Results and discussion: Fig. 2 shows the typical current/voltage (I/V) characteristics of a laser on Si substrate. Excellent p-n diode characteristics are retained after the high-temperature annealing at 700°C during bonding. Although the current passes through the n-InP/n-InP bonded interface, the same series resistance as that of lasers on InP substrates was obtained, which means no current barrier exists at the bonded interface. 

In applications such as optical interconnects and parallel data processing, extremely low threshold current and large bandwidth at low bias would be the key requirements for laser performance. Significant progress has been made during recent years, due to the development of strained quantum well laser structures and the advances in crystal growth technology [1-4]. In this Letter we report a systematic study into the threshold behaviour of single quantum well (SQW) laser with various cavity lengths and mirror reflectivities. Record low threshold currents were demonstrated for short cavity lasers.

The lasers used in this work were strained layer SQW InGaAs/AlGaAs buried heterostructure (BH) lasers fabricated by a two-step molecular beam epitaxy/liquid phase epitaxy hybrid growth technique [2]. To reduce the gain saturation effect and state filling effect [5], we used a relatively thick SQW (301-μm). The width of the active stripe of the BH laser was 1.5μm. The lasers displayed very low threshold current, 1mA at cavity lengths of 300-400μm. However, when the cavity length became shorter, the threshold current increased rather rapidly, reaching ~2mA at a cavity length of 200μm and >3mA at cavity lengths shorter than 100μm. This behaviour is well understood through a mechanism known as gain

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Parametric study of cavity length and mirror reflectivity in ultralow threshold quantum well InGaAs/AlGaAs lasers


Indexed terms: Semiconductor junction lasers, Semiconductor quantum wells, Laser cavity resonators

Record low CW threshold currents of 16μA at room temperature and 21μA at cryogenic temperature have been demonstrated in buried heterostructure strained layer, single quantum well InGaAs/AlGaAs lasers with a short cavity length and high reflectivity coatings.

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The threshold current can then be derived as \[ I_{th} = \frac{a}{1 + 2 \ln \left( \frac{R_i R_o}{J G_0} \right)} \] (1)

where \( J, G_0 \) are the saturation parameters, \( \alpha, \eta \) are internal loss and internal quantum efficiency, \( \Gamma \) is the optical confinement factor, \( R_i \) and \( R_o \) are front and rear facet mirror reflectivity, and \( W \) and \( L \) are active layer width and cavity length, respectively.

It is seen from [2] that for very long cavity lengths, the threshold current decreases when cavity length decreases. However, as \( L \) becomes very small, \( I_{th} \) increases again very rapidly with decreasing cavity length, following an exponential law. On the other hand, for a given \( L, I_{th} \) decreases monotonically with increasing \( R_i, R_o \).

Table 1: Threshold currents of SQW lasers with various cavity length and mirror reflectivities

<table>
<thead>
<tr>
<th>Laser ID</th>
<th>( L ) (( \mu \text{m} ))</th>
<th>( R_i R_o )</th>
<th>( I_{th} ) (mA)</th>
<th>Room T CW</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSQW 1</td>
<td>300</td>
<td>0.3/0.3</td>
<td>1.2</td>
<td>0.99, 0.99</td>
</tr>
<tr>
<td>SSQW 6</td>
<td>225</td>
<td>0.3/0.3</td>
<td>2.0</td>
<td>0.99, 0.99</td>
</tr>
<tr>
<td>SSQW 4</td>
<td>125</td>
<td>0.3/0.3</td>
<td>2.8</td>
<td>0.99/0.99</td>
</tr>
<tr>
<td>SSQE 2</td>
<td>90</td>
<td>0.3/0.3</td>
<td>3.0</td>
<td>0.99/0.99</td>
</tr>
</tbody>
</table>

In our experiments we cleaved lasers into different cavity lengths, then applied high reflectivity (HR) coatings to the laser facets and measured threshold current for each laser with different facet coatings. Typical measured threshold currents along with the estimated mirror reflectivities are summarised in Table 1. Experimental data are given in Fig. 1.

Because the thresholds of high reflectivity lasers are limited mostly by optical absorption in the semiconductor, we measured the threshold current of laser SSQW 4 at cryogenic temperature. The threshold current dropped continuously with decreasing temperature, reaching a value of 21\( \mu \text{A} \) at 6K. This is, to our knowledge, the lowest threshold current ever reported for any kind of semiconductor laser.

Some important issues related to very low threshold operation are discussed as follows: First, it is worth noting that at such a low current level, leakage currents which bypass the laser active layer either through the current blocking junction or through growth defects play a significant role in determining laser threshold current, therefore, they should be minimised. In our lasers, a narrow mesa \((\sim 10\mu \text{m} \text{ in width})\) was etched through the blocking layers and an SiO\(_2\) film was deposited on the whole wafer surface. Metal contact was accomplished through a 3µm opening on top of the mesa. This greatly reduced the leakage current. The very low threshold current at low temperature showed that the crystal imperfections and growth defects can contribute no more than 21\( \mu \text{A} \) to leakage current in our laser structure.

Secondly, the minimum threshold currents will only be realised (see eqn. 1) in lasers with large \( W \) and small \( \alpha \). Variations of these parameters always exist from laser to laser even on the same wafer. To demonstrate low threshold current, we should start with those as-cleaved lasers which display the highest external quantum efficiency.

In Fig. 1 it is evident from Fig. 1 that the threshold current for an as-cleaved laser \( (R_i = 0.3, R_o = 0.3) \) increases when cavity length decreases from 300 to 90\( \mu \text{m} \). However, when the same lasers are coated to a high reflectivity, the threshold currents of short cavity lasers drop much more than those of their long cavity counterparts. A record low CW threshold current 163\( \mu \text{A} \) has been measured at a cavity length of 125\( \mu \text{m} \) and mirror reflectivities of 0.99 (laser SSQW 4). Similar results were also obtained for a 90\( \mu \text{m} \) long laser \( (I_{th} = 175\mu \text{A}) \). The L-I curves for laser SSQW 4 are shown in Fig. 2a and b.

Figure 2 Light output characteristics of laser SSQW 4, \( L = 125\mu \text{m} \). 
Inset: (i) \( R_i = 0.3, R_o = 0.99, \eta_\text{th} = 0.5 \text{mW/mA} \)
(ii) \( R_i = 0.3, R_o = 0.3, \eta_\text{th} = 0.35 \text{mW/mA} \)

Figure 3 L-I curve of one low-threshold SQW laser, showing low-threshold and reasonable external quantum efficiency

\( R_i = 0.92, R_o = 0.99, I_{th} = 0.28 \mu \text{A} \)

Thirdly, a wavelength change of 580\( \AA \) was observed for laser SSQW4 after the laser facets were coated. In the as-cleaved condition, the short cavity laser operated in the second quantised energy state.
State [7]. The measured wavelength was 0.9463 μm. When the laser facets were coated to \( R = 0.99 \), the threshold dropped by \( \times 10 \). It operated in the first quantum state with a lasing wavelength of 1.90±0.02 μm. 

Fourthly, low threshold lasers can be tailored for different applications. The laser with 165 μA threshold current had very low external quantum efficiency of 0.003 mW/mA. This is due to the very high mirror reflectivities (estimated as higher than 0.99). For some applications more optical power and higher external quantum efficiency may be preferred. In these cases, the reflectivity of one mirror should be relaxed. Fig. 3 shows the L-I curve of another low threshold laser. The cavity length of the laser was 120 μm and the mirror reflectivities were \( R = 0.92, \); \( R = 0.99 \). The room temperature CW threshold current of the laser was 0.25 mA, but the external quantum efficiency increased to 0.3 mW/mA. An example of the high power operation of low threshold lasers is as follows: the cavity length of the laser was 200 μm, the rear facet mirror was coated to \( R = 0.99 \) (\( R = 0.3 \)). The CW threshold of the laser was 0.65 mA and the front facet external quantum efficiency was 0.66 mW/mA. More than 30 mW linear optical power was delivered from the uncoated front facet.

In conclusion, a room temperature CW threshold current of 165 μA and cryogenic temperature (6 K) threshold current of 21 μA have been demonstrated in a BH InGaAs/AlGaAs laser with 125 μm cavity length and \( \times 0.99 \) mirror reflectivities.

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Self-starting soliton modelocked Ti-sapphire laser using a thin semiconductor saturable absorber


Indexing terms: Solid lasers, Laser mode locking

Using a 15 nm-thick antireflection-coated GaAs absorber layer on an AlGaAs/AlAs Bragg mirror as a nonlinear reflector, we achieved self-starting passive modelocking of a Ti:sapphire laser with 346 pulses without Kerr lens modelocking.

The device (Fig. 1) incorporates a Bragg mirror with 25 pairs of AlAs/AlGaAs grown by metal-organic chemical vapour phase deposition (MOCVD) on a GaAs substrate giving a maximum reflectivity of 99.5% (Fig. 2). A 50 nm-thick AlAs spacer was grown by molecular beam epitaxy (MBE) on top of the mirror, which shifts the absorber layer into a maximum of the standing

Fig. 1 Structure of a nonlinear semiconductor saturable absorber Bragg reflector

Not to scale