Very Low Threshold AlGaAs/GaAs Lasers Grown on Tilted (100) GaAs Substrates by Molecular Beam Epitaxy

H.Z.Chen, H.Morkoç[a)], and A.Yariv

California Institute of Technology

Pasadena, CA 91125

The threshold current density of semiconductor lasers has seen a rapid and considerable reduction in recent years. The progress however, appeared to slow down giving rise to speculations that perhaps the fundamental limits were being approached. It is always however, very delicate to separate bottlenecks associated with the technology from the fundamental properties particularly during the development phase. In this paper, we show that threshold current densities as low as 80 A/cm^2 can be obtained in optimized graded refractive index AlGaAs/GaAs lasers with quantum well thicknesses of about 100 Å.

The structures were grown by molecular beam epitaxy (MBE) on straight (100) and tilted (100) by 4° towards the nearest (111A) substrates that were mounted side by side on the same substrate holder. A series of quantum well lasers were then grown either by varying quantum well size under the same growth conditions or varying growth conditions for a fixed quantum well size. A few of the details of the laser structures used are that the cladding layers are of 1.5 μm thick $Al_{0.5}Ga_{0.5}As$ and the 3500 Å waveguide is a parabolic index guide with the Al mole fraction dropping to 20%. The active layer, waveguide and cladding layers were all grown at 700°C under As stablized conditions.

The threshold current densities for straight and tilted (100) substrates associated with about 3mm long cavities are shown plotted against the quantum well thickness in Fig.1. As can be seen, the tilted substrates consistently led to lower threshold current densities even under the optimum growth conditions as is the case here. In the quantum well thickness range of about 60 to 160 Å, there is no noteworthy dependence of the threshold current density on the well thickness which represents a deviation from the previously observed behavior. The present data (details of which are tabulated in Table I) in fact can be explained by the competing effects of carrier confinement against the volume being pumped. When the quantum well thickness exceeds about 160 Å, the above balance is upset as the increased volume that must be inverted dominates and the threshold current density increases over 300 and 480 Å wells. This observation is true for lasers grown on-axis and off-axis substrates with the primary difference being that tilted ones lead to lower threshold current densities.

The wafer with the 125 Å quantum well was studied extensively in that short cavity lasers were also examined. A minimum threshold current density of 93 A/cm^2 for 520 μm cavity was obtained on the tilted substrate. This is by far the lowest ever achieved in any semiconductor laser. In addition, in the cavity length range of 500 - 3300 μm the the end losses are relatively small, there does not appear to be the well accepted strong dependence of threshold current density on the cavity length as shown in Fig.2. This is expected since the threshold current densities obtained are approaching the transparency. However, below 500 μm, the end losses become substantial and the threshold current increases as expected (not shown).

The effect of substrate tilting becomes very noticeable when growth conditions and the temperature other than the optima are used. For example, when the substrates were degassed at temperatures higher than those that provide As stablized surfaces before the growth, the resultant laser threshold current densities turned out to be 543 A/cm^2 and 203 A/cm^2 on straight (100) and (100) tilted by 4° towards (111)A substrates, respectively, for a quantum well thickness of 35 Å. Likewise, when the growth temperature of the layers including the waveguide and the quantum well is reduced to 680 and 660 °C, the threshold current densities on straight substrates drastically increased while those on tilted ones showed a much reduced degradation as shown in Table II. The quantum well thickness in this series was 125 Å.

The results discussed indicated laser properties that differ greatly from the previous ones in that, a) the threshold current is more or less independent of quantum well thickness in the range of about 60 to 150 Å, b) the threshold current is weakly dependent on cavity length between 500 and 3300 μm because the current densities are close to transparency. In addition, the use of tilted substrates widens the range of growth parameters within which good device results can be obtained. It is also clear that under optimum growth conditions, the tilted substrates lead to a noticeable inprovement in laser threshold current with best figures being 80 and 93 A/cm^2 for 3.3 mm and 520 μm long cavities, respectively.

This work is supported by the Office of Naval Research, the Air Force Office of Scientific Research and the National Science Foundation. The authors would like to

CH2515-5/87/0000-0887 $1.00 © 1987 IEEE

thank A.Ghaffari for the technical assistance. One of us, H.M. is also a distinguished visiting scientist at Caltech Jet Propulsion Laboratory and is supported partially by SDIO-IST.

a) On leave from Coordinated Science Laboratory, University of Illinois, 1101 W.Springfield Avenue, Urbana, Illinois 61801

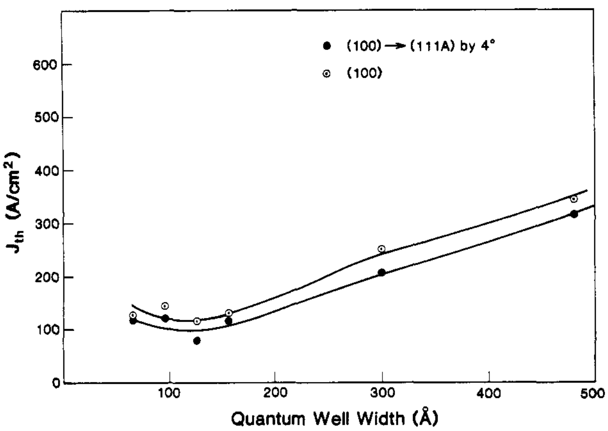

Fig.1. The threshold current density vs. the quantum well thickness in lasers grown on (100) and tilted substrates for cavity lengths of about 3mm.

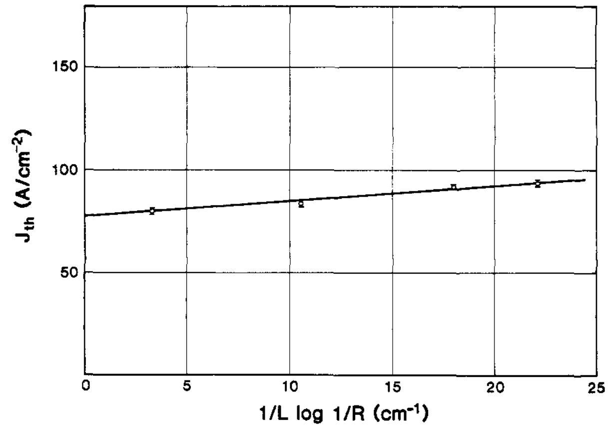

Fig.2. Threshold current density plotted against the (1/L)log(1/R) for lasers with a quantum well thickness of 125 Å on a tilted substrate.

Table I. Laser Characteristics vs. quantum well width grown at 700°C

Substrate	L_z	L	λ_{ave}	J_{th}
(100)	480 Å	3.15mm	8860 ± 17 Å	343 A/cm²
4° → (111)A	480 Å	3.01mm	8867 ± 22 Å	316 A/cm²
(100)	300 Å	3.28mm	8870 ± 25 Å	238 A/cm²
4° → (111)A	300 Å	3.14mm	8850 ± 18 Å	203 A/cm²
(100)	165 Å	3.20mm	8712 ± 26 Å	130 A/cm²
4° → (111)A	165 Å	3.29mm	8692 ± 31 Å	115 A/cm²
(100)	125 Å	3.26mm	8652 ± 26 Å	114 A/cm²
4° → (111)A	125 Å	3.30mm	8628 ± 17 Å	80 A/cm²
(100)	95 Å	3.18mm	8582 ± 19 Å	148 A/cm²
4° → (111)A	95 Å	3.09mm	8574 ± 23 Å	120 A/cm²
(100)	65 Å	3.19mm	8378 ± 20 Å	124 A/cm²
4° → (111)A	65 Å	3.24mm	8349 ± 18 Å	117 A/cm²

Table II. Laser Characteristics vs. Substrate Temperature During Growth and Outgassing conditions.

Substrate	T_{sub}	L_z	L	λ_{ave}	J_{th}
(100)	680°C	125 Å	3.08mm	8636 ± 7 Å	472 A/cm²
4° → (111)A	680°C	125 Å	3.06mm	8670 ± 20 Å	163 A/cm²
(100)	660°C	125 Å	3.14mm	——	not lasing
4° → (111)A	660°C	125 Å	3.16mm	8675 ± 21 Å	403 A/cm²
(100)*	700°C	35 Å	3.10mm	8017 ± 29 Å	548 A/cm²
4° → (111)A*	700°C	35 Å	3.17mm	8075 ± 31 Å	205 A/cm²

* the substrate was outgassed at an extremely high temperature.