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Investigation of Carrier Conduction Mechanism over InAs/InP Quantum Dashes and InAs/GaAs Quantum Dots Based p-i-n Laser Heterostructures

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Abstract

Charge transfer characteristics of the long wavelength semiconductor laser structures, containing quantum dot layers (QDs), were investigated by means of temperature dependent current-voltage and electroluminescence measurements over InAs/InP, and InAs/GaAs based p-i-n structures. In InAs/InP elongated QDs (QDashes) structure, injected carriers were tunneled from the quantum well into QDashes through a thin barrier and subsequently recombined within QDashes. Meanwhile, for InAs/GaAs structure, tunneling kind transport was exhibited in both forward and reverse bias voltage directions. The onset of light took place when the forward bias exceeded 1.3 V (3 V) for InAs/InP (InAs/GaAs) p-i-n structure through electroluminescence measurements. The peak value of emitted laser light for InAs/InP QDashes and InAs/GaAs QDs occurred in 1.55 µm and 1.3 µm, respectively.

Keywords

Long Wavelength Laser Diode, Quantum Dots, Quantum Dashes, Electroluminescence, Temperature Dependent Currentdensity-Voltage Characteristics

1. Introduction

III-V semiconductor low dimensional structures are attractive for optoelectronic devices, including laser diodes and infrared photodetectors [1]-[6]. The semiconductor quantum dots/quantum dashes (QDs) devices have a lower threshold current density, with a higher gain, and higher thermal stability because of energy confinement compared to bulk and quantum well lasers [4]. InAs/GaAs-based QDs devices emit a laser light at 1.3 μm wavelength [7] [8] [9], while InAs/InP-based QDs devices allow a laser emission in the 1.4 to 1.6 μm wavelength range [2] [3] [4] [5] [6].

Therefore, the charge transport properties are essential for the dynamic of a high-speed semiconductor laser [10] [11]. Nagarajan *et al.* discussed that the main limitation for laser structures was the charge transfer mechanism [10]. The discussion was carried out through optical and electrical measurement. Optical properties are found out by electroluminescence (EL) measurement for the analysis of optical properties [12] [13] [14] while the electrical characteristic of these structures is determined using current density-voltage (*J-V*) measurements [15] [16] [17] [18]. Furthermore, the properties of the present structures in the literature [4] [19] [20] are studied through various optical spectroscopy techniques such as photoluminescence (PL), photoreflectance (PR), and photoluminescence excitation (PLE) to derive the energies of the optical transitions in the system and to get insight of the carrier transfer. In this work, carrier transfer characteristics are investigated through current-voltage and electroluminescence measurements. In brief, carrier transportation properties are clarified in electrical stimulus rather than optical one. Additionally, the scheme of the present structures (given as inset of **Figure 1** and **Figure 2**) is constructed by means of PL, PLE studies. It was observed that in InAs/InP QDashes structured carriers were first tunneled from the quantum well into QDashes in InAs/InP and then recombine within QDashes to emit a long wavelength laser light at 1.55 μm while in InAs/GaAs QDs, the tunneling transport of carriers was the governed conduction mechanism in the range of examined bias voltages.

2. Experiment Methods

State of the art device quality InAs/InP-based QDashes—elongated quantum dots-devices were grown by gas source molecular beam epitaxy on S-doped (100) InP wafers. The schematic structure was shown in the inset of **Figure 1**. Nine nominally undoped InAs QDashes layers have been stacked within a standard In GaAsP separate confinement heterostructure for increased modal gain. The nominal thickness of the InAs layer to achieve 1.55 μm emission is about 2 nm. P-type and n-type doped InP cladding layers were used for light confinement, which results in a p-i-n diode. On the other hand, InAs/GaAs-based QDs was grown by a molecular beam epitaxy on a semi-insulating GaAs (0 0 1) substrate. The schematic structure was shown in the inset of **Figure 2**. Nine InAs QDs layers have stack within In GaAsP. P-type and n-type doped $Al_{0.85}$ $Ga_{0.15}$ As cladding layers were used for light confinement. The whole structure was capped with 10 nm of GaAs. InAs/GaAs QDs and InAs/InP QDashes p-i-n laser heterostructure were studied using current density-voltage measurements in the range of 295 to 400 K. The current voltage measurements were carried out using a Keithley 2400 voltage/current source meter and Lake Shore 334 temperature controller. The EL measurements were performed using Keithley 2400 voltage/current source meter, equipped with an Oriel Cornerstone 260 monochromator and InGaAs photodiode, produced by ThorLabs. The emitted laser light from p-i-n structures was collected in the monochromator by using lenses. At the rear slit of the monochromator, InGaAs photodiode was used to detect the wavelength dependence of emitted light.

3. Result and Discussion

SEM images of the long wavelength laser heterostructure in the p-i-n diode were presented in **Figure 3**, demonstrating good morphology. For the electrical characteristics, the temperature dependent *J*-*V* measurement was performed in the range of 295 to 400 K to investigate the carrier conduction mechanism. The results of *J*-*V* measurement of InAs/GaAs QDs and InAs/InP based QDashes laser heterostructure were shown in **Figure 1** and **Figure 2**, respectively. These figures showed an increase in the magnitude of current density with increasing temperature.

To elucidate the carrier conduction mechanism(s), a general diode equation is fitted, and the results are investigated in terms of activation energy (E_A) of the saturation current (I_0) and temperature dependence of the exponential factor (A) by performing temperature dependent current density-voltage measurement. In this context, the current density-voltage relation in the forward directions is expressed as [21],

$$J = J_0 \exp(AV), \tag{1}$$

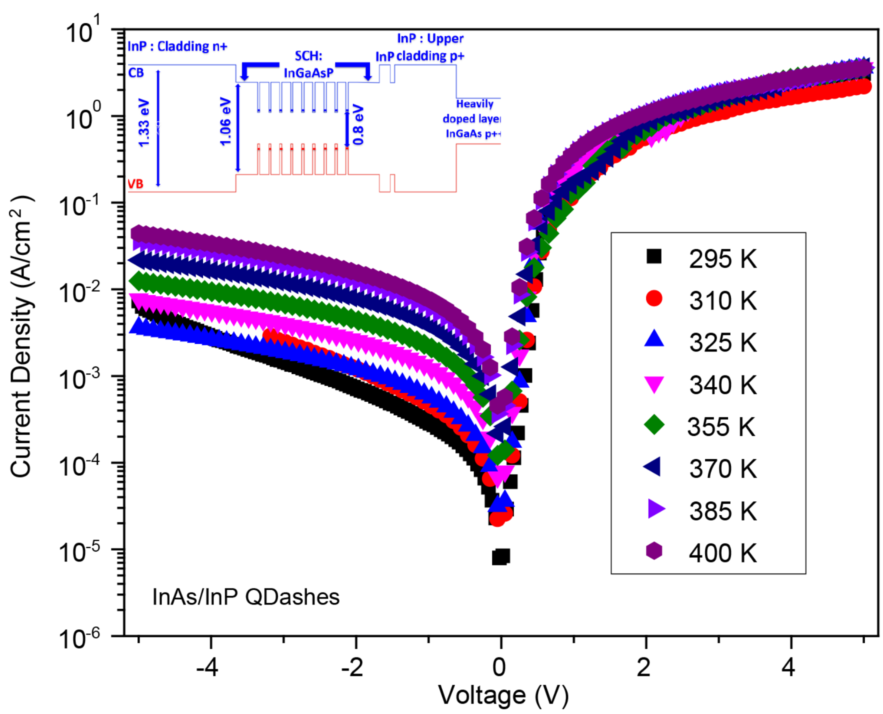

Figure 1. Temperature dependent dark *J*-*V* curves in forward/reverse direction on InAs/InP quantum dashes. The inset shows the schematic band diagram of the structure.

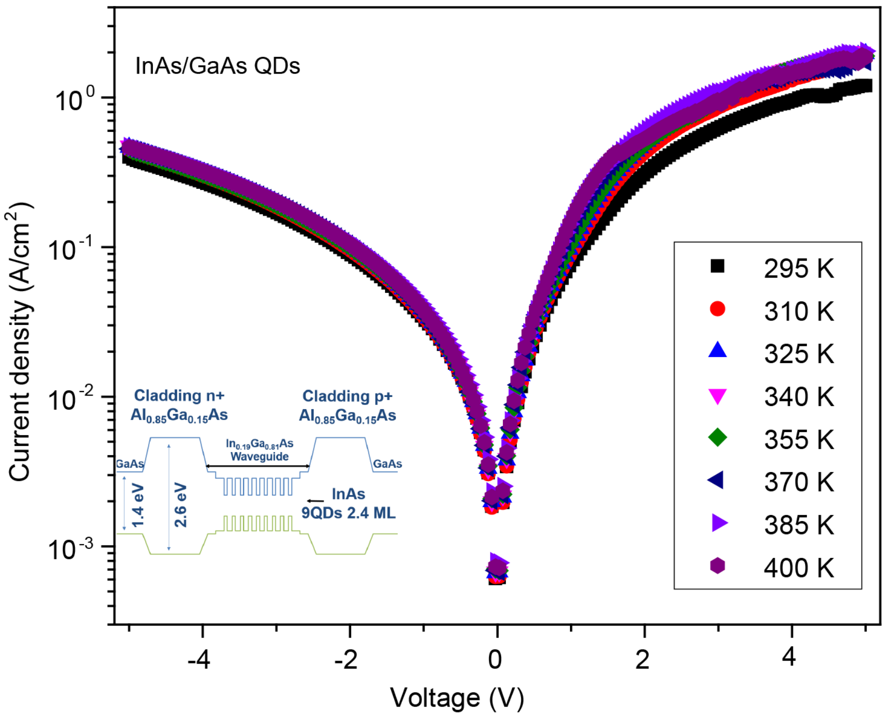

Figure 2. Temperature dependent dark J-V curves in forward/reverse direction on InAs/GaAs QDs. The inset shows the schematic band diagram of the structure.

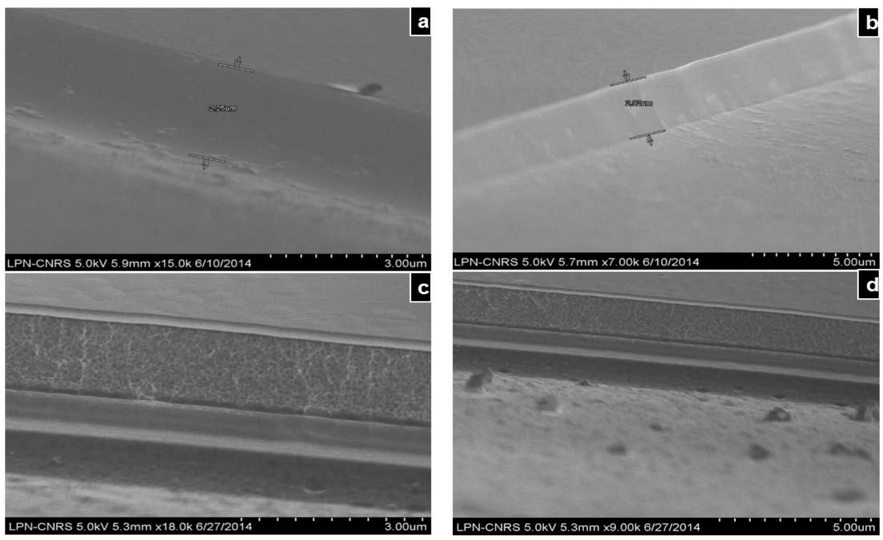

Figure 3. The SEM picture (a)-(b) of InAs/InP based QDashes and (c)-(d) InAs/GaAs QDs laser heterostructure.

where V is applied voltage. Dark saturation current density is given by

$$J_0 \cong \exp\left(E_A/kT\right) \tag{2}$$

with

$$A = q/nkT\ , \tag{3}$$

where k is Boltzmann's constant, T is the absolute temperature in Kelvin, q is electron charge, and n is ideality factor.

In reverse direction, reverse current density-reverse bias followed the expression,

$$J_R = J_{rev,0}(T)(V_{bi} - V_R) \tag{4}$$

with

$$J_{rev,0} \cong \exp(E_{A,rev}/kT), \tag{5}$$

where V_{bi} is built-in voltage, V_R is applied voltage in reverse bias, b is temperature independent exponent, and $J_{rev,0}(T)$ is dark saturation current density in reverse bias, and $E_{A,rev}$ is reverse bias activation energy.

For QDashes based p-i-n laser heterostructure, the forward J-V characteristic manifested two distinct behaviors depending on the bias range ($V_F < 0.2$ V and $0.2 < V_F < 0.6$ V). From the slopes of Arrhenius plots of ln J_0 vs. T^{-1} and A vs. T^{-1} variations, E_A was deduced as 0.4 eV, and A was independent of temperature (**Figure 4**). Therefore, dominant conduction mechanism was the tunneling type. For the bias range of $0.2 < V_F < 0.6$ V, E_A and n were determined as 0.4 eV and 2, respectively. Also, Arrhenius plot of the reverse current density versus reciprocal of temperature at constant bias voltages, resulting activation energy as 0.4 eV, like in forward direction. Both temperature independence of A together with the same activation energy in forward and reverse bias voltages in dictated tunneling of carrier conduction and followed by recombination/generation current flow once the bias voltage exceeded 0.2 V.

Similarly, InAs/GaAs Quantum Dot based p-i-n structure was analyzed (**Figure 5**). Remarkably, rather than two kinds of carrier conduction mechanism, tunneling type conduction was manifested for bias voltage range in reverse/ forward direction.

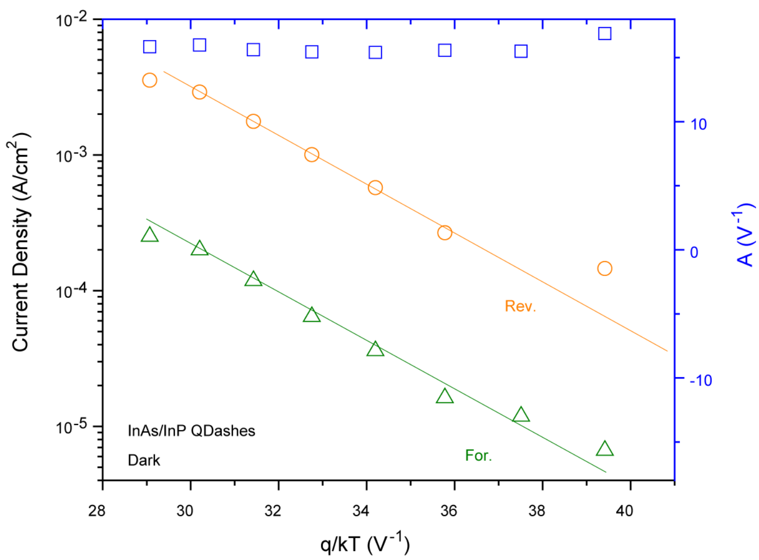

Figure 4. The activation energy of InAs/InP QDashes in forward/reverse direction and A versus q/kT to obtain ideality factor from the slope of semi log current density bias variation.

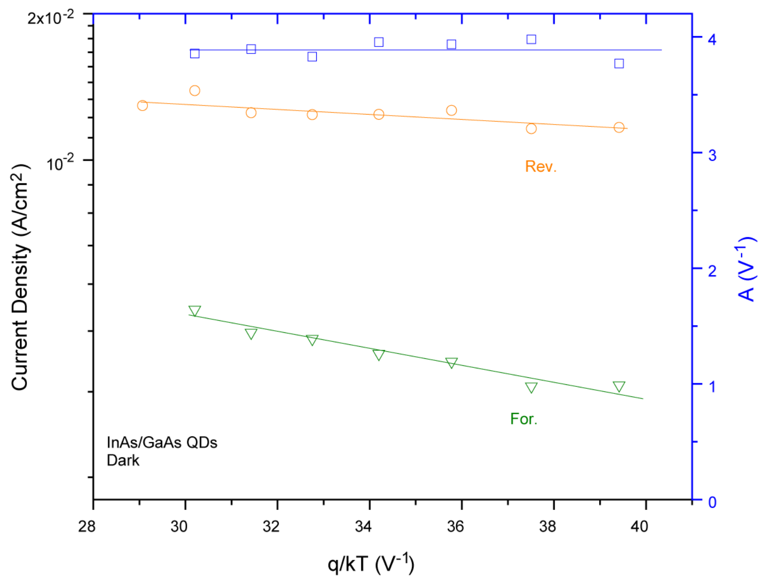

Figure 5. The activation energy of InAs/GaAs QDs in forward/reverse direction and A versus q/kT to obtain ideality factor from the slope of semi log current density bias variation.

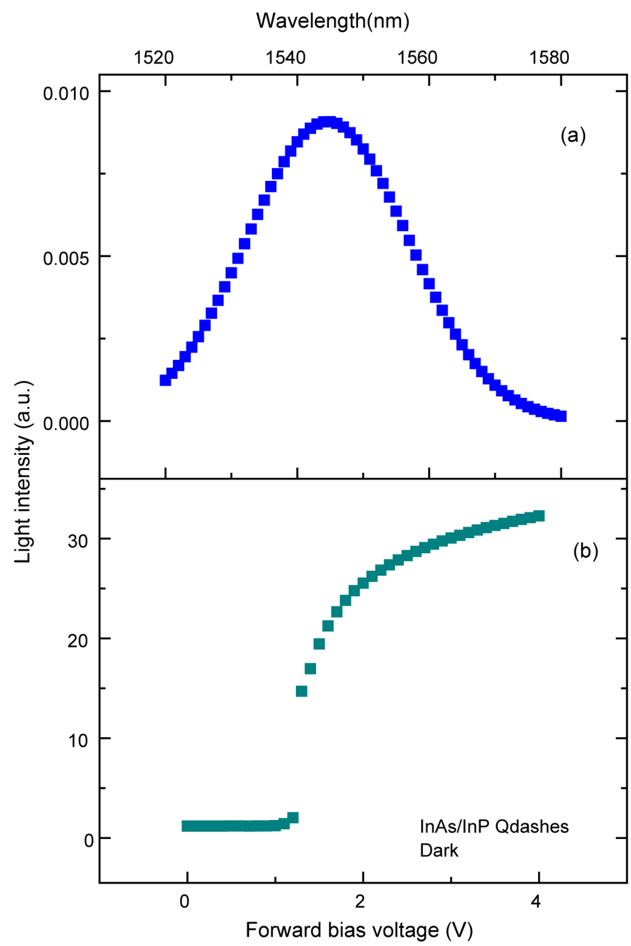

Figure 6. (a) Wavelength dependence of light produced from InAs/InP QDashes at room temperature; (b) EL measurement on this structure.

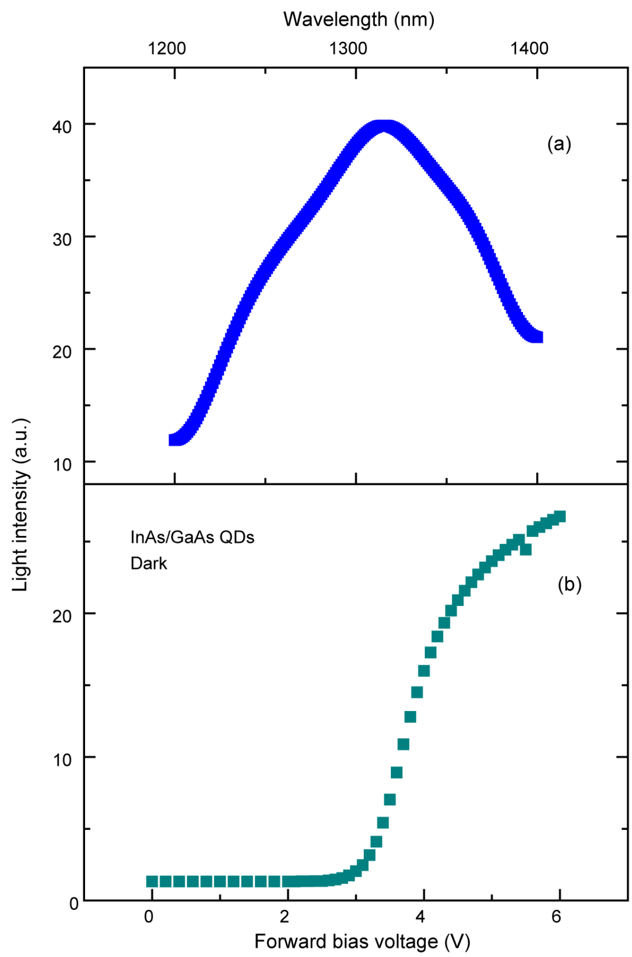

Figure 7. (a) Wavelength dependence of light generated from InAs/GaAs QDs at room temperature; (b) EL measurement on this structure.

Furthermore, when the junctions entered the space charge limited region ($V_F >$ 1 V for InAs/InP Quantum dash and $V_F >$ 2 V for InAs/GaAs Quantum Dot), the laser light was observed (**Figure 6(b)** and **Figure 7(b)**). As shown in there, the onset of light took place when the bias exceeded 1.3 V for InAs/InP Quantum dash while 3 V for InAs/GaAs p-i-n structure. Moreover, the intensity of light grew with the increase in bias voltages and finally saturated for both structures. **Figure 6(a)** and **Figure 7(a)** showed wavelength dependence of light produced from InAs/InP QDashes and InAs/GaAs QDs in which the peak value of emitted laser light took place in 1.55 μm and 1.3 μm, as expected.

4. Conclusion

Long wavelength laser diodes in the p-i-n structure were investigated by temperature dependent current density-voltage measurements. Tunneling kind carrier conduction mechanism was identified for InAs/GaAs-based p-i-n structure for whole bias voltages, whereas transition of tunneling type to recombination/generation kind carrier conduction was discerned in InAs/InP-based p-i-n laser diode. As to the EL measurements, laser light emerged for both structures, peaking at 1.55 μm and 1.3 μm, respectively.

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