The Microstrip Laser

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***Abstract*— We present a novel semiconductor laser structure, the microstrip laser, where the epitaxial laser layers sit directly above a thick gold layer, instead of on a conventional semiconductor substrate. This design provides advantages for both high frequency and high-power performance compared to conventional ridge waveguide structures. Results indicative of an improved structure are presented, including a factor of 3 reduction in the thermal resistance of the microstrip laser compared to a conventional laser.**

***Index Terms*— High-power lasers, high-speed lasers, semiconductor lasers, wafer bonded lasers.**

I. INTRODUCTION

HIGH FREQUENCY and high-power performance are key properties for semiconductor lasers. In fiber optics applications high-speed lasers are needed as switchable light sources and high-power lasers are needed as pump lasers for erbium-doped fiber amplifiers (EDFA's). Additionally, high-power lasers have great utility in a diverse range of applications, such as in medicine for laser surgery, or in heavy industry for cutting of various materials. The high power capacity is also important for high-frequency lasers, since high-cavity photon densities are needed to minimize stimulated recombination lifetimes that ultimately limit the speed performance. A laser structure that simultaneously could operate as a high-speed and high-power device should be an important technology for a variety of applications. The microstrip laser is presented here and shown to have significant performance potential in both the high-speed and high-power domain.

II. MICROSTRIP LASER

A schematic diagram of the microstrip laser is shown in Fig. 1(a), and a scanning electron microscope (SEM) cross section of a 10-μm ridge waveguide microstrip laser is shown in Fig. 1(b). The laser differs from a conventional ridge waveguide structure only in that the epitaxial layers sit above a 1-μm-thick gold ground plane instead of a semiconductor substrate. Two thermal advantages that can lead to high-power operation are realized in this structure. First, the thick gold layer directly beneath the lower cladding is a good heat spreader and results in a reduction in the thermal resistance. The second advantage exists because the thermal resistance depends on the location of the heat sources—the active region temperature rise is reduced when the heat is generated closer to the heat sink [1]. A reduction in the self heating comes about in our device because the fabrication procedure results in an inversion of the order of epitaxial layers—a structure grown p-up, after fabrication, is n-up. This is particularly important in the InP system where n-up material is very difficult to grow reliably due to diffusion of the p-type dopant zinc (Zn), but for which significant thermal and microwave advantages exist. The n-ridges generate minimal electrical resistance, and therefore generate minimal ohmic heating. The primary heat source in the n-ridge microstrip laser is the p-cladding; because it is located directly above the heat sink, its contribution to the active region heating is minimal.

A calculation was done assuming heat generation in the active region only. While this sort of thermal model neglects the effect of ridge doping on thermal resistance, it is useful for isolating the effect of the gold bonded layer alone. A thermal resistance reduction of 10% is calculated for an InGaAsP narrow ridge microstrip laser (<10 μm wide). This calculation assumes a 1-μm gold layer on an InP substrate. The actual thermal resistance in the n-ridge microstrip laser is experimentally shown to be up to three times smaller than that of a conventional p-ridge laser because of the n-doped ridge, as was discussed above. It should also be emphasized that the microstrip laser process is compatible with submounts with higher thermal conductivities than InP: it is feasible to plate very thick gold or thick copper onto the epi and forgo the substrate altogether, or to bond to an aluminum nitride substrate. Our devices are mounted on InP to facilitate cleaving: an etched facet procedure would allow for different submounts and an even lower thermal resistance.

The structure shown in Fig. 1 is realized with a gold bonding and substrate removal process. The process begins with the evaporation of a 5000-Å gold layer onto epitaxial laser material grown on a semiconductor substrate. An identical evaporation is performed on a second InP substrate. The gold surfaces are bonded together under conditions of elevated temperature (~300 °C) and pressure, in a special bonding fixture or in a flip-chip bonder. The original InP substrate on which the laser material is grown is removed in a wet etch that terminates on an InGaAs stop etch layer. The structure in Fig. 1 is then fabricated with standard ridge laser processing techniques.

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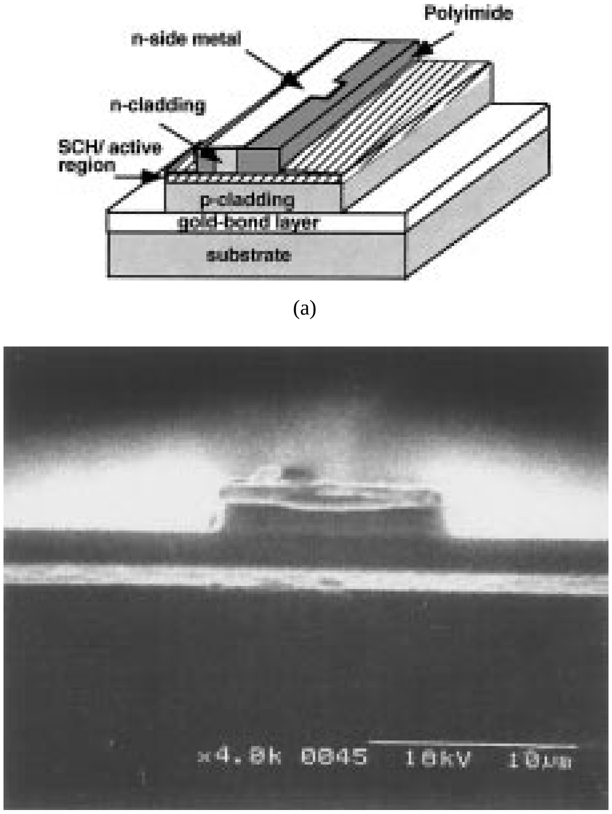

(a)

(b)

Fig. 1. (a) Schematic diagram of the microstrip laser. (b) Scanning electron microscope cross section of a 10-μm-wide ridge microstrip laser. The bright region below the ridge is the gold fused layer.

The improvement in microwave performance is predicted primarily on the basis of the improved microwave transmission line design of the microstrip laser. Semiconductor lasers on doped substrates have been shown to have extremely poor microwave propagation properties [2]–[4] that can limit the bandwidth. The microstrip laser minimizes this problem by incorporating a microstrip transmission line structure into the laser, thus, replacing the lossy doped substrate ground plane with highly conducting gold. An alternate way to solve this problem is to fabricate devices in a coplanar ground-signal-ground electrode geometry on semi-insulating substrates [5]. An advantage of the microstrip design compared to the coplanar electrode geometry is that high-frequency microwave circuits are often fabricated in microstrip, and thus, the microstrip laser is better for making high frequency transitions from the circuit to the laser.

III. RESULTS

In Fig. 2, the threshold current density versus cavity length characteristics of both 10-μm-wide microstrip lasers and 50-μm conventional broad-area lasers fabricated from the same base material are shown. The 10-μm ridge lasers have threshold current densities about 20%–30% higher than the broad-area lasers showing that there is not excessive degradation in material quality as a result of thermal stress from fusion. The increase may be largely due to excess optical scattering and lateral current spreading in the narrower ridge device, and not a result of material degradation at all.

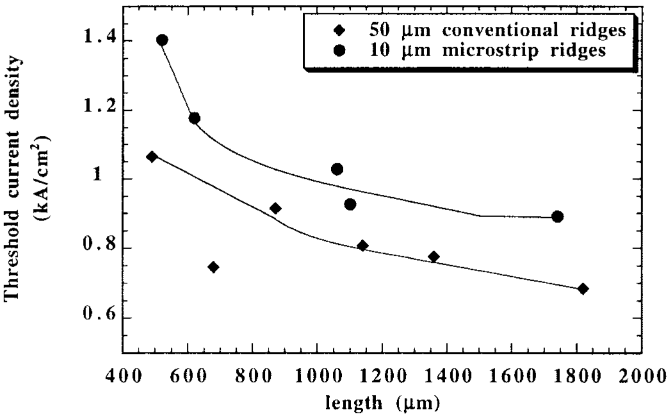

Fig. 2. Threshold current density versus device length for 10-μm-wide ridge microstrip lasers and 50-μm-wide conventional broad-area lasers.

Since a high-frequency laser requires a narrow ridge that tightly confines the optical mode, narrow ridge microstrip lasers were also fabricated. Continuous-wave (CW) light versus current (*L–I*) characteristics for 5-μm-wide microstrip lasers of varying lengths were measured for temperatures between 10 °C and 50 °C. The threshold current densities of the narrow ridge lasers were higher, by a factor of 6, than the broad-area lasers. Lateral spreading of the electron current in the separate-confinement-heterostructure (SCH) and active region of the narrow ridge devices is a primary cause of the higher thresholds, because the high electron mobility results in a leakage current spanning a width of about 10 μm. Spontaneous emission spanning this width has been observed in the near field of the laser mode, confirming this as the problem.

Etching through the SCH and the active region of the n-ridge devices eliminates the lateral leakage, and should result in lower thresholds. This solution is supported by simulations of devices with n-ridges etched in this way—the simulated thresholds of the etched n-ridge devices are comparable to simulated p-ridge device thresholds. Surface recombination velocities in the InGaAsP–InP system are low, on the order of 10^4 cm/s (compared to 10^5 cm/s in GaAs), and the calculations show that sidewall recombination does not offset the threshold reduction effected by the etch. Recent experiments show a two-fold increase (relative to broad-area lasers) in the threshold current density of 5-μm n-ridge microstrip lasers with etched SCH and active region. This is a significant improvement over the six-fold increase measured in the unetched case.

Despite the high thresholds in devices with an unetched SCH/active region, these lasers still operate CW, indicative of superior thermal performance. For example, at 50 °C for a 620-μm-long device, CW operation was achieved with a threshold near 300 mA. A conventional device will not lase at such a high threshold. The thermal resistance of the microstrip laser and the conventional p-ridge laser were measured at room temperature, and the results are shown in Table I, along with active region temperature rise and total heat dissipation. The thermal resistance of the microstrip laser

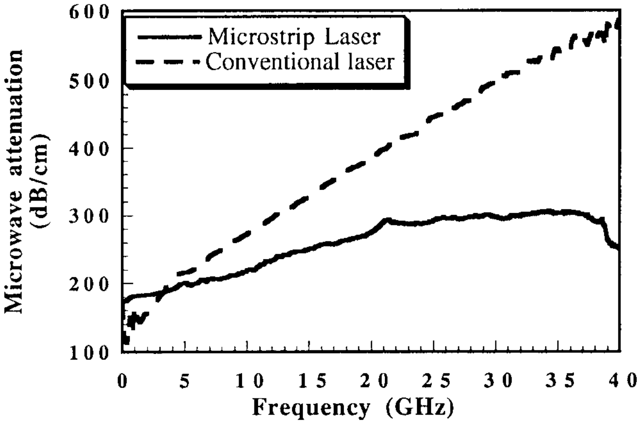

Fig. 3. Comparison of microwave attenuation versus frequency for a microstrip laser and a conventional laser. The attenuation is two times smaller in the microstrip laser.

TABLE I
THERMAL COMPARISON OF THE p-RIDGE CONVENTIONAL LASER AND THE n-RIDGE MICROSTRIP LASER

	Conventional p-ridge laser	Microstrip n-ridge laser
Heat dissipated at threshold	56 mW	221 mW
Temperature rise in active region	4.4 K	5.4 K
Thermal resistance	79 K/W	24 K/W

is much smaller, suggesting extremely high-power operation if the laser threshold were to be reduced. The data in Table I were obtained by measuring both the pulsed thresholds of the lasers at different mount temperatures, and then measuring the CW thresholds at room temperature (20 °C). Negligible heating was assumed in the pulsed case (300-ns pulses, 0.1% duty cycle). The active region temperature in the CW case was determined by mapping a CW threshold to a temperature on the pulsed threshold—temperature curve. The heat power generated at threshold is determined from the current versus voltage (I–V) product at threshold, with the spontaneous emission power subtracted out.

As described earlier, the reduction in thermal resistance results from the heat spreading properties of the gold layer and, even more significantly, from the fact that most of the heat power in this microstrip laser is generated in the lower (p) cladding where it does not significantly heat the active region. The n-ridge microstrip laser therefore provides a similar function as does p-side down mounting in a conventional laser, but the function is incorporated into the fabrication process rather than in a complicated postprocessing technique. The electrical resistance is also low, on the order of 2 Ω, which further contributes to minimal heating effects.

The ultimate bandwidth capability of the microstrip laser should be realized with a reduction of the laser thresholds. Measurements of the microwave attenuation characteristics of the microstrip laser and the conventional doped substrate laser were performed by doing a two-port calibrated network analyzer measurement on both devices, to 40 GHz. The loss in the microstrip laser is smaller by a factor of 2 as is shown in Fig. 3. As a result, the bandwidth limit caused by poor propagation will be at a much higher frequency than in a conventional laser. Lasers on semi-insulating substrates with coplanar electrode geometries are also an improved microwave structure as mentioned earlier; the bandwidth limit in those devices is 40 GHz or greater [5]. The microstrip laser should perform as well or better.

In conclusion, a novel device, the microstrip laser, has been presented and has demonstrated significant reductions in active region heating and in high-frequency microwave attenuation, two factors that are critical for allowing a high-speed laser to realize its full bandwidth capability. High thresholds in the narrow ridge devices have been found to be caused by lateral current spreading in the SCH and the active region. The problem can be solved by etching through the active region; once this is done, the capability of the microstrip laser should be realized.

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