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Characterization of InP SC QD LD After Am-Be Neutron Irradiation

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Abstract This paper is about Am-Be neutron source irradiation of InP Quantum Dot Laser diode. A QD LD was irradiated for 24 hours and 48 hours. The laser undergone IV characterization experiments before, after the first and second irradiations. A computer simulation using GAMOS helped in analyzing the given results from IV curves. The results showed an improvement in the QD LD series resistance, current density and overall, ideality factor at all measured temperatures. This is explained by the activation of the QD LD Indium composition to Strontium, ionization of the compound QD LD materials, and by the energy deposited to the QD LD.
Keywords: Quantum dot laser diode irradiation, Effect of radiation on QD LD, Am-Be irradiation effect on SC QD LD.

1. Introduction

Group III-V semiconductor (SC) materials are promising type of semiconductors. These devices are, nowadays, fabricated in small quantities because they are still in their study phase. They are fabricated to make many devices like sensors, LEDs, and lasers. Laser diodes (LDs) emit a focused beam of light. The color light coming from them depends on the band gap. The light efficiency of these devices is found by the ideality factor. These devices are also parameterized based on their series resistance and current density.

Ideality factor is a factor that refers to the efficiency of the laser diode. It is used as an indicator of the performance of the laser diode. This ideality factor is a number which is in the ideal case equal to one. This number refers to the losses and non-radiative combination of electrons and holes in the device. The less the number is the better its efficiency. The series resistance of a laser diode is a measure of the current flowing in the diode, the more the resistance is, the more voltage it needs to operate or reach a lasing threshold. Current density, from the name, implies the volume of current running the laser medium, which is an area specific to a quantum dot laser diode when fabricating it. It is an important factor in the light output power of a laser.

2. Radiation Effects on Semiconductor Quantum Dot (QD) Laser Diode

Neutron radiation has some effects on semiconductor materials. These effects include but are not limited to radiation damage, carrier mobility, displacement effects and others. Effects induced by radiation can be beneficial when properly applied [1]. Many research groups studied the effect of neutrons on semiconductor materials. [2]–[5]. Activation of materials and ionization of materials are key concepts in this study. For instance, InP (Indium Phosphide) is ionized at (4.5) eV and has a neutron capture cross-section of 0.02-2.5 barn at energies below 10 MeV [6], [7].

N.G Kolin and his group in 2000 studied the electrical properties of Indium Phosphide after nuclear reactor irradiation (transmutation). The study they performed focused on the electrical characteristics of the InP after irradiation. They found that the mobility of charge carriers in the compound have increased by two folds, and the concentration of charge carriers increases by ten folds. These experiments were carried in several temperature environments from 100C – 900C [8].

Ahmad Fauzi and his group in 2018 studied GaAs (Gallium Arsenide) infrared diodes after neutron irradiation. This group conducted research on the electrical properties of the said semiconductor compound after neutron exposure for different time intervals. The research revealed that the forward and reverse bias leakage current has increased while the capacitance and carrier concentration have decreased. Also, this research showed that the I-V (Current-Voltage) curve revealed an increase in current density with an increasing neutron fluence rate. The same group performed the same experiment on a dot in a well InAs/GaAs quantum dot-based device. The results showed that the device I-V character increased by neutron fluence rate[9], [10].

In 2018, Elchin M. Huseynov researched about nanocrystalline SiC neutron irradiation. He studied the behavior of the I-V curve before and after the irradiation of neutrons. The I-V characteristic showed a decrease in the electrical resistance of the dots and an increase in electrical conductivity. The author explains this behavior after fast neutron irradiation by dangling bonds, formation of defects, or charge carriers. The increase in time interval of irradiation, however, slightly increases the resistance [11].

3. InP Semiconductor Quantum Dot Laser Diode Structure

InP SC QDs LDs can be fabricated by many methods and by many structures. In this work, the laser in question is fabricated by MOVPE (Metal Organic Vapor Phase Epitaxy) at 620 Degrees Celsius and it consists of 24 layers of group III-V materials. The active region of this device has 5 repeats of, AlGaInP, GaInP, and InP QDs. Figure 1 shows the active region schematic diagram of the active region layers. The laser also consists of two layers surrounding the active region, composed of AlInP. These two layers isolate the active region, which promotes light beam generation. These two layers are also capped by the substrate which is doped in the outer regions of the device. Table (1) illustrates all the layers grown in this QD LD device.

Table 1 – SC QD LD structure thickness and doping levels

Repeats	Thickness Å	Material	Growth Temp C	Dopant (100)	Type	Concentration
1	3000	GaAs	*690*	Zn	p	5.00E+18
1	100	GaInP	690	Zn	p	1.00E+18
1	9500	AlInP	690	Zn	p	5.00E+17
1	500	AlInP	690			
1	**860**	**AlGaInP**	730			
5	**160**	**AlGaInP**	730			
5	80	GaInP (Quantum Well)	620			
5	6	InP (Quantum Dot)	620			
1	1000	AlGaInP	730			
1	10000	AlInP	690	Si	n	5.00E+17
1	100	GaInP	690	Si	n	1.00E+18
1	6000	GaAs	690	Si	n	2.00E+18

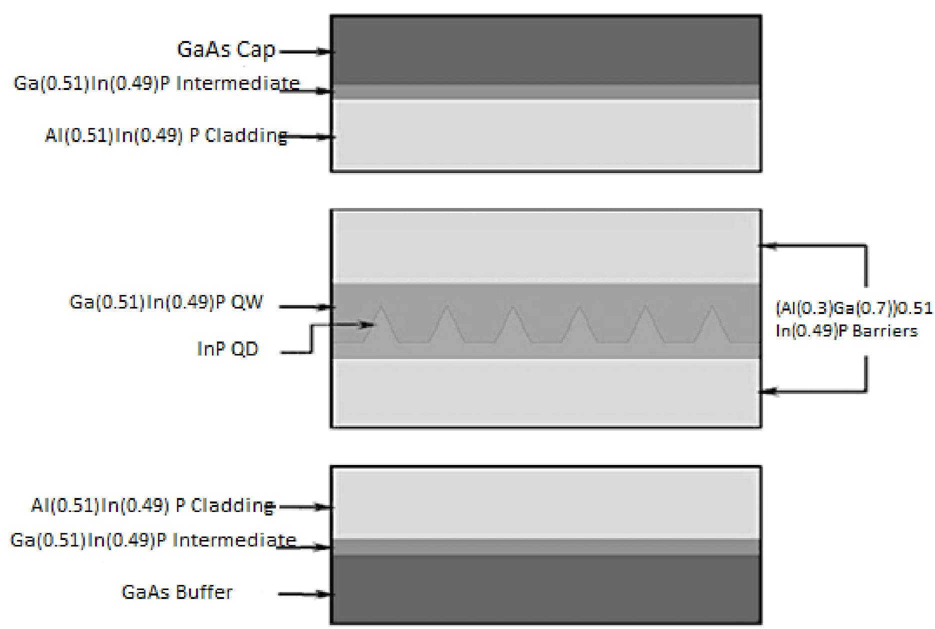

Figure 1 - The structure of the InP QD SM LD device used in this work. The thickness of each layer is not written here.

4. GAMOS Simulation

In this work, we have irradiated InP QD LD by Americium Beryllium neutron sources of 5 Ci and 3 Ci inside an irradiator compartment [12]. The same simulation geometry of the irradiator is coded to mimic our laboratory Am-Be irradiator. We have simulated this scenario in GEANT4-based software (i.e. GAMOS), to find the exact energy deposited in the laser, and the changes that happened to the semiconductor material in the laser after irradiation. The simulation for irradiation setup is shown in Figure 2. The InP semiconductor laser is placed inside a tube of radius (5cm). The placement inside the irradiator is between the two Am-Be sources. The number of beams in the simulation was 400000 beams and *a radioactive physics* list was used. Irradiator geometry and Am-Be specifications were exactly mimicked to represent the irradiator in the laboratory [12]. The QD LD structure is also coded to represent the thicknesses of each layer. The density of the materials in the simulation was taken from the literature for each and all compounds [13]–[17].

5. Irradiation of InP SC QD LD

The irradiator located in our laboratory is used in this research [12]. It is composed of two neutron sources, one of which is 5 Ci and the other is 3 Ci. The irradiator is shielded by light Z material (i.e. polyethylene). The QD LD was inserted in the center slot of the irradiator. Then, the sample was irradiated for 24 hours as per the simulation settings. The LD was put inside a thick plastic bottle to ensure safety from harmful betas after the irradiation. The irradiation took place two times, each time duration is 24 hours. IV characterization is performed before the irradiation and after both irradiation scenarios.

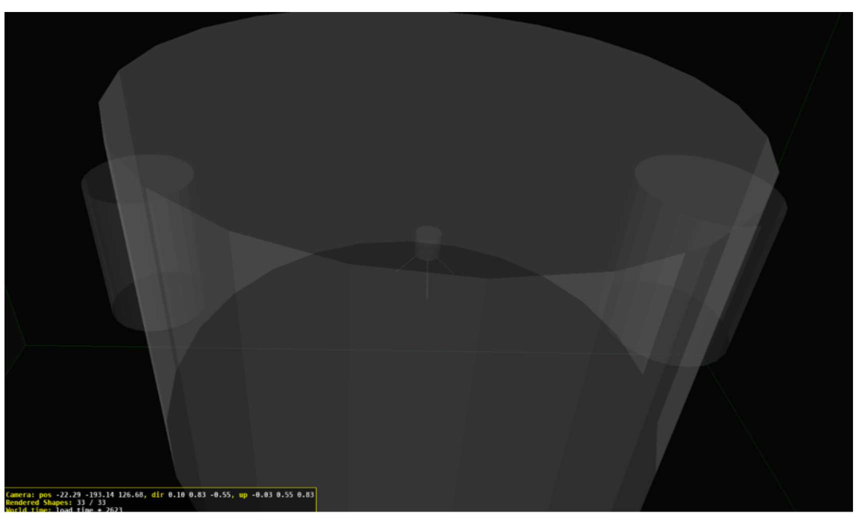

Figure 2 - GAMOS visualization showing the setup and the two Am-Be neutron sources inside the irradiator.

6. IV Experiment

The InP quantum dot semiconductor laser was tested before irradiation, after 24 h, and after 48h of irradiation by I-V characterization equipment to find the ideality factor, series resistance, and current density at a wide range of temperatures from 77K to 400K with a steady increment of 25 degrees. The devices used to measure the performance of the QD LDs IV are current source, cryostat, a temperature controller, and a vacuum pump. Both the cryostat and the temperature controller are Oxford Instruments DN, while the current source is Keithley 6220. These are connected as shown in Figure 3. The QD LD is placed inside the cryostat, connected by wires to the current source. The vacuum pump is then operated to create a vacuum cavity in the cryostat. The vacuum cavity created by the pump is 3.6e-4 Torr. Then, the cryostat is filled with liquid nitrogen to reach 77K, and a temperature controller is used to control the temperature of the cryostat cavity, where the QD LD is connected by wires to the current source. The IV data is then used to calculate the ideality factor, series resistance and the reverse current density of the QD LD.

7. Results

GAMOS simulation of the irradiation scenarios showed that the energy deposited is $4.1\ x\ 10^{-6}$MeV in the first irradiation interval. The energy deposited in the second irradiation is $8.6\ x\ 10^{-6}$ MeV based on the simulation. The simulation also showed that the Indium in the semiconductor material is ionized and is activated into Sr in the first irradiation scenario [18]. IV characterization showed that both irradiations, improved the behavior of the IV curve in this specific laser diode. The IV curve shifted to the left which improved the efficiency of the laser and reduced the current resistance.

Figure 3 - IV experiment setup schematic diagram showing the main equipment used to detect the IV characters of the QD LD

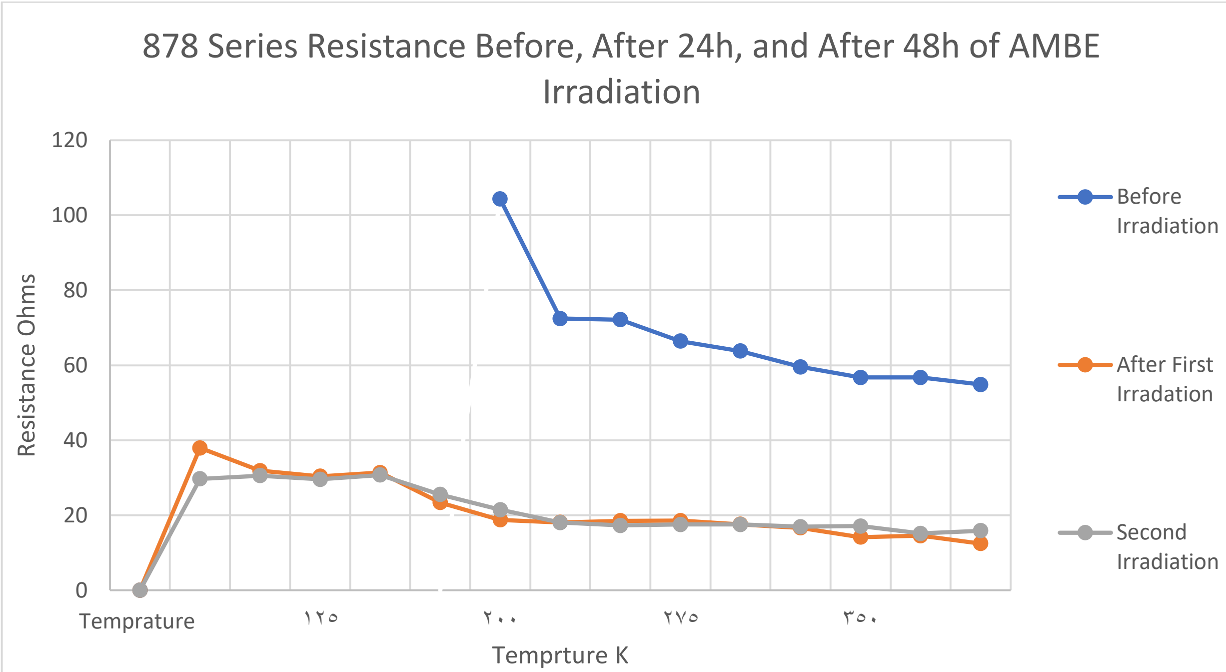

Figure 4 - Series Resistance of the Laser before, after first and second irradiations. The less the resistance the more current goes in the laser medium.

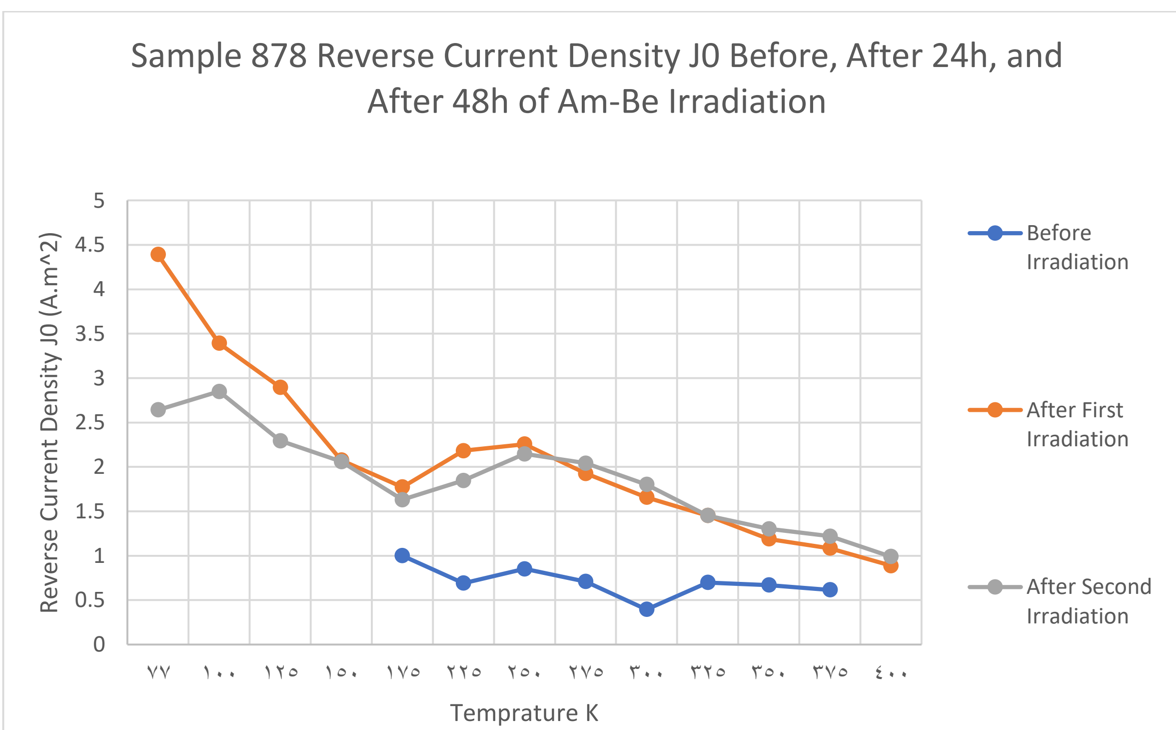

Figure 5 – Reverse Bias Current Density Comparison from 77 to 400 K for the three scenarios. The more current flowing in the laser the more light output it used to deliver.

Figures 4 shows the series resistance improvement after the first irradiation. The series resistance has decreased in the first irradiation scenario. This reduction in resistance is clear in all temperatures; it caused the device to have more carrier mobility. At low temperatures the device has also made carriers available to jump to the conduction band. The ionization of the QD LD and the transmutation to Sr has increased the electrons fermi energy and enabled the device to lase at lower temperatures.

Figure 5 shows the curve shifted down for both irradiation and at all tested temperatures. This indicates that the LD transmuted to Sr from the first irradiation. This means that the irradiation by neutrons have improved the performance of this device, the crystal structure change from In to Sr promoted the increase in current density and current flow. The decrease in series resistance is resulted from defects that were created in the laser diode crystals, these defects are related to dislocation in the materials lattice and the activation of In and its transformation to Sr (Tin).

The curves in Figures 6 also shows that the material immediately changed from Indium (In-116, $T_{1/2}$=14 seconds) to Strontium (Sr-116, $T_{1/2}$= Stable) in the first 24 hours of irradiation. The grey curve is where the material was Indium. This crystal change in the LD is irreversible and cannot be undone. The irradiation times in this QD LD case influence the behavior of the LD after irradiation. This means that there is a region in between where one can only adjust the desired current density, series resistance or ideality factor. Controlling the time interval of the irradiation will surely lead to these regions.

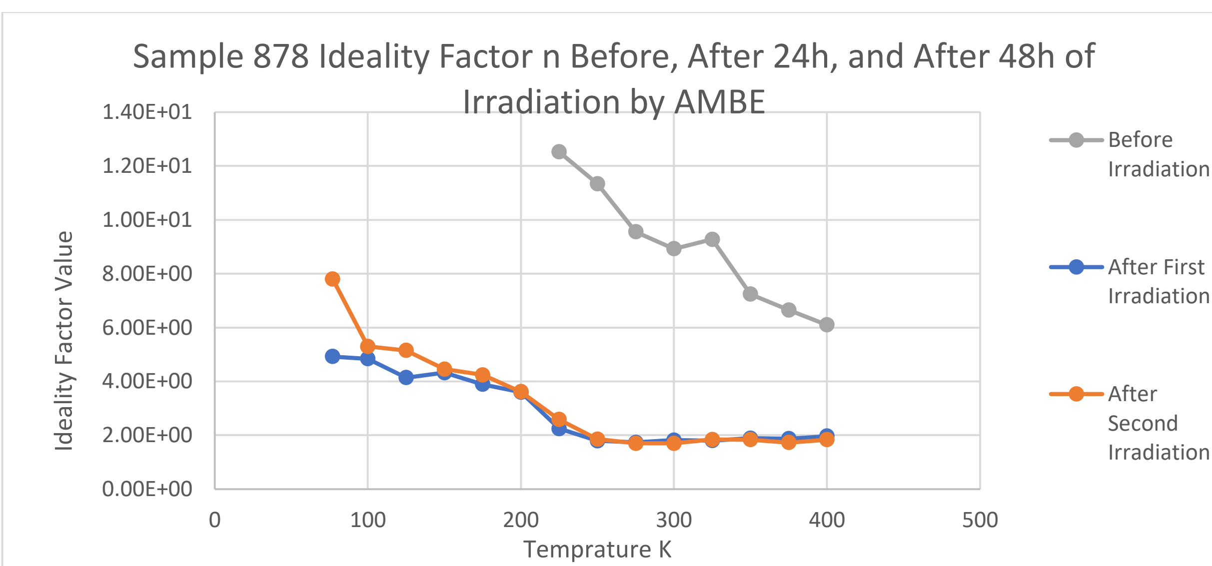

Figure 6 - Ideality factor of laser is closer to (1) which is the most ideal ideality factor in laser diodes. This shows the decrease of the ideality factor in the laser after irradiation.

8. Conclusion

InP QD LD fabricated with many different designs and structures, indium composition is a key to the irradiation effects. The QD LD fabricated with more indium percentage in their composition is more suitable to these changes (i.e., ionization and activation). These two mechanisms can lead to an improvement in QD LD, and the other various semiconductor devices grown with the same technology. The QD LD studied here has an increase in current density and its' ideality factor has reached unity. Also, the series resistance of the QD LD in this study has decreased, which allowed more current to go through the active region. All these parameters indicated the improved performance of this QD LD in this study. This can be applied in other semiconductor devices like LEDs, solar panels, and sensor, if their growth conditions are the same to the one in this study.

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تأثير الاشعاع النيوتروني على الخصائص الكهربائية لليزرات ثنائية القطب المكونة من نقاط كم الانديوم فوسفات

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مستخلص. في هذا البحث، قمنا بتشعيع، ليزر من اشباه الموصلات ثنائية القطب متعددة الطبقات التي تحتوي على نقاط الكم المكونة من الانديوم فوسفات، باستخدام مشعع الامريشيوم بيريليوم لمدة ٢٤ ساعة و٤٨ ساعة. وقمنا باختبار ليزر نقاط الكم الشبه موصل عن طريق جهاز تشخيص التيار والفولطية قبل وبعد التشعيع. قمنا باستخدام البيانات المخرجة من جهاز التشخيص لحساب المقاومة ومعامل المثالية وكثافة التيار الكهربائي لليزر نقاط الكم. وقد استخدمنا برنامج (جاموس) لمحاكاة تجربه التشعيع بنفس مواصفات وابعاد التجربة في المعمل ونفس مواصفات ومواد الليزر الكمي المستخدم في البحث، ووجدنا التفسير المنطقي للتغير في ليزر نقاط الكم من الانديوم فوسفات.