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Effect of Temperature on the Electrical Parameters of Indium Phosphide/Aluminum Gallium Indium Phosphide (InP/AlGaInP) Quantum Dot Laser Diode with Different Cavity Lengths

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Abstract

The current-voltage (I–V) characteristics of indium phosphide/aluminum gallium indium phosphide (InP/AlGaInP) quantum dot laser diodes with different cavity lengths were measured at different temperatures (77–400 K). From the forward bias I–V characteristics, the laser diode electrical parameters such as the ideality factor (*n*), the reverse saturation current (J_s), and series resistance (R_s) were extracted. The values of the ideality factor depend slightly on the temperature in the temperature range above 150 K while it increases as the temperature decreases below this value. It is noticed that the increase of *n* for a longer cavity is greater. This may be attributed to the freeze out of the mobile charge carriers in the n and p emitters of the diode. Conversely, J_s increase with the temperature. It follows almost an exponential increase with temperature probably because of the thermal generation of electron-hole pairs across the energy gap of the material. R_s behaves in a similar way where it is almost constant at T > 150 K. It appreciably increases with further lowering of the temperature with the shortest cavity having the greatest increase. *R*s decreases as the cavity length increases. This may again be attributed to the freeze-out or the mobile charge carriers in the end emitter regions of the device. To our best knowledge, such results are reported for the first time for these diodes.

Keywords: InP/AlGaInP quantum dot laser diodes; Activation energy; Series resistance; Ideality factor; Cavity length.
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1. Introduction

Self-organized quantum dot (QD) laser diode systems have increased interest in laser diodes and their applications, which were suggested by Sakaki *et al*. in 1982.[1] The separate energy states improve the optoelectronic properties of the laser diode. This technique is essential and has contributed to the development of many applications, such as communications,[2] frequency comb generation,[3] optoelectronic oscillators for millimeter-wave generation[4], and photodynamic therapies for cancer treatment.[5] In general, high-stability signal carriers require high-performance uncooled diode lasers. Hence, studying the effect of temperature characteristics on the electrical properties of the diode lasers operating in the 725-740 nm spectral domains will help identify the variables that restrict QD laser's ability to optimize threshold currents[6] and high-speed characteristics.[7]

In recent years, there have been intensive experimental studies of I-V characteristics for extracting and studying the electrical parameters of the diode, including the series resistance R_s, ideality factor *n*, and the reverse saturation current J_s of laser diodes.[8-10] In the laser diode techniques, the use of an indium phosphide (InP) QD grown on GaAs as a substrate and aluminum gallium indium phosphide (AlGaInP) as a barrier can realize high-temperature lasing operation. Thus, understanding the recombination mechanisms in an InP QD at a high temperature is important.

In a recent study, the fabrication of InP QD on AlGaInP as a barrier has been extensively studied. The development of QD lasers has been tried utilizing self-assembled and selective-area techniques with promising results in terms of the performance of laser diodes being achieved.[11] Among these techniques, the I–V characteristics of InAs/InP QD laser

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diodes have been thoroughly explored in a few studies,[12] but there are not enough studies on the I–V characteristics of InP/AlGaInP QD laser diodes. These characteristics are significant and may be used to predict the junction temperature, the conduction mechanism, and the band gap of the InP/AlGaInP QD laser diode. In this work, the InP/AlGaInP QD laser diodes are manufactured by the metal-organic vapor phase epitaxy (MOVPE) technique at 730 °C as a layer growth temperature. To examine the effect of the cavity length on the diode properties, the diodes are fabricated with different cavity lengths and constant wide oxide-isolated stripes. Our study is devoted to exploring the temperature dependence of the I–V characteristics of our laser diode at a wide temperature range from 77 to 400 K. We extract the electrical diode parameters such as R_S, n, and J_s from the I–V characteristics as a function of temperature. These parameters are essential to model the laser diode as a circuit element at different temperatures in electronic circuit simulators. Knowing these diode parameters, one can solve for its driver circuits at different operating temperatures. In addition, one can then predict the effective conduction mechanism in the diode and estimate the energy gap of the radiative layers.

2. Materials and methods

The structure of the InP/AlGaInP QD oxide stripe laser grown on GaAs is shown in Fig. 1. Five layers of the diode were grown on GaAs substrate using the metal-organic vapor phase epitaxy (MOVPE) technique. The epitaxial layers were grown at a temperature of 730 °C. After finishing the epitaxial growth, the chips were cooled to a specific temperature at a rate of 0.3 °C/min. The layer stack of the final device as seen in Fig. 1 is as follows: an N-type $Ga_{0.51}In_{0.49}P$ as the bottom intermediate layer of ~10 nm thickness, an N-type$Al_{0.51}In_{0.49}P$ layer as a bottom cladding layer of ~1000 nm thickness and an N-type $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ and a bottom barrier layer of ~100 nm thickness. Five layers from a combined InP QD of ~0.75 nm thickness and $Ga_{0.51}In_{0.49}P$ quantum well (QW) of ~8 nm thickness acted as the active laser layer so that every combined layer from InP QD and $Ga_{0.51}In_{0.49}P$ QWs was sandwiched between two $(Al_{0.3}Ga_{0.7})_{0.51}In_{0.49}P$ of ~16 nm thickness as the barrier layers. A P-type $Al_{0.51}In_{0.49}P$ layer was added as the top cladding layer of ~1000 nm thickness, with P-type $Ga_{0.51}In_{0.49}P$ as a top intermediate layer of ~10 nm thickness. Finally, a 300 nm cap layer of P-type GaAs was deposited as the topmost layer. The detailed layer structure is given in the reference.[13]

According to Fig. 2, all the layer structures were processed into 50 μm wide oxide stripes in laser devices. The cavity lengths in the oxide stripe of these devices were adjusted at 1000, 2000, 3000, and 4000 μm, respectively. Finally, the devices of the InP/AlGaInP QD laser diode were mounted under the microscope by using a TO-5 transistor header to be measured in the I–V measuring setup.

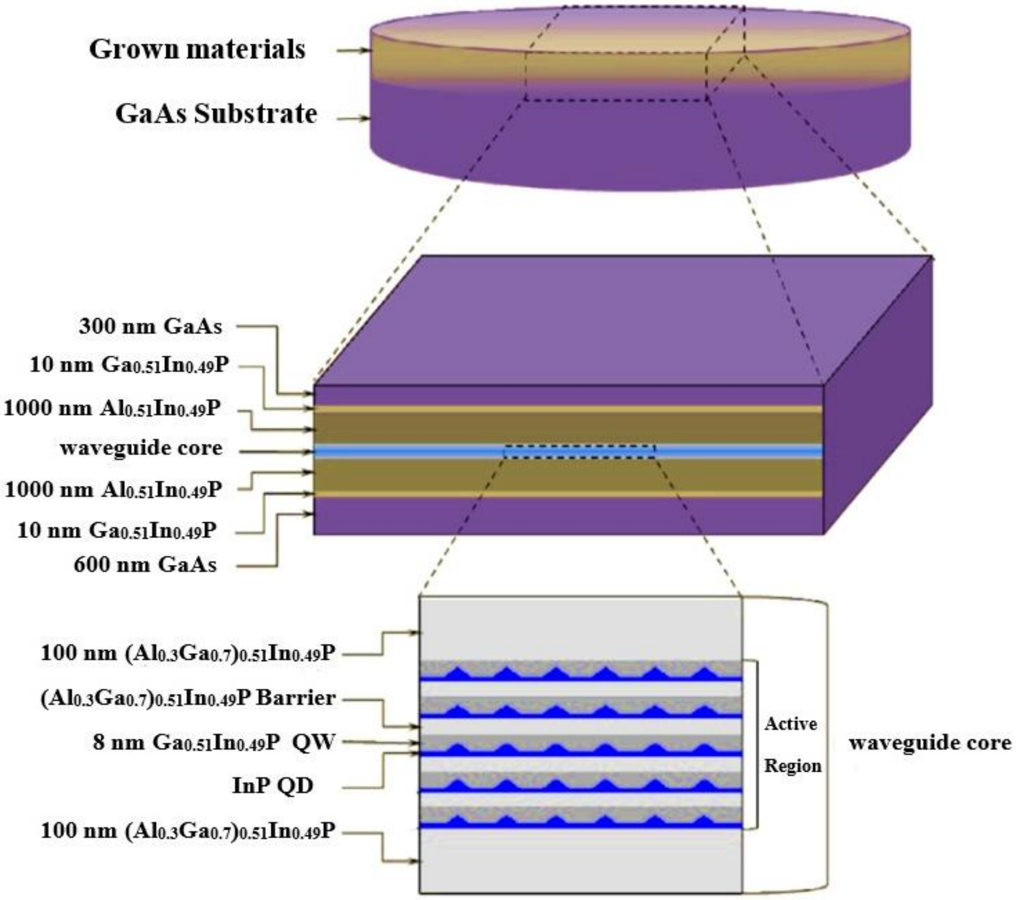

Fig. 1 Oxide-stripe laser with five layers from InP/AlGaInP QD in the active region.

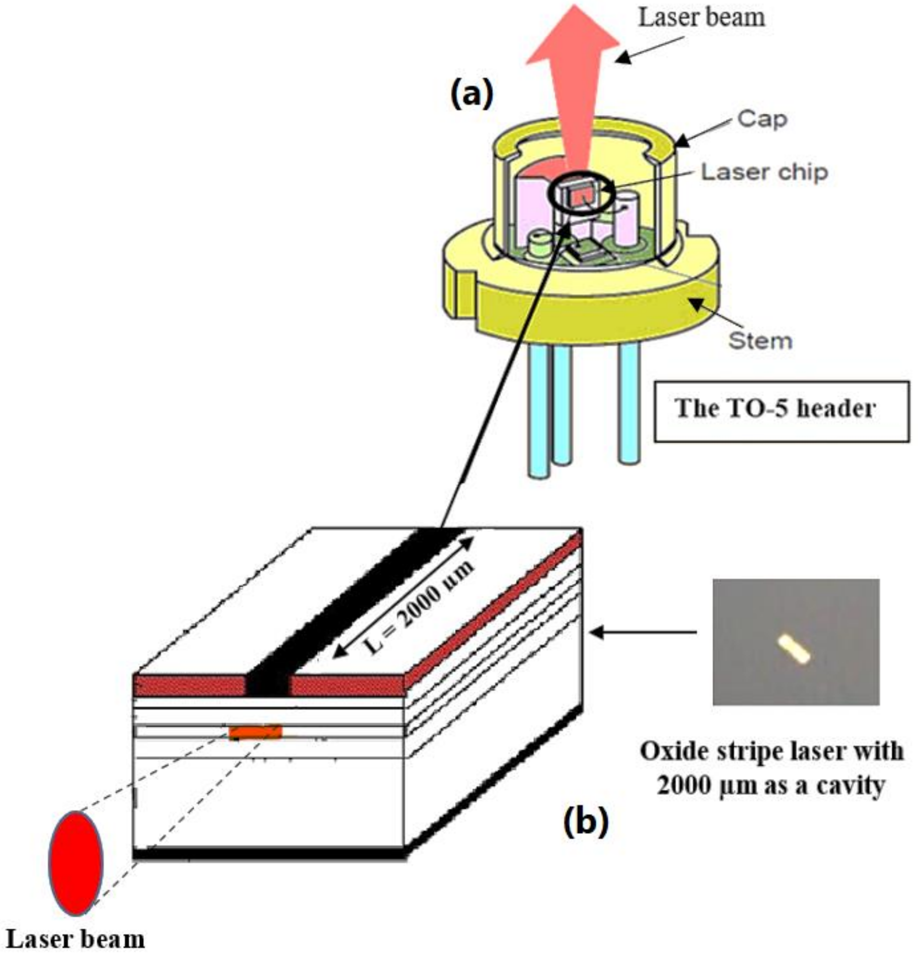

Fig. 2 Schematic diagram of (a) InP/AlGaInP QD laser diode device (b) the oxide stripe laser with 2000 μm cavity length.

In Fig. 3, thecurrent–voltage characteristics measurement of the InP/AlGaInP QD laser diodes was performed inside an evacuated OXFORD cryostat in the temperature range from 77-400 K by using the temperature controller to exchange the temperature. The device was connected to Keithley 6220 Source/Measure unit for direct current (DC) measurement via the equipped suitable coaxial cable. The current source provided currently to the laser device such that its voltage changed from –2 to 3 V to acquire the I–V characteristic of the laser diode in the forward and reverse bias. Measurement was automated with a personal computer. The relationship between current and voltage with increasing temperature was measured after 30 minutes between each temperature and another in the range of 77–400 K with 25 K as a temperature difference.

3. Results and discussion

3.1 Analysis of current-voltage (I–V) characteristics

The measured I–V characteristics of our InP/AlGaInP QD laser diodes with a cavity length of 1000 μm at different temperatures from 77 to 400 K are shown in Fig. 4, where the applied voltage on the diode was scanned in the range from –2 to 3 V. The temperature increment is 25 K.

One sees that the I–V curves of the InP/AlGaInP QD laser diode with a 1000 μm cavity length are similar to those of a positive-intrinsic-negative (PIN) laser diode. As the temperature is lowered, the forward I–V curves shift to the right, meaning that the forward voltage drops increase at the same diode current. In the reverse bias, the reverse current decreases as the temperature are lowered. Specifically, the turn-on voltage of the diode decreases from 2.7 V at 77 K, to only 1.3 V at 400 K. Accordingly, these diodes have ordinary behavior as PIN diodes.

In the next sections, we will turn our attention to the extraction of the electrical parameters of the diode at different temperatures. These parameters are the ideality factor n, the reverse saturation current $J_{s,}$ and the series resistance R_s. These three parameters are sufficient to reproduce the measured I–V curves according to the theory of the solid-state diodes including the laser diodes. By extracting these parameters, one may have a complete description of the diode through them where one can recalculate the diode curves at any temperature point. One can also use these parameters in the circuit simulator to solve the electronic circuits containing these laser diodes, as well as to compare the laser diodes and sort them. The final use of these parameters as a function of temperature is that one can extract some internal physical parameters of the diode such as the dominant conduction mechanism and the energy gap.

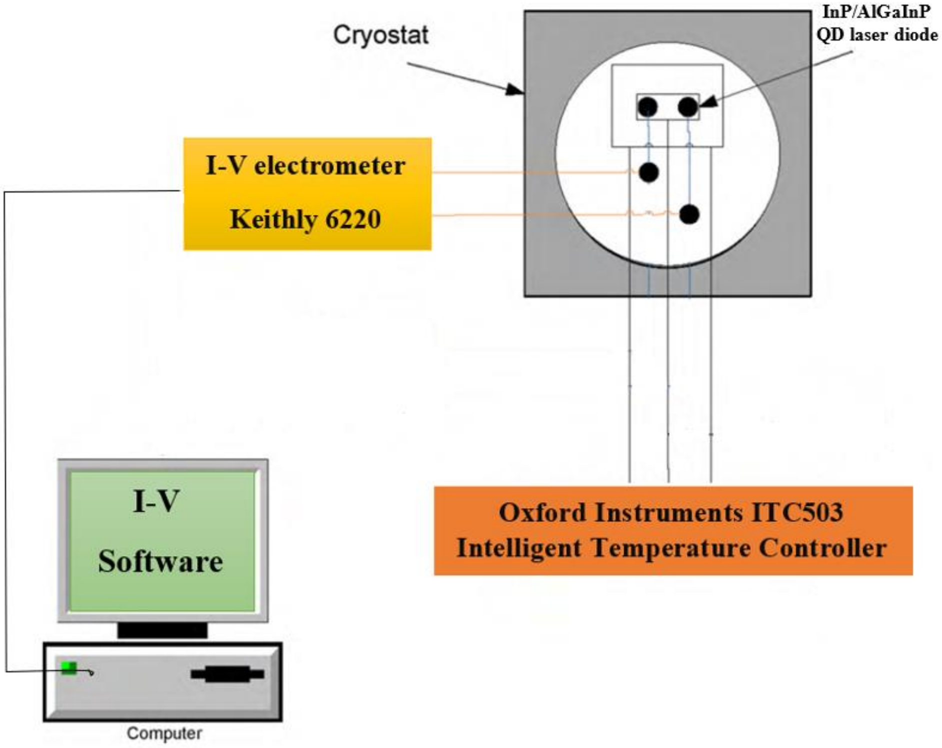

Fig. 3 Schematic diagram of I–V characteristics measurement.

3.2 The ideality factor (*n*)

The I–V characteristics of the InP/AlGaInP QD laser diode can also be described by the conventional Shockley diode equation[12]:

$$I = I_s \exp[(\frac{qV-IR_S}{nkT}) - 1] \quad (1)$$

where I am the diode current, I_S is the reverse bias saturation current, k is the Boltzmann constant, q is the electron charge and R_s is the series resistance and n is the ideality factor. Assuming that we located the portion of the I–V curve where the IRs drop can be neglected compared to the applied diode voltage such that V >> IR_s, then the above equation will be reduced to:

$$I = I_s \exp\left(\frac{q(V)}{nkT}\right) \quad (2)$$

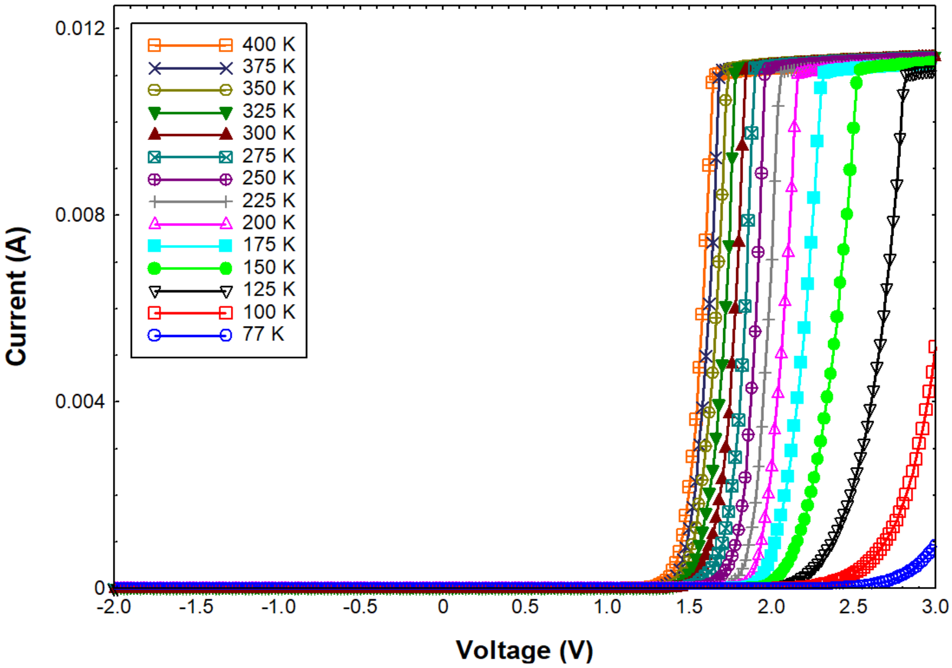

Fig. 4 The I–V characteristic of InP/AlGaInP QD laser diodes with a cavity length of 1000 μm at different temperatures from 77 to 400 K.

Taking the *ln* of both sides gives:

$$Ln(I) = Ln(I_s) + \left(\frac{q}{nkT}\right) V \tag{3}$$

According to this equation in the range of the I–V characteristics where V >> IR_s, the semilogarithmic plot of the I–V characteristics will result in a straight line whose slope $d(\ln I)/dV$ is equal to q/nkT and its zero-voltage intercept is equal to Ln (I_s). Accordingly, the ideality factor can be calculated using the formula:

$$n = \frac{q}{kT}\left(\frac{dV}{d(lnI)}\right) \tag{4}$$

One can extrapolate this straight line to the zero voltage where the extrapolated line intercepts the LnI axis in Ln I_s from which one can calculate the value of I_s:

$$\text{Ln}\, I = \text{Ln}\, I_s \quad \text{at V} = 0 \tag{5}$$

The extraction of diode parameters is given in detail in the reference.[14] The semilog plot of the measured I–V characteristics of the diode at different temperatures is depicted in Fig. 5. One sees that in every curve there is a straight-line portion in the intermediate current range from which one can determine n and I_s.

Accordingly, the values of the slopes of LnI versus V curves are calculated from the linear part of the forward-biased semi-logarithmic I–V characteristic at the middle current range where equation (3) is valid.

The extracted values of the ideality factor at different temperatures for the InP/AlGaInP QD laser diodes with different cavity lengths are plotted in Fig. 6. It is clear that the values of n increase at lower temperatures. As the temperature decreases from 175 K to 77 K, n increases from 2.9 to 4.38 in devices with 1000 μm cavity lengths, 2.9 to 11.72 in devices with 2000 μm cavity lengths, 2.9 to 19.2 in devices with 3000 μm cavity lengths and 2.9 to 26.5 in devices with 4000 μm cavity lengths according to Table 1.

When the temperature increases from 200 to 400 K, n remains almost constant at around 3. If the diode works as a pin diode, n will be equal to 2 at high injection. But as n is found to be around 3, meaning that the recombination at the heterojunctions and the emitters contribute an appreciable part in the diode current.[15] Irrespective of the conduction mechanisms in the laser diodes, their I–V characteristics are phenomenologically fitted by a Shockley-type equation. Irrespective of the quantum wells and QDs which trap the injected carriers from the emitters of the end regions of the structure, the laser diode still has a form of a pin diode whose I–V characteristics will be limited by the injection of electrons and holes from the end emitter regions and their subsequent recombination in the active region. If the interface recombination is negligible then the recombination inside the bulk of the active region will dominate the conduction process of the diode. In addition, if the junction interface to the active region is symmetrical then the ideality factor of the diode will be about 2. This is well known from the theory of the pin diode.[16] If the ideality factor is different from 2, then it may be that the ideality factor becomes greater than 2.[17] In fact, for specifying the conduction mechanism one has to make more investigations which is beyond the scope of this work.

The difference in the ideality factor at low temperatures may be partly due to measurement errors. There is a need for a rigorous conduction theory to interpret all these results. Table 1 shows the values of n at 77, 175, and 300 K, respectively.

Table 1. The values of the ideality factor of different cavity lengths at 77, 175, and 300 K, respectively.

Cavity length (μm)	Ideality factor (n) at 300 K	Ideality factor (n) at 175 K	Ideality factor (n) at 77 K
1000	3.17069	2.9	4.38
2000	3.18639	2.9	11.72
3000	3.18639	2.9	19.05
4000	3.17852	2.9	26.5

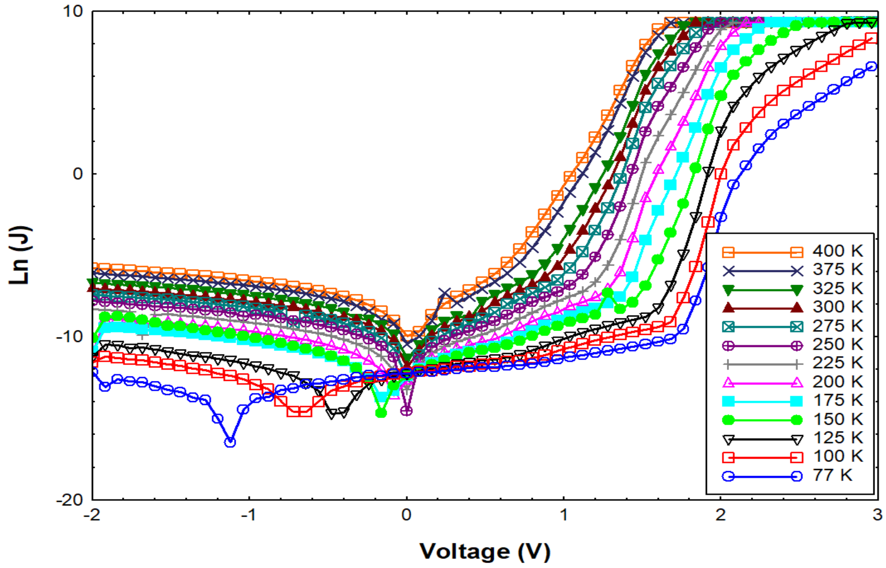

Fig. 5 Semilogarithmic plot of measured I–V curves at different temperatures T from 77–400 K for the diode with a cavity length of 1000 μm.

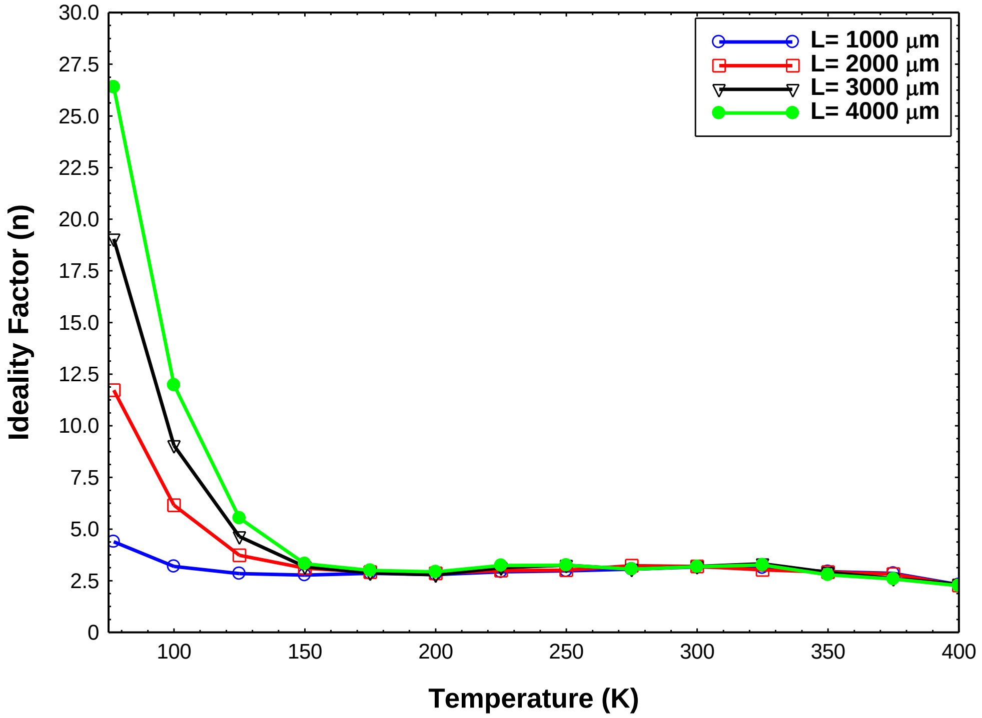

Fig. 6 The extracted ideality factor (n) versus temperature for InP/AlGaInP QD laser diode with different cavity lengths.

3.3 The reverse saturation current density (J_s)

The extracted reverse saturation current density J_s according to equation (5) is plotted in Fig. 7 as a function of temperature at different cavity lengths. Specifically, the plot is ln J_s versus 1000/T at different cavity lengths L. As for the reverse saturation current it is caused by the thermal generation process of electrons and holes in the middle region, either from the valence band or from the occupied traps. Hence it is always a thermally activated process. Our formulation here seeks only phenomenological activation energy without specifying the source of the generation. As the diode is a pin diode then it is most probable that the activation energy approaches the minimum energy gap in the middle region which is the QDs.

As the reverse saturation current results from the thermal generation of electron-hole pairs which is a thermally activated process then one can assume that:

$$J_S = J_{S00} \exp\left(\frac{-E_a}{V_t}\right) \tag{6}$$

where J_{s00} is the reverse saturation current pre-exponential factor which is independent of temperature, E_a is the activation energy in electron volt and V_t = kT/q is the thermal voltage.

Taking the ln of both sides then one gets after some rearrangements:

$$Ln\, J_s = Ln\, J_{S00} - \left(\frac{qE_a}{1000\, k}\right)\left(\frac{1000}{T}\right) \tag{7}$$

The straight-line equation will have the slope = (qE_a/1000 k), which results finally in an activation energy E_a of J_s as:

$$E_a = slope \left(\frac{1000\, k}{q}\right) \tag{8}$$

The quantities q, k, and T have their usual meaning.

From the slopes, we calculated the activation energies given in Table 2 at different cavity lengths L. The values of the activation energy are almost equal pointing out the same thermal activation processes and the same conduction mechanisms of the diode current. These values most probably are related to the energy gap of materials of the QDs since it is expected that the reverse saturation current is proportional to the intrinsic concentration n_i when adopting the pin diode model. One can see from the table that the activation energy approaches half the energy gap of the QD. More investigations are required to confirm this adopted pin model.

Table 2. The values of the activation energy and energy gap of InP/AlGaInP QD laser diodes with various cavity lengths.

Cavity length (μm)	Slope	The activation energy (eV)	The energy gap of the QDs (eV)[18]
1000	6.8	0.587	1.35
2000	6.766	0.584	1.35
3000	6.657	0.575	1.35
4000	6.587	0.569	1.35

3.4 The series resistance (R_s)

To extract the series resistance R_s, let us refer to equation (1) of the diode and differentiate it concerning the voltage of diode V. After performing the differentiation and reduction one can get the following formula to extract the series resistance from the linear plot of the I–V curves such that:

$$R_s = \left(\frac{dV}{dI}\right) - \left(\frac{nV_t}{I}\right) \tag{9}$$

where dV/dI is the inverse slope of the I–V curve and Vt is the thermal voltage (kT/q).

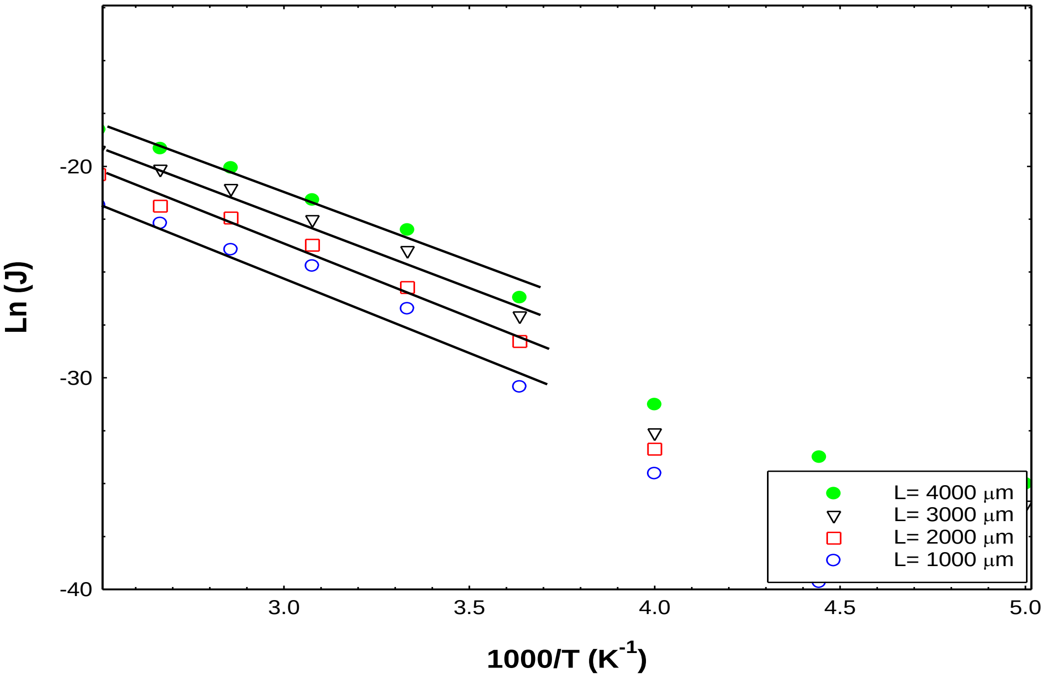

Fig. 7 Semilogarithmic plot of Ln (*J*) versus 1000/T.

To get R_s, one has to know the value of n and calculate Vt in addition to calculating the slope at a specific value of the diode voltage. One can also choose the range of the I–V curve where R_s >> (nVt/I).

It is clear from the equation that the most suitable points are those having the highest value of the diode current. Then R_s = ~ 1/slope of the I–V curve in the highest current range. After estimating R_s in this way, one has to check the validity of the approximation by calculating (nVt/I) and this is what we did.

The calculated values of series resistance at different temperatures from 77–400 K are shown in Fig. 8. It is clear from the figure that as the temperature is decreased from the room temperature the resistance decreases slightly and then increases appreciably again at the low-temperature range. This behavior is typical behavior of the series resistance as it sums up the ohmic resistance of the neutral regions of the semiconductor layer. Then when the temperature is decreased from the room temperature the mobility increases and then at the low-temperature range freeze out of the mobile charge

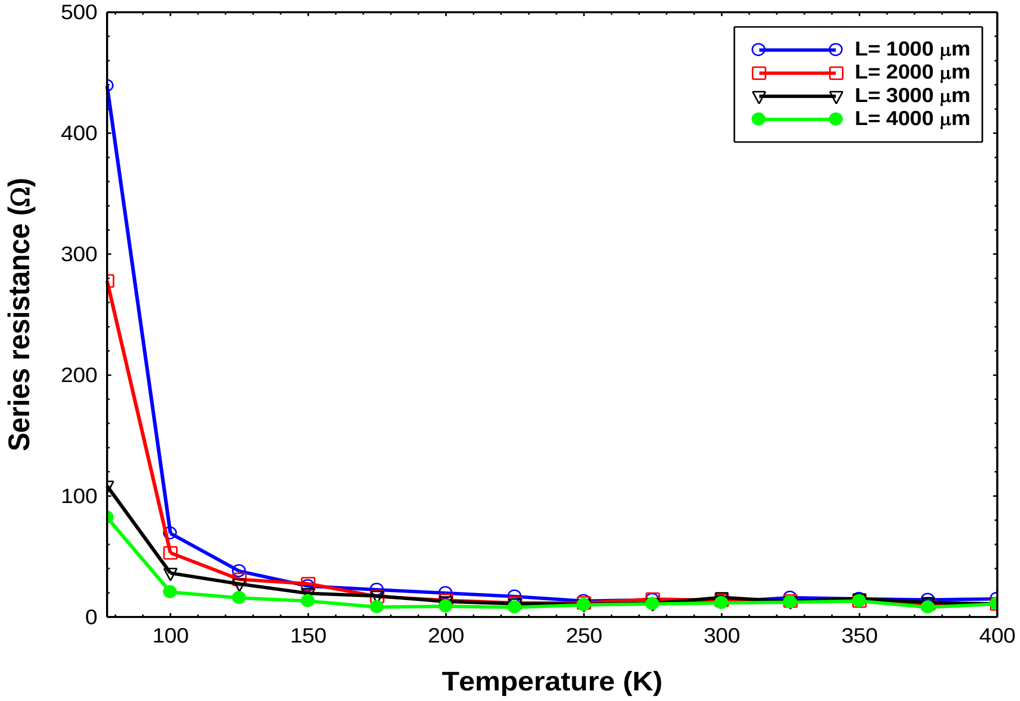

Fig. 8 The series resistance versus temperature T for InP/AlGaInP QD laser diode with different cavity lengths.

carriers occur at their doping atoms' parents. The activation energy of the freeze-out is the ionization energy of the doping atoms. The cavity length increments decrease the series resistance of the diode because it increases the cross-sectional area of the current conducting region. These results presented in this current work have not been found in the literature.

4. Conclusion

InP/AlGaInP QD laser diodes were prepared with the MOVPE technique at 730 °C with a cooling rate of 0.3 °C/min. Four InP/AlGaInP QD laser diodes were manufactured with different cavity lengths. The forward I–V curves of the InP/AlGaInP QD laser diodes were measured at temperatures ranging from 77 to 400 K. Then, the electrical parameters of the diodes were extracted from the measured I–V curves resulting in determining the dependence of these parameters on the temperatures and the cavity length. The behavior of n, J_s, and R_s with temperature and cavity length was interpreted and explained in light of the conduction theory of laser diodes and their dependence on the physical and technological parameters of the diode. To our best knowledge, such results are reported for the first time for these diodes. They help find the dominant conduction mechanism and apply the laser diodes in optical communication systems to use such model parameters in designing appropriate electronic drivers. For a more precise interpretation of these results, one must perform more theoretical analysis.

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Conflict of interest

There are no conflicts to declare.

Supporting information

Not applicable.

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