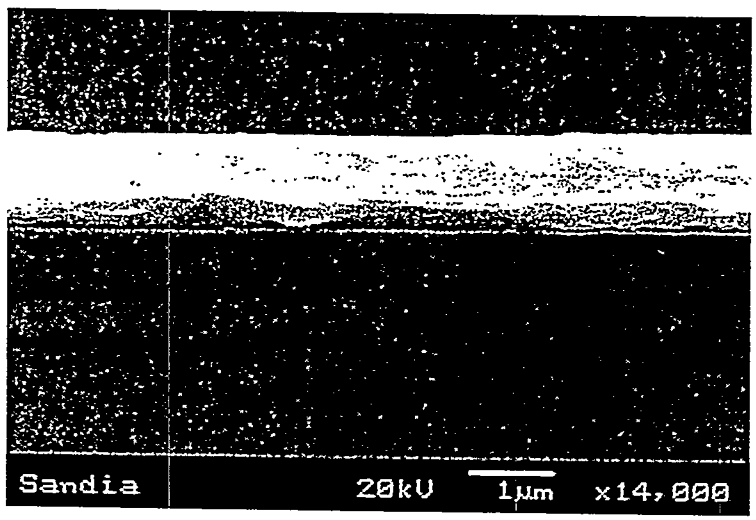
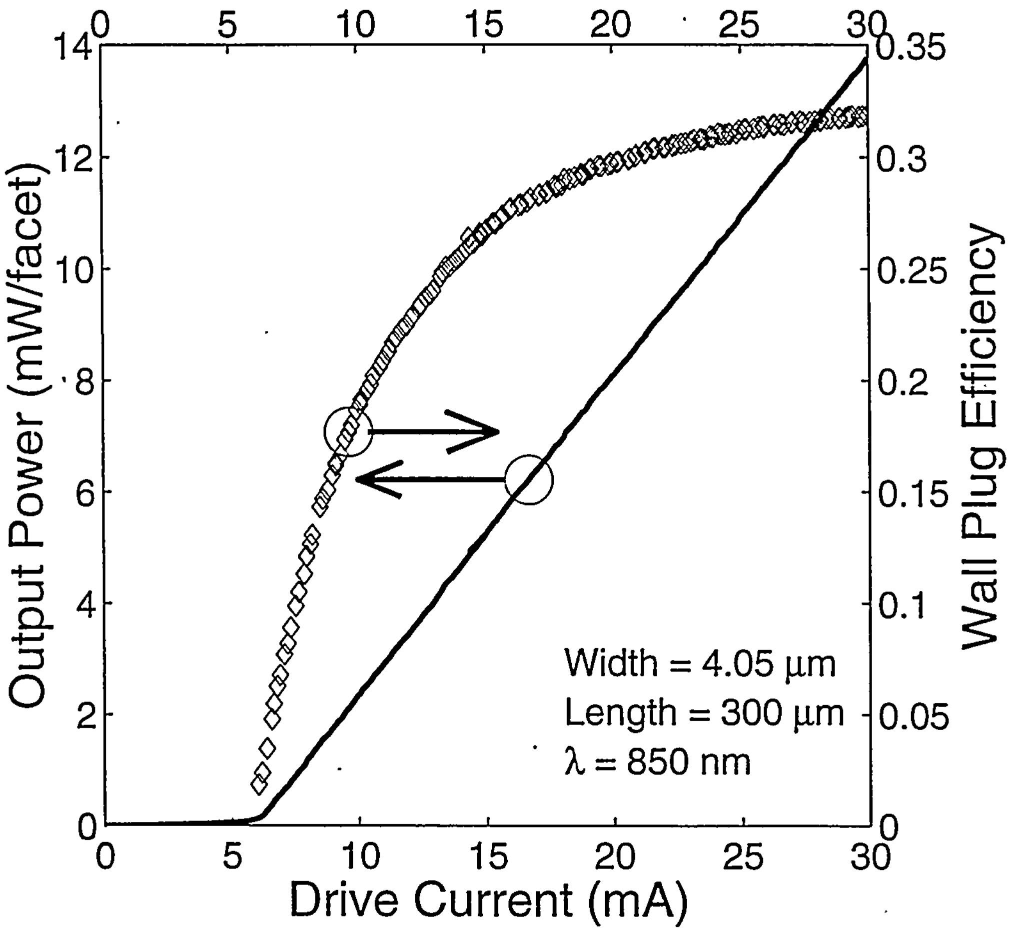


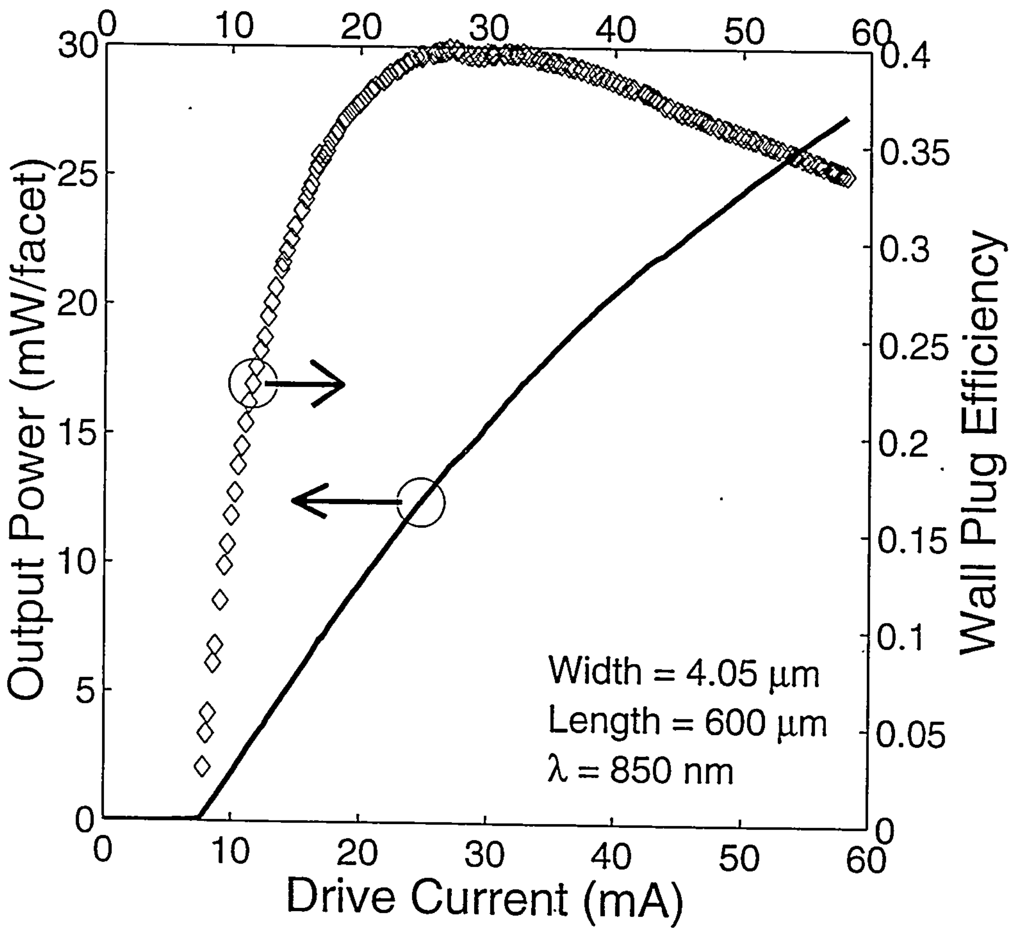
FIG. 2

/-WiER


0
5
10
15
20
25
30
14
12
10
8
6
4
2
0
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
Output Power (mW/facet)
Wall Plug Efficiency
Width = 4.05 µm
Length = 300 µm
λ = 850 nm
Drive Current (mA)

'AWTER

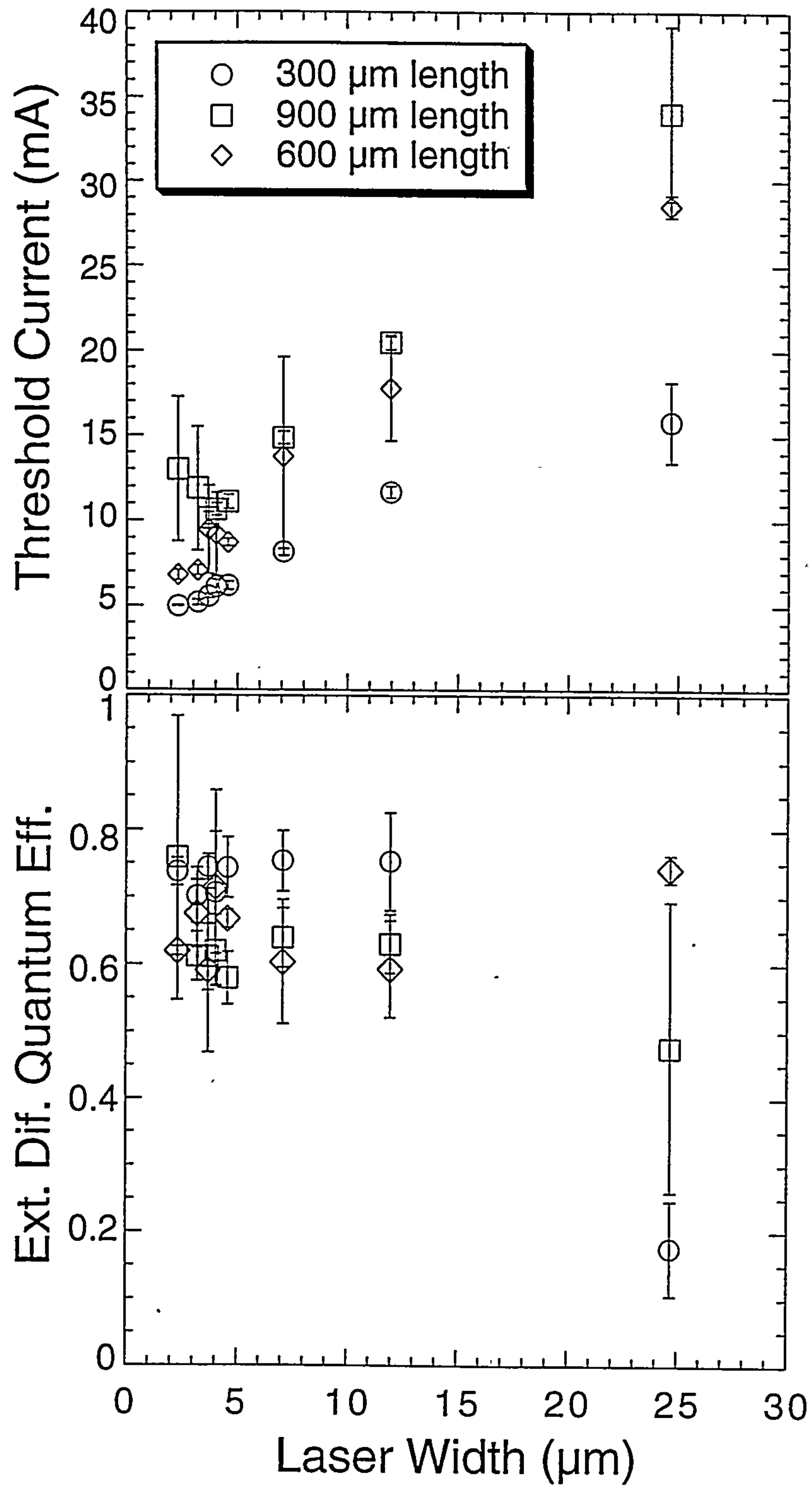
FIG. 3



Output Power (mW/facet)
Wall Plug Efficiency
Drive Current (mA)
Width = 4.05 µm
Length = 600 µm
λ = 850 nm
0
5
10
15
20
25
30
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
10
20
30
40
50
60

FIG. 4

9256.2



40
35
30
25
20
15
10
5
0
Threshold Current (mA)
300 μm length
900 μm length
600 μm length
1
0.8
0.6
0.4
0.2
0
Ext. Dif. Quantum Eff.
0
5
10
15
20
25
30
Laser Width (μm)

FIG. 5