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.

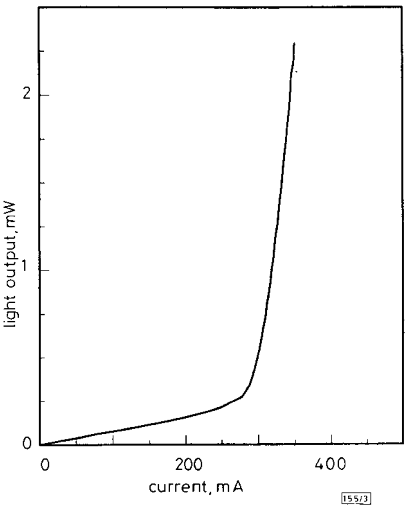

Fig. 3 *Typical I/V characteristics (30μm cavity length) of laser on Si under RT pulsed operation (300ns – 1kHz)*

RT, 300ns, 1kHz
J_{th} = 1.7kA/cm²

The lasers on both Si and InP substrates were tested under an RT pulsed condition (300ns – 1kHz). Fig. 3 shows the typical current/light (I/L) characteristics (330μm cavity length) of a laser on Si. The threshold current density is estimated to be as low as 1.7 kA/cm². Furthermore, dependence of the threshold current density (J_{th}) on the reciprocal of cavity length ($1/L$) was investigated and plotted in Fig. 4 for the lasers on Si and InP substrates. Although the data points are somewhat scattered, the lasers on both substrates have essentially similar dependence, demonstrating that the performance of the lasers on Si is comparable to that on InP. This result agrees well with the excellent EPD value, about 10^4cm^{-2}, which we previously reported [6].

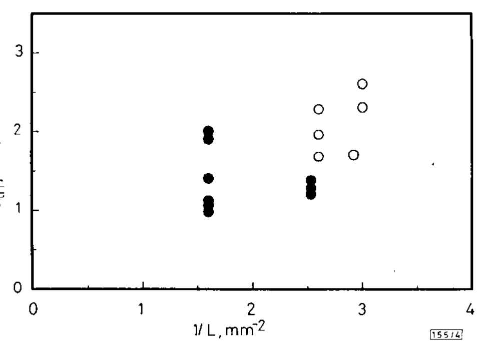

Fig. 4 *Dependence of threshold current density (J_{th}) on reciprocal of cavity length (1/L) for lasers on Si and InP substrates*

○ MQW LD on Si
● MQW LD on InP

Conclusions: The first low-threshold RT pulsed operation of long-wavelength InGaAs/InGaAsP MQW mesa-stripe lasers on Si substrates fabricated by direct bonding was demonstrated. Excellent *p-n* diode characteristics were retained after the high-temperature bonding process, and there was no current barrier at the *n*-InP/*n*-InP bonded interface. The mesa-stripe broad-area lasers had a threshold current density of 1.7kA/cm², which was comparable to the value for lasers on InP substrates.

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

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Indexing 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.

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 (80Å). 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 for cavity lengths shorter than 100μm. This behaviour is well understood through a mechanism known as gain saturation. The gain of a quantum well laser medium can be closely approximated by a logarithmic function

$$G = G_o \left(\ln \frac{J}{J_o} + 1 \right) \qquad (1)$$

The threshold current can then be derived as [6]

$$I_{th} = \frac{WL}{\eta_i} J_o \exp \left\{ \frac{1}{\Gamma G_o} \left(\alpha_i + \frac{1}{2L} \ln \frac{1}{R_f R_r} \right) - 1 \right\} \qquad (2)$$

where J_0, G_0 are the saturation parameters, α_i, η_i are internal loss and internal quantum efficiency, Γ is the optical confinement factor, R_f and R_r 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_f, R_r.

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

Laser ID	L	R_f/R_r	I_{th} Room T CW
	μm		mA
SSQW 1	300	0.3/0.3	1.2
		0.3/0.98	0.68
		0.75/0.99	0.44
SSQW 6	225	0.3/0.3	2.0
		0.3/0.98	0.8
		0.98/0.99	0.37
SSQW 4	125	0.3/0.3	2.8
		0.3/0.99	0.7
		0.99/0.99	0.165
SSQE 2	90	0.3/0.3	3.0
		0.3/0.99	1.4
		0.99/0.99	0.175

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.

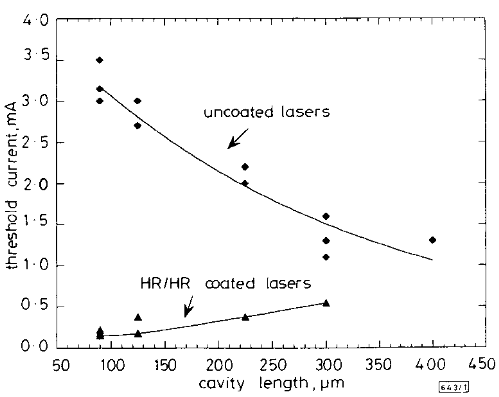

Fig. 1 *Threshold current change of SQW lasers with different cavity lengths after HR coating*

It is evident from Fig. 1 that the threshold current for an as-cleaved laser ($R_f \simeq 0.3$, $R_r \simeq 0.3$) increases when cavity length decreases from 300 to 90μm. 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 165μA has been measured at a cavity length of 125μm and mirror reflectivities of ~0.99 (laser SSQW 4). Similar results were also obtained for a 90μm long laser ($I_{th} \simeq 175$μm). The L-I curves for laser SSQW 4 are shown in Fig. 2*a* and *b*.

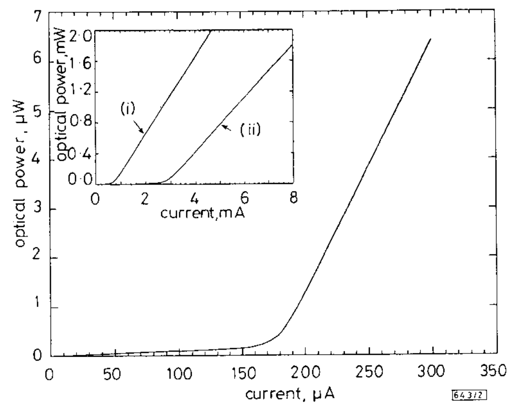

Fig. 2 *Light against current characteristic of laser SSQW 4, L = 125μm*

$R_f \simeq 0.99$, $R_r \simeq 0.99$
Inset: (i) $R_f \simeq 0.3$, $R_r \simeq 0.99$, $\eta_D = 0.5$mW/mA
(ii) $R_f \simeq 0.3$, $R_r \simeq 0.3$, $\eta_D = 0.35$mW/mA

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 21μA 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 (~10μm 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 21μA to leakage current in our laser structure.

Secondly, the minimum threshold currents will only be realised (see eqn. 2) in lasers with large η_i and small α_i. 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.

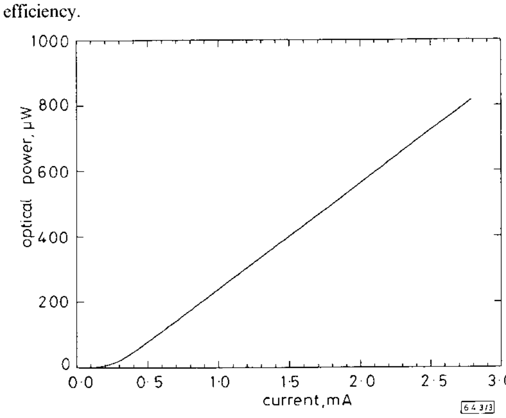

Fig. 3 *L-I curve of one low-threshold SQW laser, showing low-threshold and reasonable external quantum efficiency*

$R_f \simeq 0.92$, $R_r \simeq 0.99$, $I_{th} = 0.28$mA

Thirdly, a wavelength change of ~500Å was observed for laser SSW4 after the laser facets were coated. In the as-cleaved condition, the short cavity laser operated in the second quantised energy state [7]. The measured wavelength was 0.9463 μm. When the laser facets were coated to $R \simeq 0.99$, the threshold dropped by ×10. It operated in the first quantised state with a lasing wavelength of 1.0102μm.

Fourthly, low threshold lasers can be tailored for different applications. The laser with 165μA threshold current had very low external quantum efficiency of 0.005mW/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_f = 0.92, R_r = 0.99. The room temperature CW threshold current of the laser was 0.28mA, but the external quantum efficiency increased to 0.3mW/mA. An example of the high power operation of low threshold lasers is as follows: the cavity length of the laser was 200μm, the rear facet mirror was coated to R_r = 0.99 ($R_f \simeq 0.3$). The CW threshold of the laser was 0.65mA and the front facet external quantum efficiency was 0.66mW/mA. More than 30mW linear optical power was delivered from the uncoated front facet.

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

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

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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 34fs pulses without Kerr lens modelocking.

The discovery of Kerr lens modelocking (KLM) [1] has stimulated intensive research in the area of passively modelocked solid-state lasers over the past several years. Currently, the shortest pulses obtained directly from a laser (8.5fs) have been achieved with a KLM Ti-sapphire laser [2]. KLM, however, is generally not self-starting because it scales with peak intensities. Most KLM experiments therefore rely on an active starting mechanism such as a shaking mirror or a regenerative active modelocker. Self-starting KLM pulses with durations longer than 50fs have been obtained from specially designed cavities very close to the limit of the stability regime [3, 4], and therefore with very critical alignment tolerances. In contrast, it has been demonstrated that a slow saturable absorber could be used as a starting mechanism [5].

Semiconductor saturable absorbers seem very promising because they are compact, inexpensive, and cover a wide wavelength range from the visible to the infra-red. In general, however, they introduce too much loss, saturate too easily, and have too low a damage threshold. All these issues can be solved by use of the antiresonant Fabry-Perot saturable absorber (A-FPSA), which sandwiches the absorber between two Bragg mirrors, forming a Fabry-Perot cavity with an antiresonance at the wavelength of interest [6, 7]. This antiresonant design decreases the losses introduced in the cavity and increases the saturation intensity and the damage threshold. The saturable absorber parameters of an A-FPSA can be fully designed to give optimum modelocking performance [8]. The design parameters of the A-FPSA are absorber bandgap, thickness of absorber, carrier lifetime and the top reflector. Many different solid-state lasers have been successfully modelocked using an A-FPSA.

Given our understanding of the A-FPSA's parameters, we can scale the device to thinner saturable absorber layers, which in turn requires a decrease in the top reflector to couple more light into the device and maintain the same saturation behaviour. In this work, we take this scaling to the limit where we have a very thin saturable absorber and an antireflection coating on the top (instead of a high-reflector) to fully couple the laser light into the device. Our modelling has shown we could fabricate this device with bleached losses of ~5%, which is acceptable for typical Ti:sapphire lasers. To prevent significant CW saturation the laser spot size on the absorber has to be increased compared to an A-FPSA design. We used a thin (15nm) GaAs saturable absorber layer on an AlGaAs/AlAs Bragg mirror as a nonlinear reflector (Fig. 1) in an argon-ion pumped Ti:sapphire laser, achieving self-starting 34 fs pulses in a regime where KLM is insignificant or even counteracts pulse formation. The pulse generation is based on soliton modelocking [9].

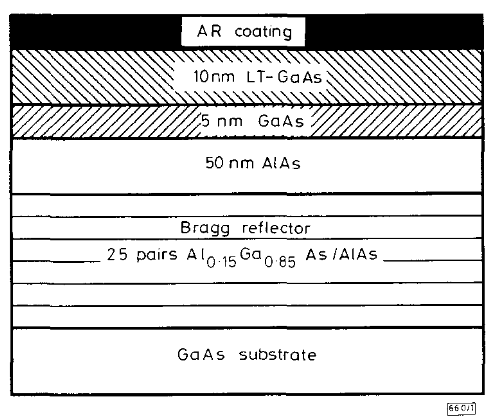

Fig. 1 *Structure of a nonlinear semiconductor saturable absorber Bragg reflector*

Not to scale

The device (Fig. 1) incorporates a Bragg mirror with 25 pairs of AlAs/$Al_{0.15}Ga_{0.85}As$ grown by metal-organic chemical vapour phase deposition (MOCVD) on a GaAs substrate giving a maximum reflectivity of 99.5% (Fig. 2). A 50nm-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