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First demonstration of a 1.52 μm RT InAs/InP(3 1 1)B laser with an active zone based on a single QD layer

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Abstract
This paper presents experimental results obtained on a laser structure containing a single QD layer, epitaxially grown on InP(3 1 1)B substrate. The sample shows laser emission on the ground state in the 1.55 μm telecommunication window at room temperature. Its threshold current density is 320 A cm^{-2}, which is relatively low for an InP-based QD laser. Its modal gain, attributed to a high QD density and low QD size dispersion, explains this first achievement of lasing with a single QD layer on an InP substrate.

(Some figures in this article are in colour only in the electronic version)

Much research is devoted to the realization of optical semiconductor devices. Quantum well (QW) lasers are nowadays state-of-the-art systems, and commercially available [1]. Many studies are now dedicated to devices with quantum dots (QDs) as an active medium [2]. QDs are structures where the confinement theoretically takes place in the three dimensions of space, which should lead to very attractive properties, such as low threshold current [3], very high differential gain [4] and low temperature sensitivity [5]. The superiority of properly optimized QD lasers as compared to QW lasers has already been experimentally demonstrated in the InAs/GaAs system [6]. However, while laser emissions from 1 μm to 1.3 μm were successfully performed with QDs on this type of substrate, it remains difficult to extend operation out to the long-haul telecommunication band at 1.55 μm. Recent results report lasing at 1.45 μm for InAs QDs layers on GaAs substrate, but 1.55 μm is still out of reach [7, 8]. Instead of GaAs, an alternative consists in using InP substrate which allows emission at 1.55 μm with QDs [9]. Furthermore, devices grown on (3 1 1)B oriented InP substrates, and even more those grown under optimized growth conditions [10], and with the 'double cap' procedure [11], are promising. This substrate orientation allows the growth of real QDs, and with a very high density. Previous works have already demonstrated state-of-the-art performances for a QD laser on InP at room temperature [12]. This paper presents experimental results obtained on a structure with a single QD layer. For the first time, to the best of our knowledge, lasing at room temperature (RT) is obtained with a relatively low threshold current density for QD structures on InP, and at 1.52 μm, which proves the good quality of the epitaxied nanostructure material. This result also shows that a single QD plane has a modal gain sufficient for compensating high InP intrinsic losses, allowing lasing. Although these performances must be improved, they open the way to the future realization of a 1.55 μm single mode laser on an InP substrate with a reduced number of QD stacks.

The structure was grown by gas source molecular beam epitaxy (MBE) on an n-type (3 1 1)B oriented InP substrate. Figure 1(*a*) shows the laser structure, which consists of a waveguide of 160 nm of lattice-matched quaternary alloy $Ga_{0.2}In_{0.8}As_{0.43}P_{0.57}$ with gap emission wavelength at 1.18 μm (so-called $Q_{1.18}$) on both sides of the active area. This active area is composed of only one layer of InAs QDs, self-assembled through the Stranski–Krastanov mode. Two growth optimizations, described below, have been performed on this sample: a reduction of the arsenic flux during the growth [11] and the double cap procedure [12]. The reduction of the arsenic flux during the growth allows reaching a high QD density. From atomic force microscopy (AFM) measurements

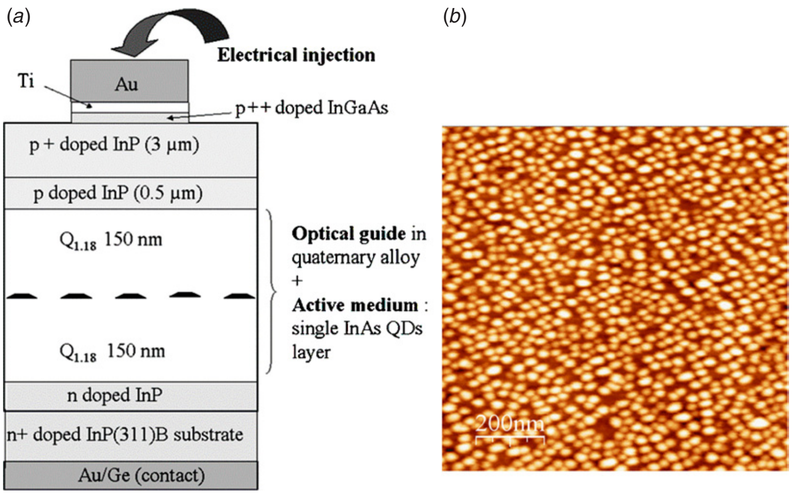

Figure 1. (*a*) Schematic drawing of the InAs/InP laser structure containing a single InAs QD layer. (*b*) AFM image of an uncapped QD layer: an average diameter of 30 nm could be deduced, along with an average height of 3 nm. The QD density was evaluated to be above 10^{11} cm^{-2}.

on uncapped reference samples (cf figure 1(*b*)), a QD density of more than 10^{11} cm^{-2} was actually estimated. Such a QD density can lead to an enhanced total gain of the structure, as well as to an efficient lateral coupling between the dots, which has been shown to improve the laser efficiency for a well-selected coupling regime [13]. The double cap procedure consists in growing the capping layer of the QDs already formed in two steps. The first capping layer, with a fixed thickness, is used to control the QD height. This layer is followed by a growth interruption under element V flux, which planarize the surface thanks to As/P exchanges. The second capping layer is then added to complete the optical confinement layer. The maximum height of the QDs is therefore controlled by the height of the first capping layer, thus allowing a reduction of the QD size dispersion. A sharper gain curve can consequently be expected for the structure, which greatly helps the losses compensation. Furthermore, the emission energy of the laser, strongly linked to the QD size, can be controlled by this technique. The wavelength can thus be tuned towards the aimed 1.55 μm telecommunication wavelength. An optimized average height of 3 nm, corresponding to the height of the first cap, and an average diameter of 30 nm were deduced from AFM measurements. This high aspect ratio is usual for QDs on an InP(3 1 1)B substrate. The 'dot' nature of the nanostructures was first confirmed by TEM measurements [14]. The carrier confinement was then studied by magneto-photoluminescence in our QDs, depending on the composition of the first capping layer, either $Q_{1,18}$ or InP [15]. It was demonstrated that the use of $Q_{1.18}$ provides better carrier confinement than InP by preventing the intermixing effect observed in InAs/GaAs QDs [16]. Cross-sectional scanning tunnelling microscopy (X-STM) measurements have confirmed the homogeneity in the composition of the InAs QDs [17].

Photoluminescence (PL) measurements were performed on this device at RT under continuous 647 nm wavelength laser excitation. Figure 2 shows a PL peak at 0.82 eV (1.52 μm), with a full width at half maximum (FWHM) of 50 meV (91 nm). This linewidth is larger than those usually observed

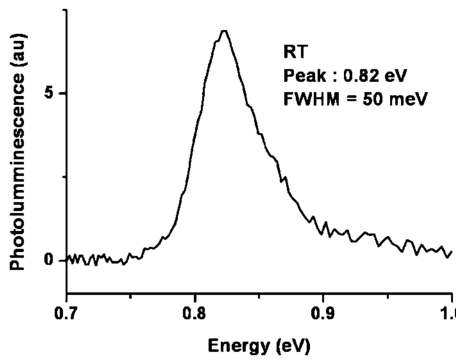

Figure 2. Photoluminescence spectrum of the epitaxied structure. The graph shows a peak at 0.82 eV (corresponding to a 1.52 μm wavelength), and a FWHM of 50 meV (91 nm). This low FWHM can be explained by the reduced QD size dispersion due to optimized growth techniques.

on GaAs substrates, where the lattice mismatch between QD and substrate material is more favourable to the QD growth. This 50 meV linewidth is, however, comparable with the best values obtained on InP substrates [9] for QDs as an active medium, and reveals a limited QD size dispersion. Furthermore, it is important to stress that the growth of only a QD layer prevents the increase of QD size usually observed when multi-stacking is employed, which may lead to a degradation of the QD size uniformity. A low linewidth, which means a sharper gain curve, is actually a critical parameter in view of achieving maximum possible gain.

Laser structures were processed on these structures. Conventional edge-emitting lasers of three different lengths—2, 3 and 4.4 mm—and with 100 μm wide ridge structures were obtained by wet chemical etching. The cavities have cleaved-facets on both extremities, which means an approximate reflectivity of 30% on both sides. Electroluminescence (EL) spectra at RT were obtained under pulsed electrical injection (1 μs pulse width, 0.2% duty cycle) on these three devices. Spectra for the 4.4 mm cavity length device are given in figure 3(*a*) for different injection levels. They show a threshold

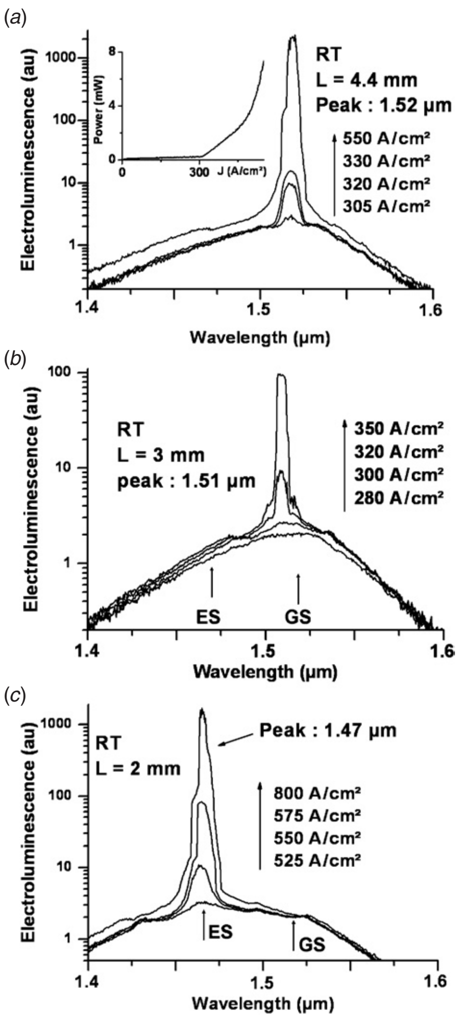

Figure 3. Electroluminescence spectra obtained at room temperature, for (*a*) the 4.4 mm, (*b*) the 3 mm and (*c*) the 2 mm cavity length devices. In the inset in figure 3(*a*) is given the light–current curve for the longer device.

current density of 320 A cm^{-2} at RT, which is quite low for a structure containing only a single QD layer on an InP substrate. Laser emission is obtained on the ground state (GS) at 1.52 μm, which is in agreement with the maximum of the PL spectrum. Let us note that without the use of the double-cap procedure no lasing could be obtained at RT for the same single stack structure [18].

The inset in figure 3(*a*) gives the light current curve for this device. This curve presents a particular shape. Above 450 A cm^{-2}, the slope of the linear part leads to a maximum external efficiency of 4.5%. This value which remains low and far from those obtained on multi-stacked structures, and especially in the GaAs system [6], or on conventional QW lasers can be explained by a non-optimum carrier capture by a single QD plane. Values taken from the literature for internal losses on InP are typically in the range of 7–11 cm^{-1} [19–21]. The internal efficiency is thus evaluated to 22%. But before reaching this linear regime, from 320 to 450 A cm^{-2}, a smooth gradual increase of the output power slope is observed. This behaviour can be explained qualitatively with the following hypothesis. At threshold, not all the QDs are filled, and no coupling is observed between them through the wetting layer. But when the current is increased, more and more QDs are filled, and the favourable coupling regime is reached, leading to a better efficiency of the whole structure as described in [13]. Other effects, such as changes in the spatial mode profile, could certainly add to this coupling effect, and influence output properties, but this has not been investigated.

The lasing wavelength starts decreasing from 1.52 μm for the 4.4 mm long device to 1.51 μm for the 3 mm long device (figure 3(*b*)), with a threshold current density of 320 A cm^{-2}. The 2 mm long device exhibits a laser emission at 1.47 μm (figure 3(*c*)), and with a higher threshold current density of about 550 A cm^{-2}. This behaviour corresponds to a progressive shift from the GS to the first excited state (ES). Spectra for this short device show a highly dissymmetric spontaneous emission spectrum, characteristic of an emission not obtained on the GS transition.

This effect can be explained because structures grown on InP show a great overlap between GS and ES gain curves [13], as observed by high power photoluminescence experiments. Indeed GS and ES are actually separated by only an average of 25 meV, and their FWHM is larger than 25 meV. Consequently, when losses increase, the first ES level starts to be filled before the GS level is totally saturated. This leads, by carrier redistribution explained in [22], to the progressive change of the lasing wavelength from 1.52 μm towards 1.47 μm, which corresponds to the expected energy difference between GS and ES, of about 25 meV [23]. In the case of InAs/GaAs QDs, where there is no overlap between GS and ES, the lasing wavelength switches abruptly from GS to ES [24].

The maximum modal gain of the GS transition is difficult to evaluate. The lasing wavelength stays stable for cavities longer than 4.4 mm, and it has already started decreasing for a cavity of 3 mm. The point where the ground state is fully saturated cannot be evaluated precisely, but it seems to happen for a cavity shorter than 4.4 mm. Mirror losses, given by the expression $\alpha_m = -\ln(R)/L$, where R is the facet reflectivity (0.3) and L the Fabry–Perot cavity length, can be evaluated for cavities shorter than 4.4 mm above 3 cm^{-1}. As said previously, internal losses (α_i) are taken to a 10 cm^{-1} value. The modal gain, given by $g = \alpha_i + \alpha_m$, of the GS transition can therefore be estimated to a minimum value of 13 cm^{-1} for a single QD plane. This value is, to our knowledge, the largest reported on structures containing QDs on InP substrate, and allows hopes for multi-layers devices, as directly modulated devices or amplifiers.

In summary, a broad area laser device with only a single stack of QDs, grown on InP(3 1 1)B substrate, demonstrates laser emission at RT on GS transition for a relatively low 320 A cm^{-2} threshold current density. This achievement of GS lasing at RT, close to 1.55 μm wavelength, for a single QD layer structure is, to our knowledge, the first reported on QD structures grown on InP, and can be explained through the optimization of QD growth techniques. A 13 cm^{-1} gain for this only QD plane could be deduced, which is the best value reported for InAs/InP QD structures. This original result, proving that high gain can be achieved on these structures, open the way to further improvements of QD laser performances at 1.55 μm on an InP substrate.

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