PERFORMANCE IMPROVEMENT OF OPTOELECTRONIC DEVICES USING GROUP-III NITRIDE BASED QUANTUM DOT

by

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A thesis submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy

School of Electrical Systems Engineering
UNIVERSITI MALAYSIA PERLIS

2014

UNIVERSITI MALAYSIA PERLIS

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Academic session	: 2014-2015

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ACKNOWLEDGEMENT

First of all thanks to the Almighty Allah S.W.T. for giving me the strength, patience and determination to complete this research successfully. Then I would like to express my sincere gratitude to my supervisor, Associate Professor Dr. Mohd Abdur Rashid and co-supervisor Associate Professor Dr. Mohd Fareq bin Abd Malek for their constant guidance, support, collaboration, inspiration and valuable suggestion throughout the entire course of my research work. Their depth of understanding, enthusiastic approach to research and their ability to relate many ideas together have provided me the right directions and made this newly approached challenging work possible.

I would like to express the appreciations to my parents who encouraged me at the every stapes of my life. I thank my family for providing me tremendous support and encouragement to inspire me during difficult moments. Special thanks to my wonderful angle and my wife for providing me motivation throughout this research. Finally, I thank everyone else who has facilitated the making of this thesis, including other colleagues.

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LIST OF ABBREVIATIONS

AlN	Aluminium Nitride
CB	Conduction Band
DHS	Double Heterostructure
DOS	Density of State
eV	Electron Volt
FF	Fill Factor
GaAs	Gallium Arsenide
GaN	Gallium Nitride
Ge	Germenium
InAs	Indium Arsenide
InGaN	Indium Gallium Nitride
InN	Indium Nitride
LEF	Linewidth Enhancement Factor
MBE	Molecular Beam Epitexy
MOCVD	Metalorganic Chemical Vapor Deposition
OCL	Optical Confinement Layer
OFC	Optical Fiber Communication
PL	Photoluminescence
QD	Quantum Dot
QDL	Quantum Dot Laser
QDSC	Quantum Dot Solar Cell
QE	Quantum Efficiency
QW	Quantum Well
QWL	Quantum Well Laser

QWR	Quantum Wire
Si	Silicon
S-K	Stranski-Krastanow
SL	Semiconductor Laser
VB	Valence Band
WL	Wetting Layer

LIST OF SYMBOLS AND VARIABLES

D_c	Number of Degrees of Confinement
D_f	Number of Degrees of Freedom
D_f	Number of Degrees of Freedom
$E_{g_{GaN}}$	Band gap Energy of GaN
$E_{g_{GaN}}$	Band gap Energy of GaN
$E_{g_{InN}}$	Band gap Energy of InN
$E_{g_{InN}}$	Band gap Energy of InN
E_h	Confined ground quantized energy levels of a hole in VB
E_e	Confined ground quantized energy levels of an electron in CB
E_g	Bandgap energy of semiconductor material
E_g	Bandgap energy of semiconductor material
I_{SC}	Short circuit current of
I_s	Saturation current
J_0	Transparency currwent density
J_{th}	Threshold current density
$L_{diffusion}$	Carrier diffusion length
L_{drift}	Carrier drift length
P_{out}	Output power
R_1, R_2	Reflectivities of the mirrors.
R_{eff}	Effective reflectivity
T_1	Lower limit of operating temperature
T_2	Upper limit of operating temperature
V_{OC}	Open circuit voltage of solar cell

$V_{ocdeficit}$	Open circuit voltage deficit of solar cell
a_B	Strength of the average electron–phonon interaction
g_0	Saturation gain
g_{mod}	Modal gain
k_F	Fermi-Wave Function
k_α	is the factor related to the geometry of the laser waveguide.
m^*	Effective mass of carriers
m_e	Electron effective mass
n_g	Refractive index of the active layer material.
n_r	Refractive index,
v_g	Group velocity
α_{fc}	Free carrier absorption loss
α_i	Internal loss of laser cavity
α_m	Mirror loss of laser cavity
η_d	External differential efficiency of QDL
η_i	internal QE of the stimulated emission
θ_B	temperature related to average phonon energy.
λ_B	De Broglie wavelength
τ_{active}	Round-trip time in the active region
τ_{avg}	Average Photon lifetime
τ_m	Momentum relaxation time
τ_{ph}	Photon lifetime
µ	Carrier Mobility
µ	Carrier mobility
Δn_{eff}	Total effective refractive index variation due to plasma and the effect of QD

d	Mean diameter
h	Planck’s constant
γ	Optical Feedback Level of Laser
ρ	Effective DOS
Γ	Confinement Factor
D	Diffusion coefficient
E	Built-in field
K	Boltzmann’s Constant
K	Boltzmann’s constant
L	Cavity length
P	Power loss of electron
T	Temperature
a, c	Lattice Constant
b	Bowing parameter
c	Speed of light in vacuum
k	Feedback strength
n	Carrier density
q	Charge of electron
t	Laser operating time
x	Indium molar fraction
x	Indium molar fraction
β, γ	Varshni’s parameters
$\delta\omega$	Fluctuation of Laser Frequency
τ	Carrier Lifetime

Peningkatan Prestasi Peranti Optoelektronik Menggunakan Kuantum Dot Kumpulan-III Nitrida Berasaskan

Kuantum dot telah menjadi subjek kepentingan yang luar biasa dalam bidang semikonduktor reka bentuk peranti optoelektronik untuk penyelidik kerana beberapa sifat-sifat mereka yang unik. Antara pelbagai jenis peranti optoelektronik beberapa ciri-ciri penting dalam sel solar dan laser telah dikaji secara meluas. Kedua-dua peranti ini dipilih kerana kepentingan peranti semikonduktor optoelektronik dalam bidang tenaga boleh diperbaharui dan komunikasi gentian optik masing-masing. Terbaharu ini ia telah mengakui bahawa penyelidik memberikan perhatian yang lebih kepada titik kuantum golongan III nitrida. Oleh itu kajian ini adalah dikhaskan untuk menyiasat peningkatan prestasi sel solar dan laser menggunakan Inn berdasarkan kuantum dot dalam lapisan aktif struktur peranti. Dalam kajian ini bekerja peningkatan prestasi kedua dua peralatan ini telah dicapai dengan menukar bahan lapisan aktif tanpa menjejaskan parameter struktur lain. Kesan pemalar kekisi pada jurang jalur pengoptimuman tenaga $In_xGa_{1-x}N$ telah disiasat pada mulanya. Dari analisis berangka ia telah mendapati bahawa $In_xGa_{1-x}N$ menawarkan jurang tenaga dari 0.7eV - 3.5eV, yang menjadikannya bahan yang sesuai untuk sel solar untuk menyerap pelbagai tenaga cahaya. Tambahan pula, ia telah menunjukkan bahawa $In_{0.87}Ga_{0.13}N$ mampu memancarkan cahaya pada panjang gelombang 1.55µm, yang menawarkan pengecilan yang paling rendah bagi penghantaran isyarat melalui gentian optik. Oleh itu, hasil daripada siasatan awal menentukan bahawa dalam $In_xGa_{1-x}N$ boleh menjadi bahan yang menjanjikan untuk menghasilkan dan menggunakan sel solar dan laser. Kemudian pergantungan suhu daripada jurang tenaga bahan semikonduktor telah dikaji dengan menggunakan model Varshni dan model Bose-Einstein. Walaupun menganalisis pergantungan suhu tenaga jurang jalur Gan menggunakan kedua model had utama model Bose-Einstein telah dikenal pasti dan pengubahsuaian model ini telah dicadangkan untuk menyelesaikan masalah pengiraan suhu kritikal. Selepas itu penyerapan dan pelepasan fenomena, kesan masa operasi kepada ciri-ciri balas pengguna dan pergantungan panjang rongga kerugian dan mendapatkan ciri-ciri dan kehidupan foton masa kuantum dot laser telah disiasat. Tambahan pula kesan suhu ke atas panjang hanyut dan panjang resapan daripada syarikat penerbangan telah disiasat bersama-sama dengan voltan litar terbuka, arus litar pintas, kuasa output sel solar. Keputusan berangka yang diperolehi berbanding dengan apa yang diperolehi dengan menggunakan bahan-bahan yang sedia ada konvensional untuk kedua laser dan sel solar. Untuk laser mendapat keputusan berangka dibandingkan dengan GaN dan AlN dot kuantum berasaskan laser dan untuk sel solar, mendapat keputusan dibandingkan dengan sel solar dan Si Ge kuantum dot berasaskan. Keputusan berangka menunjukkan bahawa ciri-ciri laser telah meningkat secara drastik dan kestabilan ciri-ciri sel solar telah meningkat dengan ketara menggunakan Inn dot kuantum sebagai bahan lapisan yang aktif. Akhirnya dapat disimpulkan bahawa Inn dot kuantum boleh menjadi bahan yang menjanjikan untuk merekabentuk peranti optoelektronik dalam masa terdekat.

Performance Improvement of Optoelectronic Devices Using Group-III Nitride based Quantum Dot

Quantum dot has become a subject of incredible interest in the field of semiconductor optoelectronic device design for the researchers due to some of their unique properties. Among the wide range of optoelectronic devices some important characteristics of solar cell and laser have been studied extensively. These two devices are chosen because of the importance of these optoelectronic semiconductor devices in the field of renewable energy and optical fiber communication respectively. Recently it has been acknowledged that the researchers are paying more and more attention to the group-III nitride based quantum dots. Therefore this research is devoted to investigate the performance improvement of solar cell and laser using InN based quantum dot in the active layer of the device structure. In this research work the performance improvement of both these devices have been achieved by changing the active layer material without affecting other structural parameters. The effect of lattice constant on band gap energy optimization of $In_xGa_{1-x}N$ has been investigated initially. From the numerical analysis it has been found that $In_xGa_{1-x}N$ offers a band gap energy ranging from 0.7eV - 3.5eV, which makes it a suitable material for solar cell to absorb a wide range of light energy. Furthermore, it has been demonstrated that $In_{0.87}Ga_{0.13}N$ is capable of emitting light at the wavelength of 1.55μm, which offers the lowest attenuation for signal transmission through optical fiber. Therefore the result of initial investigation ascertains that $In_xGa_{1-x}N$ can be a promising material for the fabrication of solar cell as well as laser. Then the temperature dependence of the band gap energy of semiconductor material was investigated using Varshni's model and Bose–Einstein model. While analyzing the temperature dependence of band gap energy of GaN using these two models a major limitation of Bose–Einstein model has been identified and a modification of this model has been proposed to solve the problem of calculation of critical temperature. After that the absorption and emission phenomena, effect of operating time on the feed-back characteristics and the cavity length dependence of the loss and gain characteristics and photon life time of quantum dot laser were investigated. Furthermore the effect of temperature on the drift length and the diffusion length of the carriers have been investigated along with the open circuit voltage, short circuit current, output power of the solar cell. The numerical results obtained were compared with those obtained by using other conventional existing materials for both laser and solar cell. For laser obtained numerical results were compared with GaN and AlN quantum dot based laser and for solar cell, obtained results were compared with Si and Ge quantum dot based solar cell. Numerical results reveal that the laser characteristics have been improved drastically and the stability of solar cell characteristics has been increased significantly using InN quantum dot as the active layer material. Finally it can be concluded that InN quantum dot can be a promising material to fabricate the optoelectronic devices in the very near future.

CHAPTER 1

INTRODUCTION

1.1 Background

For many years the general aim of the modern semiconductor technology has been the fabrication of semiconductor devices in their possible utmost minuscule dimensions. Initially the semiconductor devices fabricated with the centimetre and millimetre dimensions were considered as very small in size. However with the advancement of the solid state physics, researchers have successfully developed the devices with the physical dimensions in the scale of micro and nanometre. The breakthrough of using ultra thin layer of semiconductor occurred through the invention of quantum well (QW) in the 1980s, which gained wide spread acceptance to the scientific community. Further development in the field of semiconductor devices were achieved through the invention of quantum structures with further less dimensionality like one dimensional quantum wire (QWR) and eventually zero dimensional quantum dot (QD).

Since the first demonstration of optical properties of self-organized QDs, these materials are under extensive investigation all over the world for their applicability in optoelectronic device design. QD is formed spontaneously when a layer of a material having a large difference in lattice constant from that of the substrate is formed on the substrate (Goldstein, et al, 1985). It has been reported that if the dimension of a QD becomes comparable to the De-Brogile wavelength, the density of states (DOS) becomes a δ-function (Grundmann, et al. 1995). The δ-function like DOS and strong confinement of electron and hole wave functions are unique properties of QDs, which improve the semiconductor optoelectronic device characteristics significantly. Thus, QDs provide an ultimate limit of size quantization in solids and an extremely large change of electronic properties as compared to QWs and QWRs. The real breakthrough occurred when new class of self-organized QDs were applied for the device design.

Very recently it has been reported that QD is a subject of intense investigation on its optical properties, which are crucial for the improvement of optoelectronic device performances (Salhi, et al. 2008). Among the wide range of optoelectronic devices a theoretical investigation of laser and solar cell has been carried out in this present research work. Thus all the consecutive sections of this thesis paper have been organized in two fold for each section mentioning the lasers and the solar cells respectively.

1.2 Motivation for This Research

This section describes the motivation of improving performance of optoelectronic devices namely laser and solar cell by using InN QD in the active layer of the device structure. This section is divided into two sub-sections.

1.2.1 Semiconductor Lasers

Semiconductor laser (SL) is an active light source in optical fiber communication (OFC) due to its high quantum efficiency (QE), pure output spectrum and the narrower gain spectra, direct modulation capability and high reliability. In the early days homostructured SLs were fabricated using bulk materials. The bulk SLs required high threshold current density in the range of 10^4 ~ 10^5 A/cm^2 to create lasing action. Furthermore these lasers were only able to operate at cryogenic temperature. The active region of a bulk SL was very large. Therefore high power pump source was required in order to pump in a lot of electrons and holes to overcome this photonic re-absorption and to emit light in a self-sustaining way. A large active region also caused a greater number of uncontrolled spontaneous emissions of photons, which oppose stimulated emission as well as create optical noise. Another major problem was a large “linewidth enhancement factor (LEF)”. As the current and gain increased, the index of refraction varied as well, which altered the wavelength of the standing waves inside the laser cavity. Consequently the output wavelength and intensity danced around.

Advanced performance of heterostructure lasers compared to homostructured lasers made them capable of using in OFC since 1978. However bulk materials in the active region blocked a further improvement of heterostructure lasers and led to the development of quantum well lasers (QWLs) motivated by the strong modification of properties of a semiconductor crystal in low-dimensional heterostructures. The problems such as non-equilibrium carrier spreading out of the cavity region, facet overheating due to surface recombination, non-radiative recombination enhanced by dislocation growth due to carrier diffusion to dislocations, no possibility of free-standing micro cavities and large ground state population time associated with QWLs restricted the achievement of better performances (Bimberg, Grundmann, Heinrichsdorff, Ledentsov, Ustinov, Zhukov, et al., 2000).

Further enhancement of device characteristics is expected for SLs with lower dimensionality of the active region, such as QWR and especially QD laser where the motion of carriers is restricted from all the three directions predicting suppression of temperature dependence of threshold current (Arakawa, 2007; Arakawa, & Sakaki, 1982) and to overcome the problems of QWLs. Recent research is devoted to the improvement of revolutionary QDLs using InN QD in the active layer of the QDL structure. It has been revealed from the outcome of this research that InN QDL provide better performances such as higher effective DOS of the carriers, higher optical feedback level, reduction of frequency fluctuation, higher momentum relaxation time with reduced rate of change momentum relaxation, more uniform carrier mobility, reduced absorption loss, higher carrier density, enhanced feedback strength and superior fermi wave factor. Further improvements of the laser characteristics were reported in terms of lower threshold current density, minimization of internal loss, enhancement of modal gain and high external differential efficiency and enhanced photon lifetime.

1.2.2 Solar Cells

Power crisis has become a severe problem all over the world. Recently it has been reported that different sources of energy pollutes our environment in different ways and in different degrees (Mahrane, Chik, & Chikouche, 2010). The solar energy is widely used around the world because it is the most environmental friendly source of energy ever discovered (Sharaf, & Yang, 2005). Solar cell is the optoelectronic device that can convert the solar energy directly to electrical energy. Therefore researchers are paying more and more attention on the performance improvement of solar cell in order to make it a suitable alternative to meet the ever increasing demand in an environment friendly manner.

The majority of the existing solar cells are fabricated using conventional semiconductor materials like Si and Ge (Doi, Tsuda, Sakuta & Matsui, 2003; Fan et al. 2010). However there are some problems in solar cell performance still arises due to the material quality of different layers of the device structure (Huang, Semichaevsky, Webster, Johnson, & Goldman, 2011). Recently researchers have found that group III nitride based QDs have better potential in providing better device performance. Besides some unique properties of InN such as: narrow band gap, the strong polarization, piezo-electric effect and many others have made it attractive to the researchers.

The primary limitation of the conventional solar cell is to achieve high output power as well as more stable operation at high temperature. Therefore, this research has been devoted to achieve better stability in the solar cell characteristics with high output power. Few more problems have also been detected from earlier solar cells like local increase in the dark forward current of a cell usually that is caused by the materials. Therefore in order to increase the stability in the solar cell characteristics the main focus is to investigate the solar cell performance. This research work is based on characteristics analysis of InN QD solar cell which will be compared to the existing material like Si and Ge QD."

1.3 Research Objectives

The main purpose of this research is to improve the major characteristics of optoelectronic devices like laser and solar cell using InN QD in the active layer of the device structure. To accomplish the goal of achieving better performance of more than one device using a single material this research work was progressed based on few objectives.