行政院國家科學委員會專題研究計畫　期中進度報告

氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究

(1/3)

計畫類別：整合型計畫
計畫編號：NSC92-2120-M-009-006-
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日
執行單位：國立交通大學光電工程研究所

計畫主持人：王興宗
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計畫參與人員：張連璧（博士後）、劉淑致（研究助理）、博士生：姚忻宏、薛道鴻、張亞銜、賴芳儀、巫漢敏、張怡安、高志強、林俊榮；碩士生：朱榮堂、張峻瑋、歐陽妙佳、謝永龍、陳威佑、余國正、王薏婷、梁文燈、羅傳煜、彭裕鈞、蔡敏瑛、朱瑞溢。

報告類型：精簡報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 93 年 6 月 1 日

行政院國家科學委員會補助專題研究計畫 □ 成 果 報 告
■期中進度報告

Research on Mesoscopic GaN Quantum Confined Structures for Control of Photon Emission

氮化鎵介觀尺度下量子局限結構之光子輻射可控性研究

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計畫編號：NSC 92－2120－M－009-006
執行期間：92 年 08 月 01 日至 93 年 07 月 31 日

計畫主持人：**S. C. Wang**（王興宗）
共同主持人：H. C. Kuo (郭浩中)、H. F. Meng（孟心飛）、L.-H. Peng（彭隆瀚）、Gong-Ru Lin（林恭如）

計畫參與人員：張連璧（博士後)、劉淑致（研究助理)、博士生：姚忻宏、薛道鴻、張亞銜、賴芳儀、巫漢敏、張怡安、高志強、林俊榮;碩士生：朱榮堂、張峻瑋、歐陽妙佳、謝永龍、陳威佑、余國正、王薏婷、梁文燈、羅傳煜、彭裕鈞、蔡敏瑛、朱瑞溢。

成果報告類型(依經費核定清單規定繳交)：■精簡報告 □完整報告

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執行單位：國立交通大學光電所
中 華 民 國 92 年 05 月 31 日

Research on Mesoscopic GaN Quantum Confined Structures for Control of Photon Emission

氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究

總執行期限：2003/08/01 ~2005/07/31

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Abstract

We have accomplished the objectives of first year of this project. The main accomplishments include successfully fabrication of GaN quantum dot (QD), fabrication of GaN-based nanorod, growth and study of GaN/AlN DBR, establishment of the GaN-based micro-cavity device process techniques, growth of the Ga_2O_3 using photo-enhanced wet oxidation technique.

摘要

我們已按本計畫預期之進度順利完成第一年之工作進度。包括建立具備光學微共振腔之低維氮化鎵量子點、柱結構生長與製作,以及氮化鎵 DBR 反射膜與量子點之磊晶成長研究,氮化鎵面射型微共振腔結構之製程研究, 並以自組式光致氧化技術，生長 Ga_2O_3 之薄膜並研究其特性。

報告內容

(一) 前言

本文為奈米國家型科技計畫之氮化鎵介觀尺度下量子局限結構之光子輻射可控性研究之精簡成果報告，內容為簡介本計畫第一年所研究之實驗方法、成果以及所發表之文獻。

(二) 研究目的

本奈米國家型計畫第一年預計完成之工作為建立具備光學微共振腔之低維氮化鎵量子點、柱結構生長與製作,包含氮化鎵 DBR 反射膜與量子點之磊晶成長研究, 氮化鎵面射型雷射結構之製程研究, 以自組式光致氧化技術，生長二維奈米尺度之 AlGaO、InGaO/GaN 量子柱結構。

(三) 文獻探討

史丹佛大學 Y. Yamamoto 教授利用光學微共振腔結構成功控制單光子控制輻射元件，其研究領域囊括光學微共振腔結構之磊晶動力學機制，成長量子點、量子柱低維結構。應用雷射光譜、表面分析、電性量測等技術，配合能隙理論、量子電動力學模

型計算，研究壓電效應、庫倫封鎖，對於介觀尺度之氮化鎵低維量子結構之次能帶躍遷、電子之空間穿遂與光電交互作用，探討介觀尺度下之拘限效應對於光子輻射之可控性研究。

腔內量子電動力學的研究題材，也包含了經典原子和腔體輻射的交互作用與量子光學，而在 1980 年代中期達到鼎盛。如 MIT 的 Prof. Kleppner[1]和法國高等師範(Ecole Normale Supéieure) 的 Prof. Raimond 和 Harochei [2]發表過 Rydberg atom 之腔體耦合效應對自發性輻射之抑止和方向性增益的報導。

1997 年，D. L. Huffaker 等人利用分子束磊晶(MBE)之磊晶法，成功地成長出量子點結構之紅外光面射型雷射($In_{0.5}Ga_{0.35}Al_{0.15}As$) [3]。而在氮化物方面，N. Grandjean 利用 MBE 之自行聚集量子點成長法(稱為 Stranski-Krastanov growth) [4]來成長 InGaN/GaN 量子點結構，發現量子點結構有助於增強室溫之 PL 強度。另外，在 1999 年 7 月，德國 Wurzburg 大學 K. Tachibana 之研究群[5]，以及日本東京大學發表了光激發量子點結構的雷射(photo pumping laser)，其臨界光激發強度(threshold pump energy)為 6 mJ/cm2，TE 模式之頻譜，半高寬為 0.1 nm；他們利用 MOVPE 成長 $Al_{0.07}Ga_{0.93}N$ 包覆層(cladding lsyer)和 GaN 波導層(waveguide layer)，而波導層裡有 10 週期之 $In_{0.2}Ga_{0.8}N$ 之量子點，量子大小與高度分別為 19.5 nm 與 4.5 nm，而其每層分布密度為 $6x10^9$ cm^{-2}。H. X. Jiang 研究群將氮化銦鎵量子井結構做成微碟形結構(microdisk)，並觀察出其 Radial 模態，更做成陣列發光二極體。

(四) 研究方法、結果與討論

(1) We have established fabricating condition of GaN quantum dot (QD). The density of the GaN QD is about $5\times10^{8}cm^{-2}$ and the average size of these QDs are 45nm in depth and 45nm in width.

We have successful fabricated the GaN quantum confined nano islands in the GaN/AlN multiple layer structure using the AlN nanoholes as the shown in fig. 1.1. The surface morphology of both AlN samples were examined by the AFM shown in fig. 1.2. A 16-pair of AlN/GaN structure were grown on the sapphire substrate by MOCVD using the controllable growth interruption technique. After the AlN layer growth under N_2 ambient gas, we used a ten-second interruption growth with NH_3 and H_2 gases which was introduced to anneal the AlN surface to form nanoholes on AlN surface before the growth of GaN layer at 1040°C under H_2 carrier gas. The schematics of the growth procedures of multilayer GaN/AlN QDs structure by using AlN nanoholes template. We used transmission electron microscopy (TEM), to examine the cross-section of thick AlN/GaN bilayers as shown in fig. 1.3. The emission spectrum of QDs shown in fig. 1.4 was measured by micro-photoluminescence (μ-PL) using a commercial microscope system which consists of a Scanning Near-Field Optical Microscope (SNOM). From these μ-PL results, we conclude that the GaN QD emissions are strongly influenced by quantum confinement effect as well as by carrier localization in the QDs. In conclusion, we have successfully fabricated GaN quantum dots. These quantum dots shows strong vertical coupling effect and emits intense PL emission.

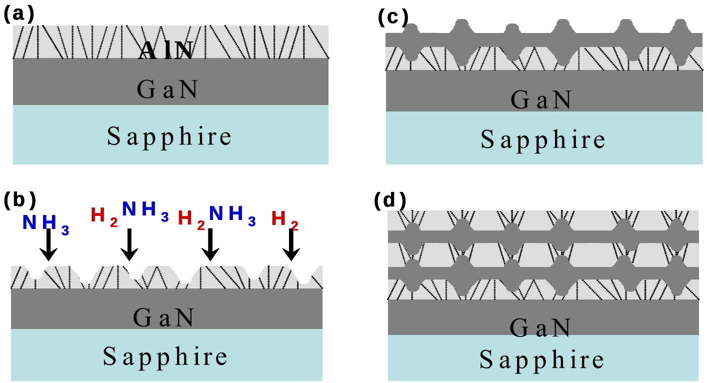

Figure 1.1 Formation principles of the GaN quantum dots

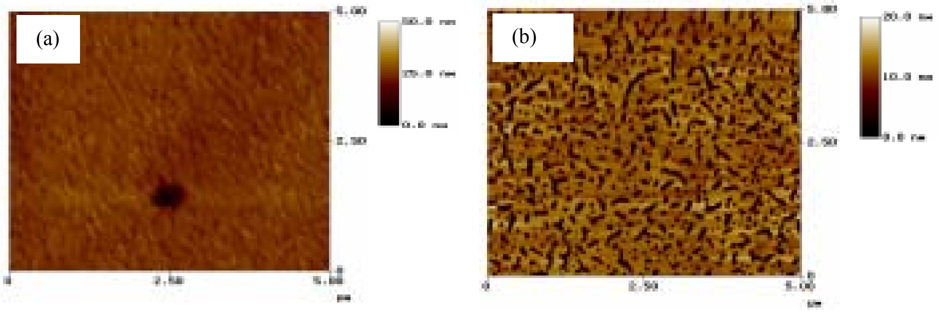

Figure 1.2 AFM morphologies of the AlN surface. (a) grown under N2 ambient, and (b) grown under H_2 ambient.

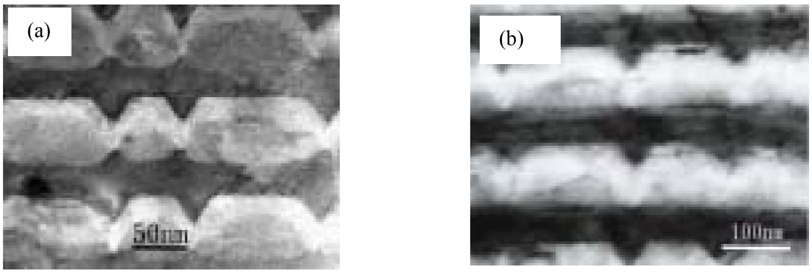

Figure 1.3 Cross-section TEM analysis results. The darker layers are GaN while the lighter layers are AlN. (a) with thin GaN layer thickness, and (b) with thick GaN layer thickness.

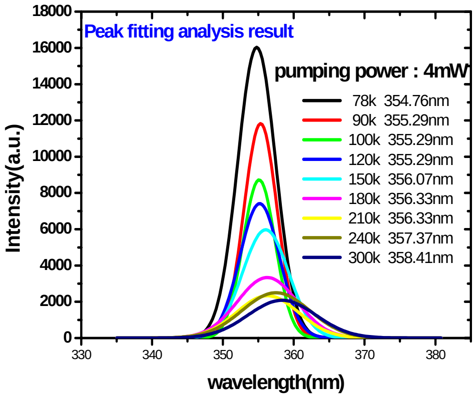

Figure 1.4 Power dependent μ -PL experiment spectra

(2) The fabrication technique of InGaN multi-quantum-wells (MQWs) nanorod was established successfully using induced coupled plasma reactive ion etching (ICP-RIE)

etching. The density of InGaN MQW nanorod is about 10^8-10^9 cm^{-2} and the diameter and height of a single InGaN MQWs nanorod were about 100 nm and 1 μm.

The fabrication technique of InGaN multi-quantum-wells (MQWs) nanorod was established successfully using induced coupled plasma (ICP) etching. In this research, two methods of InGaN MQWs nanorod fabricating were studied. The first method in this study, InGaN MQWs bulk samples grown by metal-organic chemical vapor deposition were etched by ICP dry etching directly under the fixed Cl2/Ar flow rate of 10/25 sccm, ICP/BIOS power of 200/200W, and chamber pressure of 4 pa, then the InGaN MQWs nanorod were fabricated with a density of 108-109 cm-2. In addition, the diameter and height of a single InGaN MQWs nanorod were about 100 nm and 1 μm as shown in figure 2.1 of scanning electron microscope (SEM) image. The transmission electron micrograph (TEM) image was also shown in figure 2.1. The MQWs layers were very clear to see from the TEM image. This technique provided a novel and one-step method for the fabrication of InGaN MQWs nanostructure. The optical properties of the nanorods were investigated using micro-photoluminescence (μ-PL) measurement. Figure 2.2 was the room temperature μ-PL spectra of the nanorods and the bulk which showed a large blue-shift compared with the bulk InGaN/GaN sample. The partial strain field release and the quantum confinement could be responsible of the blue-shift in the nanorod emission peak. In order to achieve the fabrication of nano-light-emitting and quantum confined device, we established another fabrication technique of InGaN MQWs nanorod using ICP dry etching with nickel (Ni) nano-mask as shown on figure 2.3. The p-GaN layer of the nano-structure fabricated by this technique not be etched, which provided a basis for the design of high efficiency nano-structure LED. In detail, about a 160 nm thick of silicon nitride (Si3N4) film was deposition on the surface of InGaN MQWs LED structure sample first by photo enhanced chemical vapor deposition (PECVD), and then the 100 nm thick Ni film was deposited using e-beam deposition system. Next the samples were treated with rapid thermal annealing (RTA) of 850 degree under nitrogen ambiance for one minute to form self-assembled Ni nanosized masks or clusters. After nanosized masks formation, the reactive ion etching (RIE) was processed using CF_4/O_2 gases to etch Si3N4 film. Then the samples were etched down to the n-type GaN layer by ICP-RIE (SAMCO ICP-RIE 101iPH). Finally, the remain of nano-masks above SiN film were removed in buffer oxide etchant and the fabrication of InGaN/GaN MQW nanorod were finished. The SEM image of the finished InGaN/GaN MQW nanorods fabricated by the ICP-RIE dry etching using Ni nano-masks is shown in figure 2.4. The mean dimension and density of the nanorods were about 80~100 nm and 1.5×10^{10} cm^{-2} respectively. In addition, the shapes of these nanorods are almost vertical and uniform. The TEM (JEOL, JEM-200CX) image of a single InGaN/GaN MQW nanorod is illustrated in figure. 2.5. It shows clearly that the diameter and length of a single nanorod are approximately 80 nm and 1 μm. The active region of five-period MQW is also observed evidently from the TEM image. The width of the quantum well and barrier are estimated to be about 5 and 25 nm.

Finally, we built up a novel and applicable technique to fabricate InGaN MQWs nano-structure LED for fabricating nano-LEDs in the future.

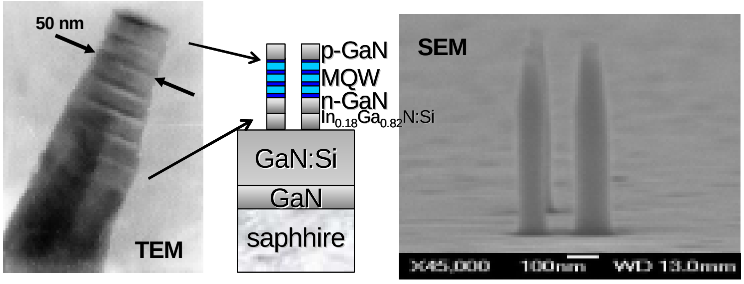

Figure 2.1 TEM and SEM images of InGaN MQWs nanorods fabricated by ICP etching directly.

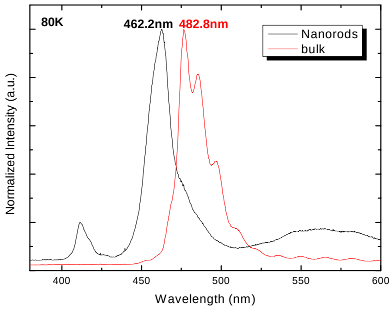

Figure 2.2 μ-PL spectra of bulk and InGaN MQWs nanorods fabricated by ICP etching directly.

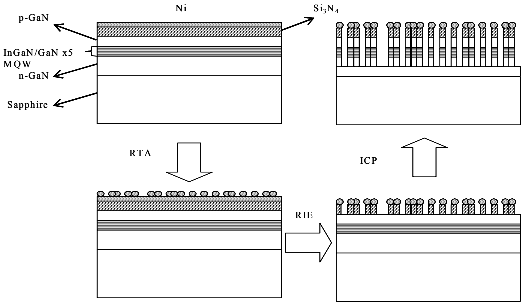

Figure 2.3 Schematic diagram showing the process of InGaN nanorods using self-assembled Ni nano-masks and ICP-RIE etching.

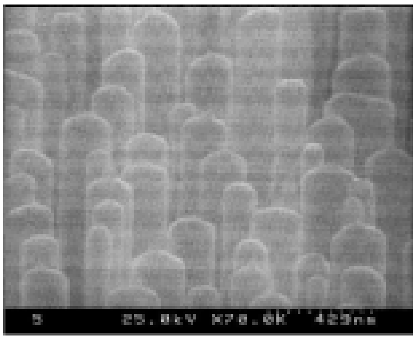

Figure 2.4 The SEM image of InGaN MQW nanorods fabricated by ICP-RIE etching using self-assembled Ni nano-masks.

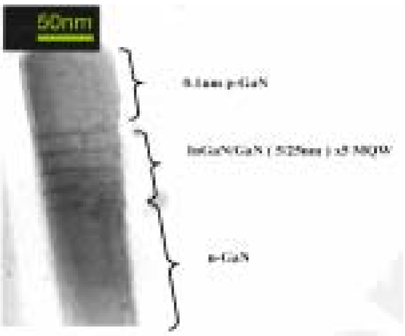

Figure 2.5 Transmission electron micrograph of a single InGaN MQW nanorod.

(3) Micro-cavity and device are successfully fabricated.

1. Successfully growth of GaN/AlN DBR and the reflectivity is about 94.5%.

The high-reflectivity AlN/GaN distributed Bragg reflector (DBR) structures were realized by metal organic chemical vapor deposition (MOCVD) growth under pure N_2 ambient for AlN epilayer growth. The TEM picture is shown in Fig.3.1. The highest peak reflectivity of about 94.5% with a stopband width of 18nm at a center wavelength of 442nm was obtained (Fig.3.2). For the DBR structure with AlN layer grown under mixture of N_2/H_2 and pure H_2 conditions, the center wavelength was blue-shifted to 418 and 371nm and the peak reflectivity also showed a reduction to 92% and 79%, respectively. The stopband width also decreases with increasing H_2 contents. The surface roughness and the grain size of the grown DBR structures showed an increase with increasing the H_2 ambient gas ratio. For realization of a high reflectivity and broad bandwidth of AlN/GaN DBR by using the MOCVD growth method, the pure N_2 ambient gas for growth of AlN layer should be preferable and optimal condition.

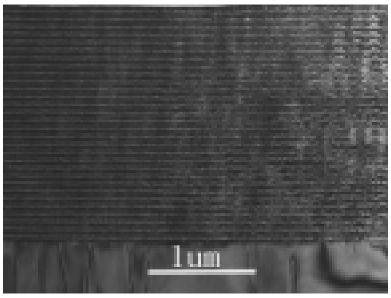

Fig. 3.1 TEM picture of GaN/AlN DBR.

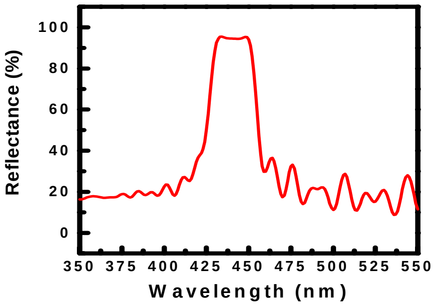

Fig. 3.2 The reclectivity of GaN/AlN DBR

2. Successfully established fabrication processes of micro-cavity GaN-based device.

The resonant-cavity light-emitting diode (RC-LED) structure was grown by MOCVD. The structure of RC-LED consisted of a 31 InGaN/GaN MQW LED cavity between the top TiO_2/SiO_2 DBR (81.7%, reflectance) and the bottom AlN/GaN DBR (90.4%) stack. The pictures of the top of the device are shown in Fig. 3.3(a)-(c) and the emission pictures are shown in Fig. 3.3(d)-(e). A stable 410nm emission peak and a low thermally induced red-shift effect (0.12 nm/kA/cm^2) were measured by varying the injection current density (Fig. 3.3(e)). The light output power of the full RC-LED device was three times higher than the RC-LED without top TiO_2/SiO_2 DBR layers under 600 A/cm^2 inject current density. The narrow line width of 7.4 nm, emission peak localization at 410 nm, and three times higher output power than the RC-LED without top TiO_2/SiO_2 DBR layers were caused by the resonance effect in this vertical cavity structure.

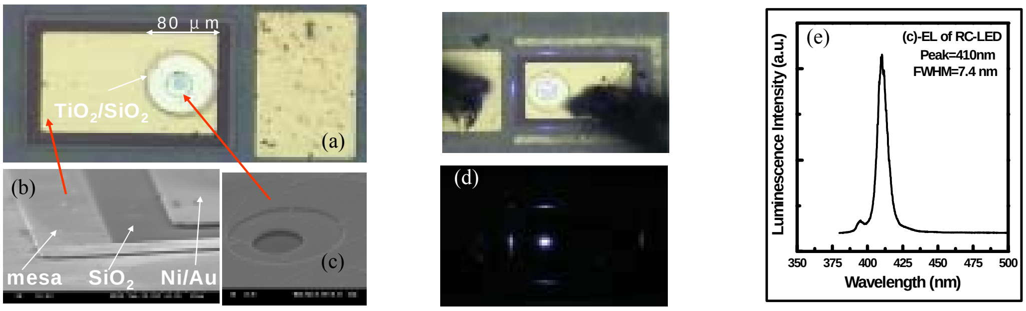

Fig. 3.3 (a) OM pictures (b)-(c) SEM pictures of GaN-based micro-cavity device. (d),(e) The emission images of GaN-based micro-cavity device. (e) The EL spectrum of the micro-cavity

3. Successfully established the framework of photo-enhanced wet oxidation to growth of Ga_2O_3 film on GaN and studied the characteristic of Ga_2O_3.

We investigate the crystallinity effect of gallium oxide (Ga_2O_3) on the electrical properties of n-gallium nitride (GaN) metal oxide semiconductor (MOS) devices. A thin strain-relieving layer (~ 20nm) of gallium oxynitride (GaON) with graded composition, as revealed by the x-ray photoemission spectroscopy, is shown to assist the oxide growth on GaN in the photo-enhanced chemical process. Improved MOS characteristics with high forward breakdown field EFB > 15 MV/cm, high value of gate oxide barrier height $_B \sim 2.2$ eV, and low interface state density $D_{it} \sim 3.5\times10^{11}$ cm^{-2}-eV^{-1}extracted by the conductance method are observed. The x-ray diffraction analyses of the oxide layer exhibit preferential orientations due to reflections from the (019) and (024) planes. These observations are ascribed to the formation of crystalline Ga_2O_3 layer on GaN as the oxide is transformed from a hydrous status into a monoclinic phase due to a post-growth thermal annealing in O_2 ambience.

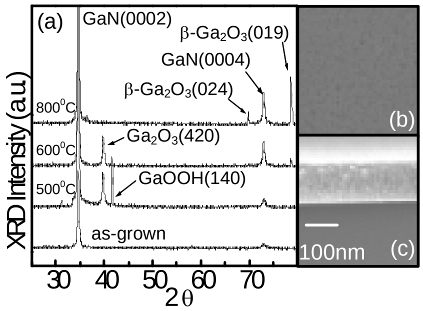

Fig. 1: (a) XRD spectra showing the progressive appearance of β Ga_2O_3 signals at 2*θ* angles corresponding to (019) and (024) planes as one increases the annealing temperature, and SEM micrograph showing (b) planar and (c) cross-section view of a Ga_2O_3 layer with ~150nm thickness on GaN.

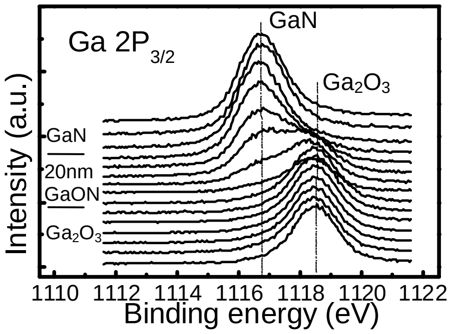

Fig.2: Depth-resolved XRS spectra showing a thin (~ 20nm) GaON intermediate layer with graded composition sandwiched between the surface Ga_2O_3 and bottom GaN layer.

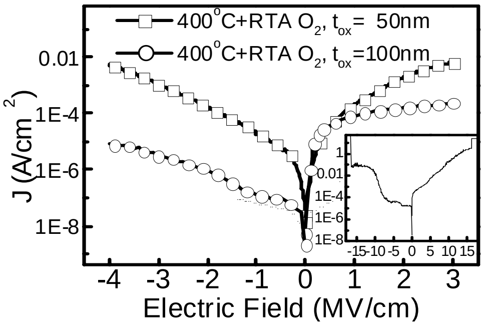

Fig.3: Field dependence of gate leakage current density in Ga_2O_3/GaN MOS devices with 50 and 100nm oxide thickness. The device area was ~ 4×10^{-4} cm.^{2}. Inset: showing a forward breakdown occurred at 15 MV/cm for the 50nm-thick Ga_2O_3/GaN MOS.

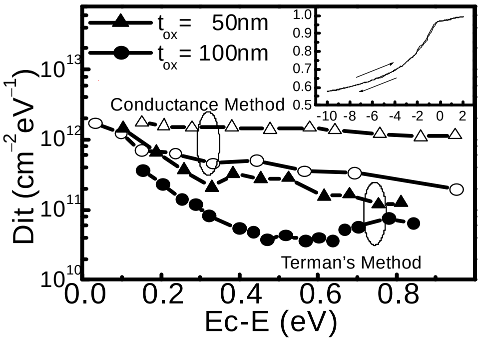

Fig. 4: measured interface state density for the 50nm and 100nm –thick Ga_2O_3/GaN MOS devices by the Terman and conductance methods, respectively. Inset: showing a narrow hysteresis window (~ 0.26V) and the MOS operation characteristics in the high-frequency (1MHz) CV data of the 100nm thick Ga_2O_3/GaN MOS device.

(五) Reference

[1] R. G. Hulet, E. S. Hilfer, and D. Kleppner, Phys. Rev. Lett. 55, 2137 (1985).

[2] P. Goy, J. M. Raimond, M. Gross, and S. Haroche, Phys. Rev. Lett. 50, 1903 (1983).

[3] E. Kapon,D. M. Hwang, M. Walther, R. Bhat, and N. G. Stoffel, Surf. Sci. **267**, 593 (1992)

[4] C. Weisbuch and B. Vinter, Quantum Semiconductor Structures (Academic, San Diego, CA, 1991)

[5] D. L. Huffaker, O. Baklenov, L. A. Graham, B. G. Streetman, and D. G. Deppe, Appl. Phys. Lett. **70**, 2356 (1997)

(六) 與國外學術合作

Prof. S. C. Wang already achieved an agreement with Prof. Yamamoto of Stanford University on cooperation of developing next generation GaN single photon emitter. This cooperation will support a Ph.D. student for a short study at Stanford University.

(七) 計畫成果自評

本計畫第一年預定目標如下：

(1) 建立具備光學微共振腔之低維氮化鎵量子點、柱結構生長與製作，包括氮化鎵DBR反射膜與量子點之磊晶成長研究。

(2) 氮化鎵面射型雷射結構之製程研究。

(3) 以自組式光致氧化技術，生長二維奈米尺度之AlGaO、InGaO/GaN量子柱結構。

在相關研究人員包括所有計畫共同主持人、博士後研究員、博碩士生在這一年的努力之下，才能有此豐富的成果報告，包括成功利用有機化學氣相沈積系統成長氮化鎵量子點、利用乾式蝕刻方式蝕刻出直徑約100 nm的奈米柱（其中奈米柱裡包含多重量子井（發光層））、設計並成長出AlN/GaN DBR 多層反射膜、以及氮化鎵微共振腔發光元件之設計與成長、以及氮化鎵氧化技術之建立，所以與原計畫所預定的目標相符程度大約有九成以上，加上所發表的學術論文及國際期刊，可說是已經和外國學術研究的主要方向一致，故已爭取到和國際學術上量子物理研究之權威，史丹佛大學的Yamamoto教授的研究群合作研究GaN QD和nanorod的特性。

因此，在第二年的目標裡將會基於第一年所研究的技術與成果建立光學微共振腔結構之物理性質量測與分析，包含氮化鎵面射型雷射結構之光學與電性特性量測、分析，氮化鎵面射型雷射結構與磊晶層之表面物理特性分析，生長AlGaO、InGaO等光致自然氧化薄膜技術，研究其對於光學微型共振腔之表面保護、光學係數匹配，以及對於光學增益係數之提昇，還需要大家在未來的日子裡，持續保持合作精神以及繼續努力，以期讓計畫有圓滿的成果。

(八) 研究成果紀錄----附件一

附件一

「氮化鎵介觀尺度下量子局限結構之光子幅射可控性研究」研究成果紀錄

總主持人：王興宗 服務機關：國立交通大學光電工程研究所

共同主持人：孟心飛，彭隆瀚，林恭如，郭浩中

計畫執行期限：92/08/01~95/07/31

填表日期：

研究成果		92 年度	93 年度	94 年度	總計
期刊論文	國內(篇數)	1			
	國際(篇數)	30			
會議論文	國內外(篇數)	42			
智慧財產權	專利(案數)	5(申請中)			
	技術移轉(件數)				
人才培育	博士生培育(人數)	13			
	碩士生培育(人數)	13			

註：人才培育人數請勿重複計算

發表之期刊論文列表

註：請按發表時間先後順序填寫，每篇請依作者姓名(主要作者請以粗體字標示)、期刊年份、題目、期刊名稱、起迄頁數、期刊資料庫類別(**SCI**、**SSCI**、**EI**…)之順序填寫。

例：1.Chen YJ, Chen PJ, Lee MC, Yeh SH, Hsu MT, and **Lin CH**. (2002) Chromosomal analysis of non-malignant liver tumors by comparative genomic hybridization. *Genes Chromosomes and Cancer* 35:2 (**SCI**)

國際期刊論文：

1. **Kuo H. C.**, Yao H. H. Chang Y. S., Chang Y. A. and **Wang S. C.** (2004) MOCVD growth of InGaAs:Sb-GaAs-GaAsP Quantum Well Vertical Cavity Surface Emitting Lasers with 1.27 m Emission Wavelength accepted to be published in *J. of Crystal Growth* (**SCI**).

2. **Kuo H. C.**, Chang Y. S., Yao H. H., Chang Y. A. and **Wang S. C.** (2004) High-Speed Modulation of InGaAs:Sb-GaAs-GaAsP Quantum Well Vertical Cavity Surface Emitting Lasers with 1.27 m Emission Wavelength submitted to *IEEE Photonic Technology Letter* (**SCI**).

3. Huang H. W., Kao C. C., Hseuh T. H., Yu C. C., **Kuo H. C.** and **Wang S. C.** (2004) Fabrication of GaN based nanorods using self-assemble Ni nano-mask submitted to *Material Sciences &Engineering B* (**SCI**).

4. Kao Chih Chiang, Huang H.W., **Kuo H. C.**, Chu J . T., Yu C. C. , Lin C. F., and **Wang S. C.** (2004) Control of GaN Etching Profile in Cl_2/Ar Inductively Coupled Plasma Reactive Ion Etching submitted to *Material Sciences &Engineering B* (**SCI**).

5. **Kuo H. C.**, Chang Y. S., Lai F. I, Hseuh T. H. and **Wang S. C.** (2004) Fabrication of high speed InGaAsP/InGaP strain-compensated VCSELs with 850 nm emission wavelength" accepted to be published in *IEEE J. of Light Wave Technologies* (**SCI**).

6. Laih L. H., **Kuo H. C.** and **Wang S. C.**, (2004) As^+ implanted AlGaAs oxide-confined VCSEL with enhanced oxidation rate and high performance uniformity" accepted to be published in *IEEE Photonic Technology Letter*, June (**SCI**).

7. **Kuo H. C.** and Wang S. C., (2004) MOCVD growth of high performance InGaAsP/InGaP strain-compensated VCSELs with 850 nm emission wavelength *J. Crystal Growth*, 261 P. 355-358 (**SCI**).

8. **Kuo H. C.,** Chang Y.S., Lai F. Y., Hseu T. H. Chu L. T., Laih L. H., and **Wang S. C.** (2004) High speed performance of 850nm silicon-implanted AlGaAs/GaAs vertical cavity surface emitting lasers, *Solid State Electronics*, vol. 48, p483-485 (**SCI**).

9. Lu T. C., Hsu W. C., Chang Y. S., **Kuo H. C.** and **Wang S. C.** (2004) Measurement of Spontaneous Emission of oxide confined VCSEL accepted to be published in *Journal of Applied Physics* (**SCI**).

10. Huang H. W., Yu C. C., **Kuo H. C.** and **Wang S. C.**, (2004) Effect of rapid thermal annealing on beryllium implanted p-type GaN *Material Sciences &Engineering B*, Vol: 107 Issue: 3, March 25 (**SCI**).

11. Kao C.C., Huang H. W., Yu C. C., **Kuo H. C.**, Wang S. C., (2004) Study of dry etching for GaN and InGaN-based laser structure using inductively coupled plasma reactive ion etching

Material Sciences &Engineering B 107, p. 283-288 (**SCI**).

12. Chu Chen-Fu, Lai Fang-I, Chu Jung-Tang, Yu Chang-Chin, Lin Chia-Feng, **Kuo H. C.**, and **Wang S. C.** (2004) Study of GaN Light Emitting Diodes Fabricated by Laser Lift-off Technique *Journal of Applied Physics* vol. 95, No.8, p3916-3922 (**SCI**).
13. Yao H. H., Lin C. F., **Kuo H. C.** and **Wang S. C.** (2004) MOCVD growth of A1N/GaN DBR structures under various ambient conditions *J. of Crystal Growth*, 262, p.151-156, (**SCI**)
14. Lin C. F., Yao H. H., **Kuo H. C.** and **Wang S. C.** (2004) MOCVD growth of GaN/InGaN RCLED *J. of Crystal Growth*, 261, p 124 (**SCI**).
15. Lu T. C., Chu Z. T., Chu J. Y., Chang Y. S., **H. C. Kuo** and **Wang S. C.**, (2004) Comparison of InP/InGaAlAs and InAlAs/InGaAlAs distributed Bragg reflectors grown by metalorganic chemical vapor deposition *Material Sciences & Engineering B*, Vol: 107 Issue: 1, February 25 (**SCI**).
16. Lin C. F., Yao H. H., and **Wang S. C.** (2004) MOCVD growth of AlN/GaN distributed Bragg reflector structures under various ambient conditions *J. Crystal Growth*, 262, 151(**SCI**).
17. Chang Y H, Lai Fang-I, Lu C Y, **Kuo H C**, Yu H C, Sung C P, Yang H P and **Wang S C** (2004) High-speed (>10 Gbps) 850 nm oxide-confined vertical cavity surface emitting lasers (VCSELs) with a planar process and reduced parasitic capacitance *Semicond. Sci. Technol.* 19 L74-L77 (**SCI**).
18. Lai Fang-I, Hsueh TH, Chang Ya-Hsien, Laih Li-Hong, **Kuo Hao-Chung** and **Wang S.C.** (2004) 10 Gb/s single-mode vertical-cavity surface-emitting laser accepted for publication in *Semiconductor Science and Technology* (**SCI**).
19. Hsueh TH, Chang YH, Lai FI, Hung HW, Ou-yang MC, Chang CW, Kuo HC, and **Wang SC** (2004) Fabrication and emission characteristic of InGaN/GaN multiple quantum wells nanorods, to be submitted *JAP* (**SCI**).
20. **Lin Gong-Ru** and Lin Chun-Jung (2004) Improving the Blue-Green Electroluminescence of a Metal-Oxide-Semiconductor Diode on SiO_2/Si by Multi-Recipe Si-Ion-Implantation and Long-Term Annealing *Journal of Applied Physics*, June (**SCI**).
21. **Lin Gong-Ru**, (2003) The Effect of Low-Temperature Annealing on the Defect-Induced Anomalous Electrical Characteristics of Silicon-Implanted Borosilicate Glass *Journal of Applied Physics*, Vol. 94, No. 12, pp. 7542-7546, December (**SCI**).
22. Lai Fang-I, Hsueh Tao-Hung, Chang Ya-hsien, Shu Wen-chun, Lai Li-Hung, **Kuo H. C.** and **Wang S. C.** (2003) Performance of 850 nm VCSEL utilizing Si implant induced disordering *Solid State Electronics*, vol. 47, issue 10, 1805 (**SCI**).
23. Lin C. F., Yao T. H., and Wang S. C. (2004) Effect of ambient gas on the AlN/GaN distributed Bragg reflector structures submitted for publication in *Jpn. J. App. Phys* (**SCI**).
24. He J. L., Lee C. K., Jung Y. J. Huang, **Wang S. C.**, **Pan C. L.** and Huang K. F. (2003) Diode pumped passively mode-locked multiwatt Nd:GdVO4 laser with a saturable Bragg reflector *Applied Optics*, Vol. 42, No.27, 5496, Sept (**SCI**).
25. Tsai J. Y., Lu T. C., and **Wang S. C.**, (2003) High reflectivity distributed Bragg reflectors for 1.55 m VCSELs using InP/air-gap *Solid State Electronics*, vol. 47, issue 10, 1825, Oct.

(**SCI**).

26. Chang L. B., and **Wang S. C.**, (2003) Numerical study of multiple-pass effect by total internal reflection on second harmonic conversion in $Kbe_2Bo_3F_2$ (KBBF) crystal accepted for publication in *Jap. J. of Appl. Phys.* Nov (**SCI**).
27. Lu T. C., Chu Z. T., Chu J. Y., Chang Y. S. and **Wang S. C.** (2003) Comparison of InP/InGaAlAs and InAlAs/InGaAlAs distributed Bragg reflectors grown by metalorganic chemical vapor deposition accepted for publication in *Material Sciences &Engineering B*, Nov (**SCI**).
28. Chang L. B., **Wang S. C.**, and Kung A., (2003) Numerical analysis of fifth harmonic conversion of low-power pulsed Nd:YAG laser with resonance of second harmonic *Jpn. J. Appl. Phys.* Vol. 42 Part 1, No. 7A, 4318, (**SCI**).
29. Hsueh T. H., **Kuo H. C.**, Lai F. I., Laih L. H. and Wang S. C., (2003) High speed characteristics of large area single transverse mode vertical cavity surface emitting lasers *Electronics Letters*, Vol. 39, No. 21, 1519, Oct. (**SCI**)
30. **Kuo H. C.**, Chang Y. S., Lai F. Y., Hsueh T. H., Lai L. H., and Wang S. C. (2003) High speed modulation of 850 nm InGaAsP/InGaP strain-compensated VCSELs *Electronics Letters*, Vol. 39, No. 14, 1051, July (**SCI**).

國內期刊論文：

1. **Lin Gong-Ru,** Chang C.-J., and Yu K.-C., (2003) 熱退火矽離子佈植二氧化矽金氧半二極體的電致藍綠螢光與電流電壓特性分析”, 工程科技通訊, *Engineering Science & Technology Bulletin*, NSC, Vol. 67, Issue 10, pp. -, October.

國內外會議論文：

A. Award:

Prof. S. C. Wang awarded *Micro-optics award* 2003.

B. 國外會議:

(a) Plenary talk

1. **Wang SC** (2003), White light–Dawn and semiconductor sun–, International *Micro Optics Conference 2003*, Plenary paper A3.

(b) Invited talk

1. **Wang SC** (2004), Fabrication and emission characteristics of p-GaN and GaN multiple quantum well nanorods, (2004) *US Airforce & Taiwan Nanoscience Initiative Workshop*, paper C5.
2. **Wang SC** (2003) Progress in GaN based blue and ultraviolet light emitting devices, *PR/CLEO 2003*, Invited Paper W4B-(2)-1.

(c) paper published

1. Hsueh TH, Chang YH, Lai FI, Hung HW, Ou-yang MC, Chang CW, **Kuo HC**, and **Wang SC** (2004), Fabrication and emission characteristic of InGaN/GaN multiple quantum wells nanorods, *CLEO 2004*, IWA20.
2. Lai FI, Chu CF, Chu JT, Yu CC, Lin CF, **Kuo HC**, and **Wang SC** (2004), Improvement of high power and high current operation of GaN lught emitting diodes by laser lift-off technique, *CLEO 2004*, CWA29.

3. **Kuo HC**, Chu CF, Chu JT, Lai FI, Yu CC, Lin CF and **Wang SC** (2004) Fabrication of GaN vertical light emitting diodes on copper substrates by laser lift-off, *ISBLLED-2004*, B2-4.
4. Yu Kuo-Cheng, Lin Chun-Jung, Ou-yang M.-J., **Kuo Hao-Chung**, and **Lin Gong-Ru**, (2004) Correlation between Surface Charge Accumulation and Pumping Intensity Dependent Red-Shifted Micro-Photoluminescence of Si-Implanted Quartz with Buried Si Nanocrystals, The 2004 Materials Research Society Spring Meeting (*MRS2004*), poster paper. A4.37, San Francisco CA, USA, April 12-16, 2004.
5. Lin Chun-Jung and **Lin Gong-Ru**, (2004) Luminescent lifetime analysis of silicon-ion-implanted glass and SiO2/Si at different annealing processes, *Photonics West 2004*, Symposia: Ultrafast Phenomena in Semiconductors and Nanostructure Materials VIII, San Jose, California, 25-29 January 2004.
6. **Kuo HC**, Chang YH, Hseuh TH, Lai FI,and **Wang SC** (2003). Development of 850nm VCSELs for OC-192 Application, *ECS conference*.
7. Chang Y. H., Hsueh T. H., Lai FangI., **Kuo H. C.**, and **Wang S. C.** (2003), Micro-spectroscopy of Mg-doped GaN nanorods, *ECS conference*.
8. Lee CK, He LL, Huang JY, **Wang SC**, Huang KF, and **Pan CL** (2003) Intra-cavity frequency doubled and passively mode-locked diode-pumped Nd:GdVO4/KTP laser with a saturable Bragg Reflector, *PR/CLEO 2003*, paper TH2I-(1)-2
9. Chen YS, Tsai SW, **Wang SC**, and **Chen YF**(2003)Diode-pumped Q-switched yellow laser with single-pass sum-frequency mixing: comparison between PPLN and PPKTP, *PR/CLEO 2003*, paper TH2I-(1)-4
10. Lai FI, Laih LH, Hsueh TH, Tseng SP, **Kuo HC**, and **Wang SC** (2003) Performances and reliability of 850nm VCSELs with various offset in gain peak and Fabry-Perot dip, *PR/CLEO 2003*, paper THP-(2)-5
11. **Kuo HC**, Shu WC, Lu TC, Chang YH, Lai FI, Lai LH, and **Wang SC** (2003) Characterization of 850nm AlGaAs/GaAs implant vertical cavity emitting lasers utilizing silicon implantation induced disordering, *PR/CLEO 2003*, paper THP-(2)-6.
12. Hsueh TH, **Kuo HC**, Lai FI, Lai LH, and **Wang SC** (2003) High performance large-area single-mode vertical-cavity surface-emitting lasers, *PR/CLEO 2003*, paper W2B-(2)-3
13. **Kuo HC**, Lu TC, Chang YS, Lai FY, Kao GC, Laih LH, and **Wang SC** (2003) Growth and characterization of 850nm InGaAsP/InGaP strain-compensated VCSELs by MOCVD, *PR/CLEO 2003*, paper W2B-(2)-7
14. Lai FI, LH Laih, Chang YS, Shei TH, **Kuo HC**, and **Wang SC** (2003), Enhancement of proton-implanted GaAs VCSEL performance by transparent overcoating, *PR/ CLEO 2003*, paper WP-(2)-9
15. Lin Chun-Jung and **Lin Gong-Ru**, (2003) Continuous-Wave and Time-Resolved Photoluminescence Analysis of Defect Density Evolution in Silicon Implanted Borosilicate Glass, The Fifth Pacific Rim Conference on Lasers and Electro-Optics (*CLEO/PR 2003*), oral paper #P1038, Taipei, Taiwan, December 15-19, 2003.
16. Yu Kuo-Cheng and **Lin Gong-Ru** (2003) Enhanced Visible Photoluminescence of

Multi-Energy Silicon Ion Implanted SiO2 Films", The Fifth Pacific Rim Conference on Lasers and Electro-Optics (*CLEO/PR 2003*), oral paper #P0485, Taipei, Taiwan, December 15-19, 2003.

17. **Lin Gong-Ru** and Lin Chun-Jung, (2003) The Blue-Green Luminescence and Current-Voltage Characteristics of MOS Diode Made on Thermally Annealed Si^+ Implanted SiO_2 Substrate, *IEEE Third Nanotechnology Conference*, Secession WK: Nano-Optics, Nano-Optoelectronics, Nano-Photonics-II, oral paper WK5, San Francisco, CA, August 12-14, 2003.
18. Yao H. H., Lin C. F., **Wang S. C.**, (2003) MOCVD growth of AlN/GaN DBR structure under various ambient conditions, *MRS*, paper PM C2.5
19. C.-J. Lin and **Gong-Ru Lin**, (2003) CW and Time-Resolved Photoluminescence Analysis of Silicon Implanted Glass Low-Temperature Annealed at Different Times, *MRS Spring Meeting*, paper #14.4, San Francisco, California, April 21-25, 2003.

C. 國內會議

1. **Kuo HC**, Chang YA, Chang GW, Tsai MY, and **Wang SC** (2004) Effect of Sb incorporation on optical properties of InGaAsN/GaAsN grown by MOCVD, *physics annual meeting 2004,* page 249
2. Hsueh TH, **Kuo HC**, Chang YS, Huang HW, Ou-yang MC, Chang CW and **Wang SC** (2004), Optical and structural properties of $In_{0.3}Ga_{0.7}N$/GaN nanowires, *physics annual meeting 2004*, page 320-321
3. Chang YH, Kao CC, Hsueh TH, Lu TC, **Kuo HC**, and **Wang SC** (2003) High speed modulation of InGaAsP/InGaP strain-compensated VCSELs, *Optics and Photonics Taiwan '03*, paper TB2-6
4. Hsieh YL, Lu JW, Yao HH, Lin CF, **Kuo HC**, and **Wang SC** (2003) Fabric ation and characteristic measurement of GaN surface light emitting devices, *Optics and Photonics Taiwan '03*, paper FA1-2
5. Lai FY, Chu CF, Chu JT, Lin CF, **Kuo HC**, and **Wang SC** (2003) Large area emission of GaN light emitting diodes fabricated by Ni bonding process and laser lift-off technique, *Optics and Photonics Taiwan '03*, paper FA1-5
6. Luo CL, Zeng GF, Chang YH, Lai FY, **Kuo HC**, and **Wang SC** (2003) Simula tion of multimode operation effects on modulation response of VCSEL, *Optics and Photonics Taiwan '03*, paper FA2-6
7. Chang CW, Lee CL, Chang YH, O-Yang MC, **Kuo HC**, and **Wang SC** (2003), Photoluminescence of gaN grown by HVPE with different V/III ratio, *Optics and Photonics Taiwan '03*, paper FA2-7
8. Lai FY, Hsueh TH, Chang YH, Hsu WC, Lai LH, **Kuo HC**, and **Wang SC** (2003) Performance of enhancement of AlGaAs/GaAs VCSEL utilizing silicon implantation induced disordering, *Optics and Photonics Taiwan '03*, paper FB3-1,
9. Ou-Yang MC, Hsueh TH, Chang YH, Chang CW, **Kuo HC**, and **Wang SC** (2003) Fabrication and optical characteristic of InGaN Multi-quantum well nanorods, *Optics and Photonics Taiwan '03*, paper FA3-3
10. Chu RT, Lu TC, Laih LH, **Kuo HC**, and **Wang SC** (2003) Optically pumped

double-fused 1.52 μm vertical cavity, *Optics and Photonics Taiwan '03*, paper FB3-3

11. Chang YA, Kuo YK, **Kuo HC**, and **Wang SC** (2003) Effect of inhomogeneous hole distribution in violet-blue InGaN quantum-well lasers, *Optics and Photonics Taiwan '03*, paper FB3-7
12. Chen WY, Lai FY, Chang YH, Laih LH, **Kuo HC**, and **Wang SC** (2003), Performance of GaAs VCSEL with a top transparent, *Optics and Photonics Taiwan '03*, paper FB3-8
13. Lu JY, Chang YH, Lai FY, **Kuo HC**, and **Wang SC** (2003) Small signal modulation response of oxide-confined VCSEL with different aperture size, *Optics and Photonics Taiwan* '03, paper FB4-2
14. Tsai JY, Lu TC, **Kuo HC**, and **Wang SC** (2003) MOCVD growth of high quality distributed Bragg reflectors for 1.55- m VCSEL application, *Optics and Photonics Taiwan '03*, paper PA1-18
15. Chang YH, Chang CW, Yu CC, **Kuo HC**, and **Wang SC** (2003) Observation of enormous blue-shift in photoluminescence spectrum of Mg-doped GaN Nanorods, *Optics and Photonics Taiwan '03*, paper PA1-10
16. Lu TC, Chang YH, Chang CW, Hsu WC, **Kuo HC**, and **Wang SC** (2003) Spectrally resolved spontaneous emission patterns of oxide-confined vertical-cavity surface-emitting lasers, *Optics and Photonics Taiwan '03*, paper PA1-11
17. Peng WL, Laih LH, Lai FY, Hsueh TH, Kuo HC, and Wang SC (2003) As+ implanted AlGaAs oxide-confined VCSEL," *Optics and Photonics Taiwan '03*, paper PA2-10
18. Lin Chun-Jung, Yu Kuo-Cheng, **Kuo Hao-Chung**, and **Lin Gong-Ru**, (2003) The defect-related blue-green photo- and electro-luminescence of thermally annealed Si$^+$ implanted SiO$_2$, *Conference of Optics and Photonics Taiwan'03*, paper , Taipei, Taiwan, Dec. 25-26, 2003.
19. **Lin Gong-Ru**, Lin Chun-Jung, and Yu Kuo-Chen, (2003) Determination of defect category and concentration in thermally annealed Si$^+$ implanted SiO$_2$ using time-resolved photoluminescence and capacitance-voltage analysis, *Conference of Optics and Photonics Taiwan'03, paper* , Taipei, Taiwan, Dec. 25-26, 2003.
20. Yu Kuo-Cheng, Lin Chun-Jung, Ou-yang M.-J., **Kuo Hao-Chung**, and **Lin Gong-Ru**, (2003) Pumping intensity dependent red-shift micro- photoluminescence of silicon-ion-implanted quartz induced by anomalous carrier transfer between self-coupled Si nanocrystals, *Conference of Optics and Photonics Taiwan'03*, paper , Taipei, Taiwan, Dec. 25-26, 2003. (2003 年光電科技研討會學生論文獎)

專利列表

類別	專利名稱	申請日期	專利申請國	申請案號/專利號碼	申請人	專利期間	備註
	產生高電洞載子濃度與低阻值歐姆接觸 P 型氮化鎵材料之製作方法		台灣		王興宗		申請中
	產生氮化鎵材料奈米結構之製作方法		台灣		王興宗		申請中
	利用雷射剝離與新型晶片接合技術製作大面積、高電流、大發光功率之氮化鎵紫藍綠光發光元件		台灣		王興宗		申請中
	氧化型垂直共振腔面射型雷射的製作		台灣		王興宗		申請中
	單模態輸出光之垂直共振腔面射型雷射		台灣		王興宗		申請中

註：「類別」請填入代碼：(A)發明專利(B)新型專利(C)新式樣專利。