Temperature dependence of electrical and optical characteristics of InAsP laser diode

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Abstract. In this article, we report experimental investigations on the current-voltage (I-V) and the current-power (I-P) characteristics of 3mm cavity length InAsP/GaAs QD laser diode emitting at 773nm over a wide temperature range of 150-400 K. The results of the (I-V-T) measurements showed a decrease in the turn-on-voltage of the sample by (-3.52 mV/K) as well as a decrease in the dynamic resistance by (-4.9 mΩ/K). Conversely, the (I-P-T) measurements strongly exhibited the temperature dependence of the threshold current density above 300 K, whilst the characteristic temperature (T₀) of the laser diode was calculated to be between 250 - 370 K as (T₀ = 70.4 K). Moreover, the external deferential quantum efficiency (η_d^ext) decreases by (-0.14% /K) from 190 to 300 K. The increases in η_d^ext of above 300 K, was observed. This opens the door for further investigations in this material such as carrier distribution and gain measurements.

1. Introduction
Quantum dot (QD) laser diode exhibited many applications in optoelectronic devices due to several advantages, such as low threshold current [1], temperature insensitive operation [2], high efficiency [3], as well as low chirp and high differential gain [4]. Ideally, the threshold current density of the QD laser diode should remain unaffected with temperature and the characteristic temperature (T₀) being extremely high. In this case, the overall injection current must go entirely into the radiative recombination in the QDs. However, due to the presence of free carriers in the optical confinement layer (OCL), a part of the injection current is lost here [5]. Hence, the device became temperature dependent. Therefore, measuring current-voltage-optical-power (I-V-P) characteristics as a function of temperature is important. For example, the current-voltage (I-V) characteristics offer to calculate the turn-on voltage, dynamic resistant and even the energy gap of the material. Current-power (I-P) characteristics conversely, allow the threshold current density, slope efficiency, deferential quantum efficiency and characteristic temperature of the device to be determined. The characteristic temperature (T₀) of the laser diode can be found by means of the relation [6]:

\[ J_{th} = J_0 e^{\frac{T}{T_0}} \]

(J_th) is threshold current density and (J_0) here is a constant. In addition, the external deferential quantum efficiency of the laser diode can be calculated from the equation [7]:

\[ \eta_d^{ext} = \frac{1}{2 \cdot \pi \cdot f \cdot \lambda} \]

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\[ \eta_{\text{ext}}^{\text{ef}} = \frac{d\eta}{dI} \left( \frac{q}{h\nu} \right) \]

\( q \) is electron charge, \( h \) Planck constant, \( \nu \) frequency and \( (d\eta/dI) \) is the gradient of the \((P-I)\). InAsP quantum dot laser diode was documented in [8, 9], as a high quality optical device. However, the operation of the device at a different temperature has not been investigated inclusively yet. Here, we investigate the current-voltage-optical power (I-V-P) characteristics of the 3mm cavity length InAsP quantum dot laser diode in the temperature range (150-400 K) and study the temperature behaviour of the important optical and electrical parameters of this device.

2. Sample structure experimental details

The active region of the samples consists of 5InAsP QD layers in wells. The sample was processed into a 50µm wide oxide strip with a 3mm cavity, as illustrated in Fig. 1a. Fig. 1b shows a cross section transmission electron microscopy (TEM) image that confirmed 5 layers of InAsP QD. For further details concerning growth condition and sample structure see [10].

To measure (I-V-P) at different temperatures, a computer controlled setup improved in Cardiff University was used (see Fig. 2). The 3mm laser diode chip was fixed inside the high vacuum chamber with a neutral density filter window to collect the output light by the integrated sphere. The laser was run in pulse condition with 0.1% of duty cycle pulse to prevent self-heating effects. The low temperature was created using liquid nitrogen, which cools the finger connected to the device. To create elevated temperatures a resistive heater was used.

Fig. 1 – (a) InAsP QD laser, (b) TEM images of InAsP QD active region.

Fig. 2 – Block diagram of the (I-V-P-T) Kit.
3. Result and discussion

The electrical and optical properties at room temperature is the starting point of the characterisation of the semiconductor lasers. Fig. 3 shows the (I-P) and (I-V) curves of the 3mm cavity length InAsP QD laser measured at room temperature (RT). The most important factors of the laser device can be extracted from Fig. 3 such as threshold current (Ith) which is the intercept of the linear part of the I-P curve with the x-axis, as shown in Fig. 3 which is observed at approximately 360 mA. Slope efficiency, which is the slope of the I-P curve above the threshold (dP/dI), is found at roughly 0.4 W/A. Moreover, from the I-V curve, the turn-on-voltage is determined as 1.57 Volts which is the intercept of the linear part of the I-V curve with the x-axis and the dynamic resistant (dV/dI) of the laser diode calculated here as 4 Ω, which is the slope inverse of the I-V curve above the turn-on-voltage. Therefore, it is beneficial to study all these parameters as a function of temperature.

![Graph showing I-V and I-P curves at RT for 3mm long laser diode under pulse mode operation.](image)

**Fig. 3** – Right y-axis, (I-P) curve, Lift y-axis, (I-V) curve at RT for 3mm long laser diode under pulse mode operation.

Fig. 4 depicts the (I-V) curves of the 3mm cavity length InAsP QD laser diode measured for a wide range of temperatures; specifically, (150-400 K) with increasing steps of 10 K. It shows smooth curves for the entire range of temperatures without any sign of cut off which indicates a high quality electrical connection. Furthermore, when the temperature increases the curves move toward low voltage.
Fig. 4 – Forward bias voltage versus current at various temperatures for the 3mm long laser diode under pulse mode operation.

Fig. 5 conversely is the plot of the turn-on-voltage and dynamic resistance as a function of temperature. The turn-on-voltage decreases by -3.52 mV/K when the temperature increases. This is expected from Varshni’s equation [11], where the main energy gap decreases with temperature. The behaviour of the dynamic resistance can be classified into two parts. From 150 to 300 K there is a rapid decrease, whereas from 300 to 400 K (above room temperature) the dynamic resistance is virtually the same. Hence, the overall factor of resistant which decreases with temperature is -4.9 mΩ/K.

Fig. 5 – Turn-on-voltage and the dynamic resistance for 3mm long laser.
Fig. 6 depicts the (I-P) curves of the 3mm cavity length InAsP QD laser measured for a wide range of temperatures; specifically, (150-360 K) with increasing steps of 10 K. It is apparent that the threshold current increases with temperature especially above 300 K (room temperature). The nearfield profile and the emission spectrum of the InAsP laser diode were also studied as illustrated in Fig. 7. The centre of the lasing spectrum is found at approximately 773nm. Moreover, the full width at half maximum (FWHM) of the nearfield profile is calculated from Fig. 7 as approximately 55µm. This value (55µm) is considered precise as the width of active region of the device when converting the threshold current to threshold current density

![Graph of Fig. 6](image1)

**Fig. 6** – Output optical power versus current at various temperatures for 3mm long laser under pulse mode operation.

![Graph of Fig. 7](image2)

**Fig. 7** – The nearfield profile of 3mm long laser under pulse mode operation inset shows the emission spectrum.
In contrast, the nearfield profile of the laser shows a high symmetric when fitted to the Gaussian function as illustrated in Fig. 7. This confirms that the current on the laser diode is driven homogenously and the laser diode has a high beam quality. The temperature dependence of the threshold current density ($J_{th}$) is depicted in Fig. 8. $J_{th}$ exhibits a slight temperature dependence between 150-250 K. At this temperature range the characteristic temperature ($T_0$) of the device is extremely high. However, from 250-270 K the $J_{th}$ of the laser diode increases dramatically with temperature. For example, the $J_{th}$ of the laser diode is roughly 190 A.cm$^{-2}$ whereas at 270 K it jumps to virtually 600 A.cm$^{-2}$. The same behaviour was found in [12, 13]. It was confirmed that this is due to increases in both thermal carrier spreading and nonradioactive recombination currents to maintain gain requirement at an elevated temperature. The $\ln(J_{th})$ versus the temperature in the 250-270 K range is also plotted in Fig. 8 according to Equation 1, which is noted to be approximately 70.4 K. The deferential quantum efficiency $\eta_{d}^{ext}$ of the InAsP laser diode calculated from Equation 2 is plotted as a function of temperature in Fig. 9. The laser diode exhibits good deferential quantum efficiency, for instance at 300 K the $\eta_{d}^{ext}$ is 26%. Furthermore, the average value of $\eta_{d}^{ext}$ was found in [14] for the 1mm InAsP QD as 28%. However, Fig. 9 shows a fluctuation in the value of $\eta_{d}^{ext}$. The linear decreases of the deferential quantum efficiency can be marked from 190 to 300 K and the decrease in value is 0.0014 K$^{-1}$. This decrease of $\eta_{d}^{ext}$ is consistent with the increase of $J_{th}$ found in Fig. 8. Nevertheless, the most interesting behaviour is the noticeable increase of $\eta_{d}^{ext}$ from 300 to 340 K, where it becomes a maximum value of approximately 42% at 340 K. This point could be clarified further through studying the gain and spontaneous emission spectra in this range of temperature [15]. Moreover, investigating the pinning of the quasi Fermi-level separation in this laser at these temperatures and current conditions also can help to explain this behaviour [16]. Furthermore, carriers distribution in this laser can assist with uncovering this behaviour where the non-thermal and random distribution of the carriers can change the available states of the QD structure [17, 18].

Finally, it should be mentioned that the $\eta_{d}^{ext}$ in this study were calculated for a short slope efficiency (dp/dI) just a low pumped level above the threshold current density, as shown in Fig. 6, (due to the limitation in the I-V-P-T kit). Additionally, it is expected that if the device is pumped to the high current level the overall slope efficiency (dp/dI) changes and the behaviour in Fig. 9 could be display a different form.
Fig. 9 – The deferential quantum efficiency $\eta_{d\text{ext}}$ of the InAsP laser diode as a function of temperature.

4. Conclusion
In summary, we examined the electrical and optical characteristics of 3mm cavity length InAsP quantum dot laser diode uncoated facets emitting at 773nm over a wide temperature range of 150-400K. The results showed a decrease in the turn-on-voltage of the sample by (-3.52 mVolt/K) as well as a decrease in the dynamic resistance by (-4.9 mΩ/K). Moreover, the laser diode strongly exhibited the temperature dependence of the threshold current density above 300K and the characteristic temperature ($T_0$) calculated between 300-370 K as 70.4 K, while a decrease in external deferential quantum efficiency $\eta_{d\text{ext}}$ by (-0.14% /K) between 190–300 K was observed. The increases in $\eta_{d\text{ext}}$ above room temperature was observed. Therefore, this encourages further studies on InAsP QD material with regard to optical gain and occupational probability. Finally, the 773 nm InAsP quantum dot laser diode showed high temperature operation and high beam quality making it a promising candidate in bio-photonic and monolithic integrated applications.

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