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

介觀尺度下氮化鎵量子侷限結構在高 Q 值微共振腔之光子輻射可控性研究(2/3)

計畫類別：■ 個別型計畫　　□ 整合型計畫
計畫編號：NSC 96－2120－M009 －006
執行期間：96 年 08 月 01 日至 97 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）、T.C.Lu(盧廷昌)、C.F.Lin(林佳峰)

計畫參與人員：李鎮宇(博士後)、邱麗君(助理)、博士生：巫漢敏、朱榮堂、王德忠、柯宗憲、賴俊峰、羅明華、邱清華、陳士偉、凌碩均、陳俊榮、鄭柏孝、劉禮榮、陳振昌、黃輝敏、劉士嘉、劉子偉、張家銘、李昀恬、林伯駿、楊恕帆、謝承恩、蘇伯源、黃建達、卓立夫、柯智淳、洪政暐、陳建綱、黃治凱、楊尚樺、劉玫君、劉亭均、蕭睿中、楊勁生。

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
本成果報告包括以下應繳交之附件：
□赴國外出差或研習心得報告一份
□赴大陸地區出差或研習心得報告一份
■出席國際學術會議心得報告及發表之論文各一份
□國際合作研究計畫國外研究報告書一份

處理方式：除產學合作研究計畫、提升產業技術及人才培育研究計畫、列管計畫及下列情形者外，得立即公開查詢
□涉及專利或其他智慧財產權，□一年■二年後可公開查詢

執行單位：交通大學光電工程學系

中　華　民　國 97 年 5 月 26 日

1. 計畫背景：

計畫主持人及共同主持人（PI and Co-PIs）：

主　持　人	王興宗　教授	國立交通大學光電工程系(所)
(PI)	Prof. S. C. Wang	Dept. Photonics, NCTU
共同主持人	彭隆瀚　教授	國立台灣大學光電工程學研究所
(Co-PIs)	Prof. L. H. Peng	Grad. Inst. EO Eng, NTU
共同主持人	孟心飛　教授	國立交通大學物理研究所
(Co-PIs)	Prof. H. F. Meng	Inst. Physics, NCTU
共同主持人	郭浩中　副教授	國立交通大學光電工程系(所)
(Co-PIs)	Prof. H. C. Kuo	Dept. Photonics, NCTU
共同主持人	盧廷昌　助理教授	國立交通大學光電工程系(所)
(Co-PIs)	Prof. T. C. Lu	Dept. Photonics, NCTU
共同主持人	林佳鋒　副教授	國立中興大學材料所
(Co-PIs)	Prof. C. F. Lin	Dept of Materials Engineering, NCHU

研究題目（Project Title）：介觀尺度下氮化鎵量子侷限結構在高Q值微共振腔之光子輻射可控性研究(Research on Mesoscopic GaN-based Quantum Confined Structures with High-Q Microcavity for Control of Photon Emission)

主持人執行機構（Organization）：國立交通大學光電工程系(所) (Dept. Photonics, NCTU)

全程計畫執行期限（Project period）：95 年 8 月 1 日-98 年 7 月 31 日 (2006/08/01~2009/07/31)

分年經費（Budget per year）：

2006	2007	2008
NTD:5,375,000 元	NTD:4,300,000 元	NTD:3,225,000 元

2. 計畫目標：

In this proposal, we propose to conduct research on the control of photon emission from mesoscopic GaN-based vertical cavity surface emitting laser (VCSEL) with quantum confined structures with high Q microcavity. The major objectives include

(1) Establishment of GaN based quantum confined structures fabrication technology;
(2) Modeling and design of high Q microcavity and cavity quantum effect;
(3) Fabrication of GaN VCSEL with microcavity and quantum confined structures;
(4) Investigation of performance of the fabricated GaN VCSEL devices;
(5) Demonstration of controlled photon emission and lasing of the GaN VCSEL devices.

3. 參與計畫單位及人數：

PI	Prof. S. C. Wang	Dept. Photonics, NCTU

Co-PIs	Prof. L. H. Peng	Grad. Inst. EO Eng, NTU
Co-PIs	Prof. H. F. Meng	Inst. Physics, NCTU
Co-PIs	Prof. H. C. Kuo	Dept. Photonics, NCTU
Co-PIs	Prof. T. C. Lu	Dept. Photonics, NCTU
Co-PIs	Prof. C. F. Lin	Dept of Materials Engineering, NCHU
Collaboration	Prof. Y. Yamamoto Prof. S. H. Fan	Stanford University, USA
Collaboration	Prof. K. Iga Prof. F. Koyama	Tokyo Institute of Technology, Japan
Collaboration	Prof. S. L. Chuang	University of Illinois –Urbana Champaign
Collaboration	Dr. R. Soref	US Air force

4. 限本奈米國家型計畫產生之研究成果統計表

篇數 / 統計類別	2005	2006	2007	2008
國外期刊論文	10	28	33	21 (up to now)
國內期刊論文	0	0	0	0

5. 請列出最具代表性之論文或專利至多 **6** 篇：

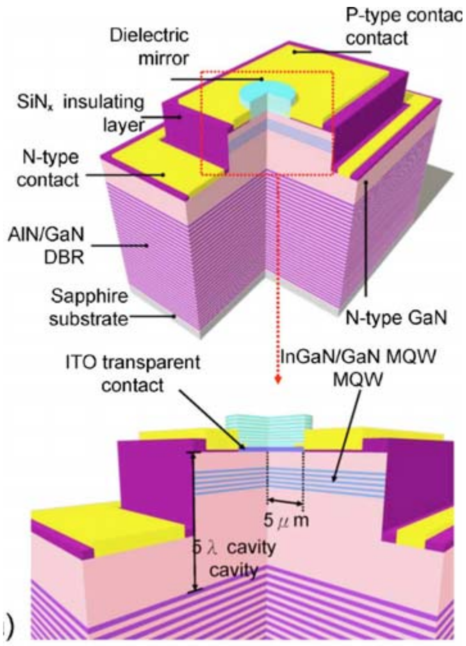
1. Tien-Chang Lu, Chih-Chiang Kao, Hao-Chung Kuo, Gen-Sheng Huang, and Shing-Chung Wang “CW Lasing of Current Injection Blue GaN-Based Vertical Cavity Surface Emitting Laser”, **Appl. Phys. Lett.**, 92, 141102 (2008).
2. T. C. Lu, S. W. Chen, L. F. Lin, T. T. Kao, C. C. Kao, P. C. Yu, H. C. Kuo, S. C. Wang and S. H. Fan, “GaN-based two-dimensional surface-emitting photonic crystal lasers with AlN/GaN distributed Bragg reflectors”, **Appl. Phys. Lett**., 92, 011129 (2008)
3. “Broadband and omnidirectional antireflection employing disordered GaN nanopillars”, accepted and to be published in **Optical Express**.
4. C. H. Chiu, T. C. Lu, H. W. Huang, C. F. Lai, C. C. Kao, J. T. Chu, C. C. Yu, H. C. Kuo, and S. C. Wang, C. F. Lin, T. H. Shueh, “Fabrication of InGaN/GaN MQW nanorods LED by ICP-RIE and PEC oxidation process with self-assembly Ni metal islands”, **Nanotechnology**, V18, N.44, p445201 (Nov. 7, 2007)
5. C. E. Lee, H. C. Kuo, Y. C. Lee, M. R. Tsai, T. C. Lu, S. C. Wang, and C. T. Kuo, “Luminance Enhancement of Flip-Chip Light-Emitting Diodes by Geometric Sapphire Shaping Structure”, **IEEE Photon. Tech. Lett.**, V20, N3, p184-186, (Feb. 1, 2008)
6. C. H. Chiu, C. E. Lee, C.L. Chao, B. S. Cheng, H.W. Huang, H. C. Kuo, T. C. Lu, S. C. Wang, W. L. Kuo, C. S. Hsiao and S. Y. Chen “Enhancement of light output intensity by integrating ZnO nanorod arrays on GaN-based laser lift-off vertical light emitting diodes”, accepted and to be published in **J. Electrochem. Soc.,** (2008)

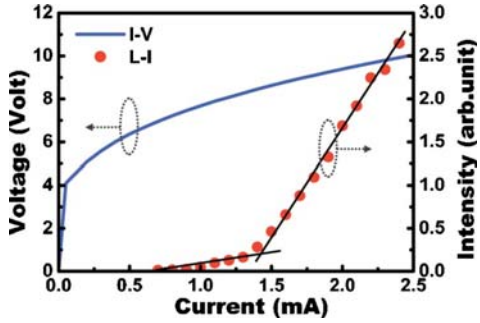
6. 計畫已獲得之主要成就與成果（請列出相關文獻及圖表，**內容以整體計畫呈現，500 字為限，請勿以分項成果條列說明**）：

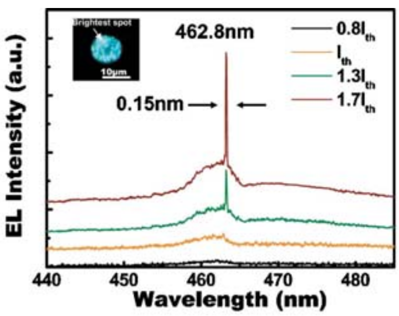
Our research team has successfully demonstrated **world first** GaN-based surface-emitting lasers, fabricated high Q cavity microcavities, and GaN nanostructure for control photon emission. The major outstanding results are listed as followed:

1. *CW Lasing of Current Injection Blue GaN-Based Vertical Cavity Surface Emitting Laser (Appl. Phys. Lett. 92, 141102 (2008))*

We fabricated and demonstrated the world's first cw laser operation of electrically pumped GaN-based vertical cavity surface emitting laser (VCSEL). The GaN-based VCSEL has a ten-pair InGaN/GaN multiple quantum well active layer embedded in a GaN hybrid microcavity of 5 λ optical thickness with two high reflectivity mirrors provided by an epitaxially grown AlN/GaN distributed Bragg reflector (DBR) and a Ta2O5 /SiO2 dielectric DBR. CW laser action was achieved at a threshold injection current of 1.4 mA at 77 K. The laser emitted a blue wavelength at 462 nm with a narrow linewidth of about 0.15 nm. The laser beam has a divergence angle of about 11.7° with a polarization ratio of 80%. A very strong spontaneous coupling efficiency of 7.5×10^{-2} was measured.

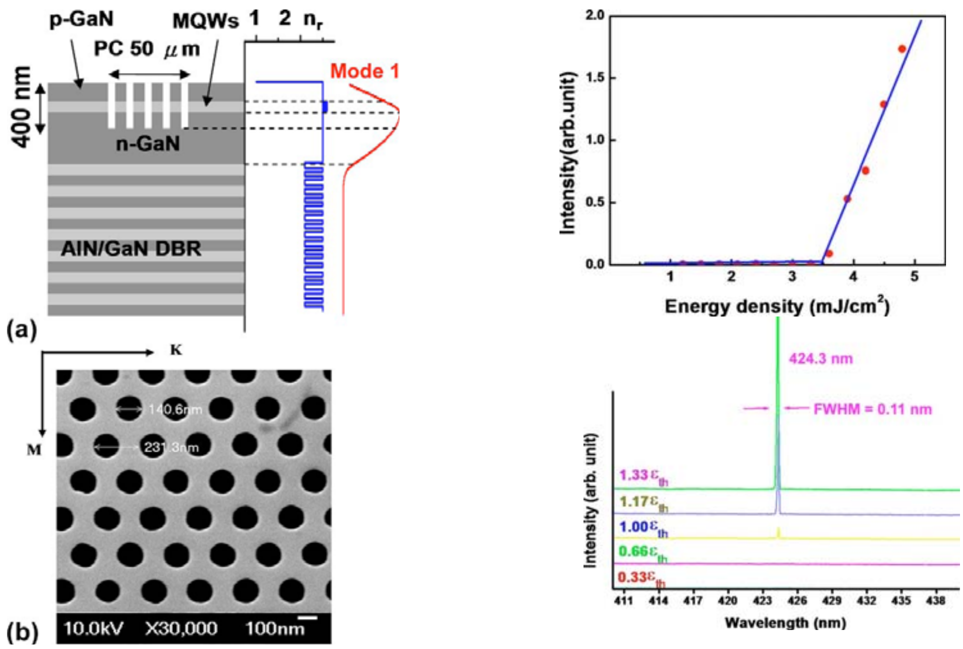






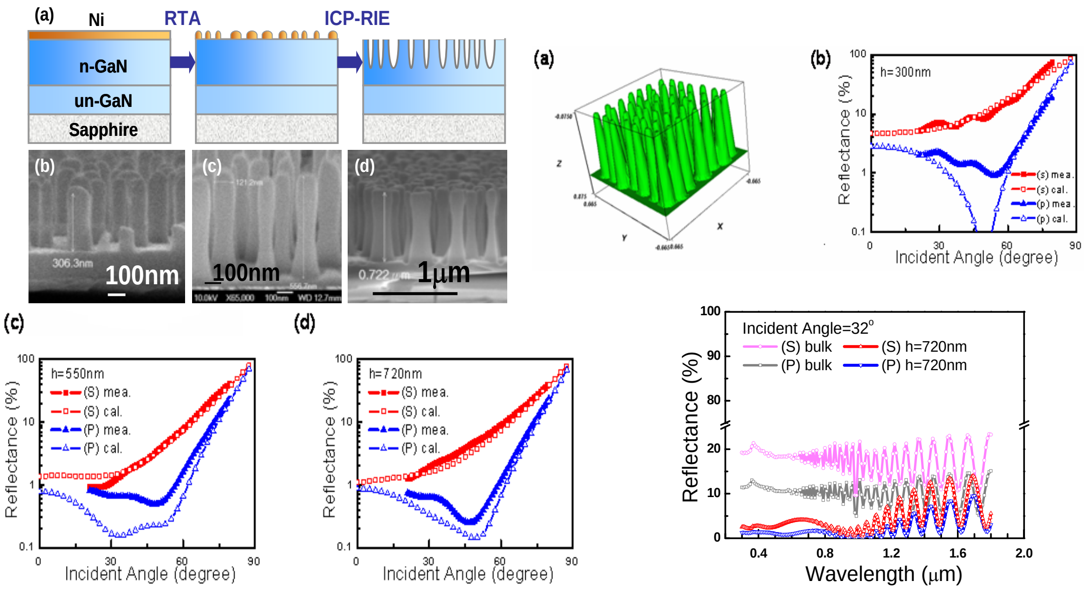
2. *GaN-based two-dimensional surface-emitting photonic crystal lasers with AlN/GaN distributed Bragg reflectors (Appl. Phys. Lett. 92, 011129 (2008))*

We have fabricated and demonstrated the world's first GaN-based two-dimensional surface-emitting photonic crystal lasers with AlN/GaN distributed Bragg reflectors. The lasing threshold energy density is about 3.5 mJ/cm2 per pulse under optical pumping at room temperature. Only one dominant emission wavelength of 424.3 nm with a narrow line-width of 1.1 Å above the threshold is observed. The laser emission covers whole circularly 2D PC patterns (50 μm in diameter) with a small divergence angle. The lasing wavelength emitted from 2D PC lasers with different lattice constants occurs at the calculated band-edges provided by the PC patterns. The characteristics of large area, small divergence angle, and single mode emission from the GaN-based 2D surface-emitting PC lasers should be promising in high power blue-violet emitter applications.



4. *"Broadband and omnidirectional antireflection employing disordered GaN nanopillars", accepted and to be published in Optical Express.*

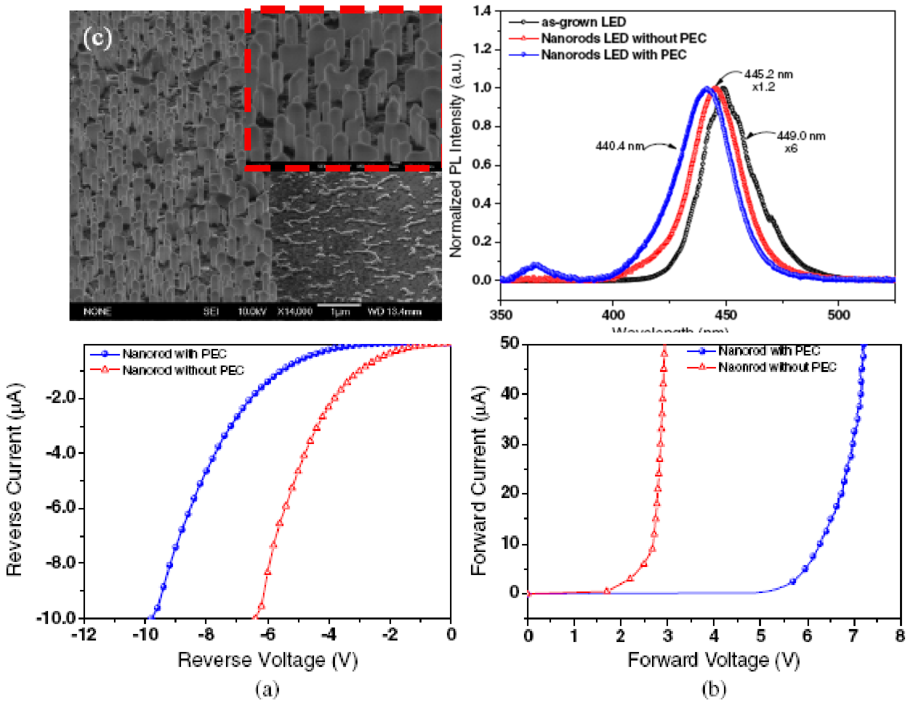
Disordered GaN nanopillars fabricated by ICP-RIE dry etching of three different heights: 300, 550, and 720 nm are fabricated. We also demonstrated the broad angular and spectral anti-reflective characteristics, up to an incident angle of 60^{o} and for the wavelength range of λ=300-1800nm. An algorithm based on a rigorous coupled-wave analysis (RCWA) method is developed to investigate the correlations between the reflective characteristics and the structural properties of the nanopillars. Calculations show excellent agreement with the measured reflectivities for both s- and p- polarizations.



4. *"Fabrication of InGaN/GaN MQW nanorods LED by ICP-RIE and PEC oxidation process with self-assembly Ni metal islands", **Nanotechnology**, V18, N.44, p445201 (Nov. 7, 2007)*

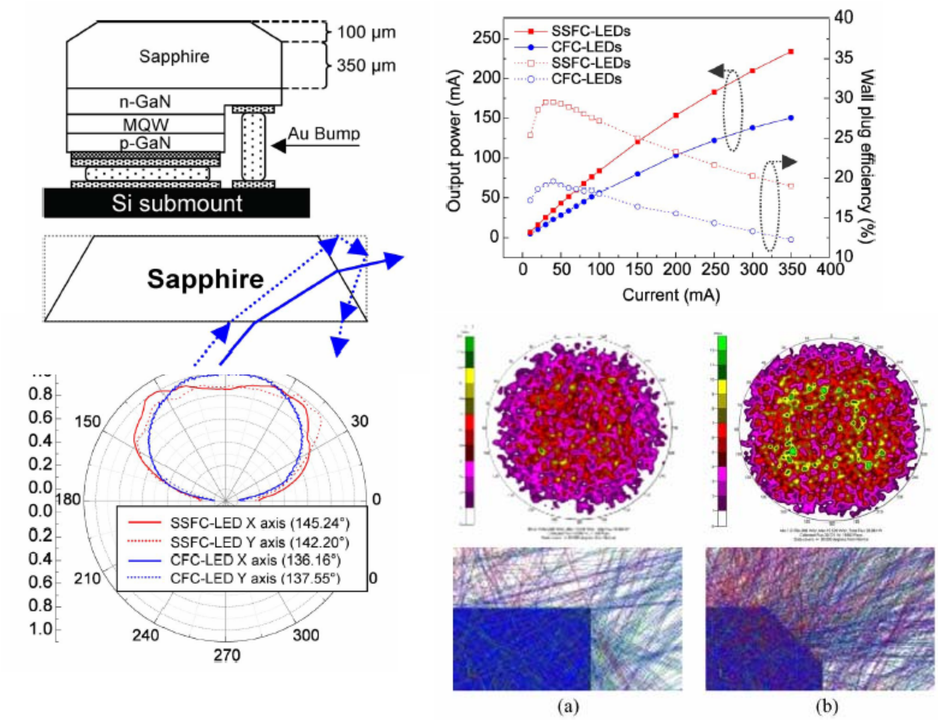
We report the fabrication of InGaN/GaN nanorod light-emitting diodes(LEDs) using inductively coupled plasma reactive-ion etching (ICP-RIE) and a photo-enhanced chemical

(PEC) wet oxidation process via self-assembled Ni nanomasks. An enhancement by a factor of six times in photoluminescence (PL) intensities of nanorods made with the PEC process was achieved in comparison to that of the as-grown structure. The peak wavelength observed from PL measurement showed a blue shift of 3.8 nm for the nanorods made without the PEC oxidation process and 8.6 nm for the nanorods made with the PEC oxidation process from that of the as-grown LED sample. In addition, we have demonstrated electrically pumped nanorod LEDs with the electroluminescence spectrum showing more efficiency and a 10.5 nm blue-shifted peak with respect to the as-grown LED sample.



5. *"Luminance Enhancement of Flip-Chip Light-Emitting Diodes by Geometric Sapphire Shaping Structure", **IEEE Photon. Tech. Lett.**, V20, N3, p184-186, (Feb. 1, 2008)*

The flip-chip light-emitting diodes (FC-LEDs) with geometric sapphire shaping structure were investigated. The sapphire shaping structure was formed on the bottom side of the sapphire substrate by a chemical wet etching technique for light extraction purpose. The crystallography-etched facets were (1010) M-plane, (1102) R-plane, and (1120) A-plane against the (0001) c-axis with the angles range between 29^{o}~60^{o}. These large slope oblique sidewalls are useful for light extraction efficiency enhancement. The light–output power of sapphire shaping FC-LEDs was increased 55% (at 350-mA current injection) compared to that of conventional FC-LEDs.



2. 上述重大研究突破，與國際上類似領域之比較（**內容以整體計畫呈現，500字為限，請勿以分項式條列說明**）：

(a) CW Lasing of Current Injection Blue GaN-Based Vertical Cavity Surface Emitting Laser (Appl. Phys. Lett. 92, 141102 (2008) : cf Appl. Phys. Lett. 79, 3720 (2001))

Vertical Cavity Surface Emitting Laser (VCSEL) with a small optical mode volume having a microcavity of only a few optical thicknesses can emit a single mode with a circular symmetry beam and a small beam divergence that are more superior to the edge emitting lasers and are desirable for many practical applications in high density optical storage, laser printing, etc. We demonstrated the world first electrically pumped GaN-based VCSEL. The GaN VCSEL has a ten-pair InGaN/GaN multiple quantum well active layer embedded in a GaN hybrid microcavity of 5 λ optical thickness with two high reflectivity mirrors provided by an epitaxially grown AlN/GaN distributed Bragg reflector (DBR) and a Ta2O5 /SiO2 dielectric DBR. CW laser action was achieved at a threshold injection current of 1.4 mA at 77 K. The laser emitted a blue wavelength at 462 nm with a narrow linewidth of about 0.15 nm. The laser beam has a divergence angle of about 11.7° with a polarization ratio of 80%. A very strong spontaneous coupling efficiency of 7.5×10^{-2} was measured. This work was highlighted in CLEO as hot topics and in Compound Semiconductor as research news. In addition, this paper was ranked number one most downloaded paper on APL website.

(b) GaN-based two-dimensional surface-emitting photonic crystal lasers with AlN/GaN distributed Bragg reflectors (Appl. Phys. Lett. 92, 011129 (2008) : cf Science vol.319, 445, (2008))

Photonic crystal surface emitting laser (PCSEL) has attracted much attention due to the several advantages for next generation laser diode. At present, Prof. Noda's group at Kyoto University has demonstrated GaN PCSEL by utilizing AROG technology. However, we propose another fabrication techniques for GaN PCSEL by using AlN/GaN DBR. The nitride based DBR with high reflectivity and low refractive index could increase the confinement of light and subsequently decrease the lasing threshold energy. The lasing threshold energy density is about 3.5 mJ/cm2 per pulse under optical pumping at room temperature. Only one dominant emission wavelength of 424.3 nm with a narrow line-width of 1.1 Å above the threshold is observed.

(c) Broadband and omnidirectional antireflection employing disordered GaN nanopillars (to be published in Optical Express: cf Appl. Phys. Lett., 90, 181923, (2007))

We have fabricated the GaN nanorod structure with different height which has anti-reflective characteristics. The density, dimension and shape of the fabricated GaN nanorod could be controlled by modifying the deposition thickness and etching condition. The broad angular and spectral anti-reflective characteristics, up to an incident angle of 60^o and for the wavelength range of λ=300-1800nm has also been demonstrated in this research. The measured results were great matched with the simulation results by RCWA algorism. In comparison to the Si anti-reflection layer, the GaN nanorod structure fabricated by ICP-RIE dry etching has the better properties on reflectivity.

(d) Fabrication of InGaN/GaN MQW nanorods LED by ICP-RIE and PEC oxidation process with self-assembly Ni metal islands (Nanotechnology, V18, N.44, p445201: cf Nano Letters, Vol. 4, No. 6, 1059-1062 (2004))

We demonstrated the realization of the high-brightness and high-efficiency light emitting diodes (LEDs) using dislocation-free indium gallium nitride (InGaN)/gallium nitride (GaN) multiquantum-well (MQW) nanorod (NR) arrays by metal organic-hydride vapor phase epitaxy (MO-HVPE). MQW NR arrays (NRAs) on sapphire substrate are buried in spin-on glass (SOG) to isolating individual NRs and to bring p-type NRs in contact with p-type electrodes. The process of nanorod manufacture by PEC is more simply and which exhibit better electrical property as shown in the plots.

(e) Luminance Enhancement of Flip-Chip Light-Emitting Diodes by Geometric Sapphire Shaping Structure (IEEE Photon. Tech. Lett., V20, N3, p184-186 (2008): cf IEEE Trans. Adv. Packag., vol. 28, no. 2, pp. 273–277, May 2005)

We demonstrated a simple approach to enhance the light output power on flip-chip GaN-based LEDs. By shaping the sapphire substrate, we could improve the light extraction efficiency from MQWs and especially the sidewall extraction. The angle of the sapphire angle could be controlled ranging from 29^o~60^o. In comparison to other approaches, the proposed method provides an easier and significant way to enhance the total power. The controllability of the etched sapphire shape enabled us to modify the far field pattern. This would have great help for realizing the solid state lighting in the future.

2. 評估主要成果之價值與貢獻度：(請從學、技術創新、經濟效益、社會衝

擊等影響面，內容以 300 字為限)：

本計畫研究氮化鎵材料及元件的奈米製程，在學術上已發表相關 75 篇重要國際 SCI 論文，74 篇國內外會議論文，其中主持人及共同主持人近五年國內外之成就與榮譽如下：

1. (1)國際微光學會獎(MOC Award 2003)

   (2)傑出人才基金會講座(1998~2003)

   (3) IEEE Life member (2006)

   (4) 潘文淵考察研究獎(2007)

   (5) 吳大猷先生研究紀念獎(2007)

   (6) 銖德青年獎章(2007)

2. (1)Plenary speaker at 2003 MOC conference(2003)

   (2) Invited talk at PR-CLEO 2003

   (3) Invited talk at ECS 2003

   (4) Invited talk at SPIE's photonics 2003

   (5) Invited talk at US Air Force & Taiwan Nanoscience Initiative Workshop 2004

   (6) Invited talk at US Air Force & Taiwan Nanoscience Initiative Workshop 2006

   (7) Invited talk at Optic East 2006

   (8) Invited talk at MOC 2006

   (9) Invited talk at PRCLEO 2007

   (10) Invited talk at Optics East 2007

   (11) Invited talk at MOC 2007

3. (1) 美國光學學會 Mess 獎章遴選委員 2002

   (2) 美國 IEEE and LEOS William Striefer 獎章遴選委員 2004

   (3) PRCLEO 共同主席 2005

   (4) ISCLC Program committee 2006

   (5) IWN Program committee 2006

   (6) PRCLEO Program committee 2007

4. (1) Collaboration with Prof. Yamamoto at Stanford 2006, 2007

   (2) Collaboration with Prof. Iga from Tokyo Institute of Technology

   (3) Collaboration with Prof. SH Fan at Stanford 2007

除了在學術上我們的研究成果受到國際各界的注目，我們在具光子可控性之奈米結構與奈米元件的研發成果，不管在技術及經濟效益上，本計畫已提出多項專利與進行產學合作移

轉我們在計畫中所研發出的專有技術。

1. (1) 申請中專利: 以超晶格方式製作高反射率無裂縫 DBR

   (2) 申請中專利: 利用光電化學氧化技術製作可電激發之奈米柱發光二極體

   (3) 申請中專利: 製作包含透明導電玻璃及無裂縫的氮化鋁/氮化鎵系列反射鏡之可電激發面射型雷射

   (4) 申請中專利: 利用圖案化藍寶石基板提升量子井結構之光萃取效率

2. 產學合作

   (1) 晶元光電: 全臺灣最大、世界第三大的專業 LED 製造公司

   (2) 全新光電:專業高速電子及 LED 製造公司

   (3) 友嘉光電: 專業 LD 製造公司

   (4) 禧通光電: 專業 VCSEL 及 solar cell 製造公司

在社會效益上，本計畫所培育的人才在學期間榮獲多次獎項如下

1. 指導學生高志強榮獲中華民國光學工程學會最佳論文獎 2007
2. 指導學生林立凡榮獲第十二屆 科林論文獎 2007
3. 指導學生李亞儒榮獲教育部千里馬計畫補助出國研究一年 2006
4. 指導學生劉瑞農榮獲朱順一合勤學業優異獎學金 2006
5. 指導學生劉瑞農通過教育部公費留學考 2006
6. 指導學生柯宗憲榮獲第一屆國立交通大學奈米科技中心成果發表會暨奈米攝影競賽特優第一名 2006
7. 指導學生高宗鼎榮獲第十一屆 科林論文獎 2006
8. 指導學生劉子維榮獲 2007 年台灣光電科技研討會學生論文獎
9. 指導學生李昀恬榮獲 2007 年台灣光電科技研討會學生論文獎
10. 指導學生陳士偉榮獲 2007 年台灣光電科技研討會學生壁報論文獎
11. 指導學生林立凡榮獲 2006 年台灣光電科技研討會學生論文獎
12. 指導學生高宗鼎榮獲 2005 年台灣光電科技研討會學生論文獎
13. 指導學生曾國峰榮獲 2004 年台灣光電科技研討會學生論文獎
14. 指導學生賴芳儀榮獲 94 學年聯發科獎學金
15. 指導學生彭裕鈞榮獲 94 學年度朱順一合勤學業優異獎學金
16. 指導學生高宗鼎榮獲 95 學年光電工程學會碩士論文獎
17. 指導學生彭裕鈞榮獲 94 學年光電工程學會碩士論文獎

學生畢業後，部分留在學術研究機構，繼續和本實驗室合作，部分(約 20 人)到產學合作或相關的公司就業，為臺灣的奈米光電產業貢獻所學，注入一股研發創新的動能。