# 行政院國家科學委員會補助專題研究計畫成果報告

※ ※※※※※※※※※※※※※※※※※※※※※※※※

※ 半導體材料之載子動力學研究 ※

※ ※※※※※※※※※※※※※※※※※※※※※※※※

計畫類別：■個別型計畫 □整合型計畫

計畫編號：NSC89－2112－M－002－082

執行期間： 89 年 8 月 1 日至 90 年 10 月 31 日

計畫主持人：孫啟光

共同主持人：(無)

本成果報告包括以下應繳交之附件：(無)

□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

執行單位：國立台灣大學光電工程研究所

中 華 民 國 90 年 11 月 21 日

# 行政院國家科學委員會專題研究計畫成果報告

## 半導體材料之載子動力學研究

## Studies of Carrier Dynamics in Semiconductor Materials

計畫編號：NSC89－2112－M－002－082

執行期限：89 年 8 月 1 日至 90 年 10 月 31 日

主持人：孫啟光　執行機構及單位名稱：台灣大學光電工程研究所

E-mail: sun@cc.ee.ntu.edu.tw

### 一、中文摘要

本計畫研究氮化鎵及氮化銦鎵材料之載子動力與聲子動力特性。

在實驗結果方面，本計畫延續 86-89 年度所執行之"半導體材料之載子動力學研究"多年期計畫，完成下列成果：

(1) 帶尾載子動力學實驗：發現氮化鎵材料之帶尾能態之載子動力學表現，由聲子輔助穿隧效應所主導。
(2) 載子擴散行為實驗：發現氮化銦鎵/氮化鎵量子井中之載子擴散具有"giant ambipolar diffusion"之特性。此特性是由於量子井中巨大之壓電場所致。
(3) 同調聲學聲子震盪實驗：利用壓電氮化鎵材料，成功以干涉方式產生同調聲學聲子震盪。其震盪生命期超過 300 皮秒，為已知震盪中最長者。
(4) 聲子震盪之同調控制實驗：利用飛秒雷射脈衝，本實驗室首次完成聲子震盪之光學同調控制實驗。聲子震盪之大小與相位均可由脈衝控制而達成。並利用此實驗發現聲子放大行為。
(5) 激子動力學行為研究：發現激子游離時間，在室溫時約在 100-250 飛秒左右。

關鍵詞：電子、電洞、聲子、激子、擴散、同調聲子震盪、壓電場、氮化鎵、氮化銦鎵

### Abstract

GaN has recently attracted a lot of attention due to its potential application in blue to UV light sources and high temperature and high field microwave electronics. Compared with the well-known GaAs and its related material systems, GaN has heavier masses, larger optical phonon energies, a large exciton binding energy, and a wurzite crystal structure. In order to understand their influence on the material performance, we perform femtosecond pump-probe experiments in order to investigate the carrier and phonon dynamics. The study is a continuous study from previous NSC project "Studies of Carrier Dynamics in Semiconductor Materials and Structures."

We have obtained the following results within this project:

(1) Bandtail state experiment: Found phonon assisted tunneling effect responsible for the carrier dynamic behaviors in GaN bandtail states.
(2) Carrier diffusion experiment: Found "giant ambipolar diffusion" behavior in InGaN/GaN multiple quantum wells. This behavior is induced by the large built-in piezoelectric field.
(3) Coherent acoustic phonon oscillation experiment: Successfully generate coherent acoustic phonon oscillations in bulk strained GaN using interferometric technique.
(4) Coherent control of phonon oscillation experiment: With a femtosecond pulse, we demonstrate for the first time the coherent control of phonon oscillations. Both magnitude and phase control were successfully achieved. High phonon amplification was found.
(5) Exciton dynamics study: Found exciton dynamics dominated by a fast ionization time on the order of 100-250 fs at room temperature.

Keywords: electron, hole, phonon, exciton, diffusion, coherent phonon oscillation, piezoelectric field, GaN, InGaN.

### 二、計畫緣由與目的

半導體材料中的基本載子為帶負電之電子與帶正電之電洞。由於研究基本載子相互之間及基本載子與週遭環境，如聲子系統，間之交互作用為了解半導體現象之基礎，載子動力學因而受到高度重視。其研究動機更跟隨近日超小與超快電子元件之

發展而增強。本計畫提出高能隙材料氮化鎵/氮化銦鎵之載子動力學研究。

由於在藍光二極體、藍光至紫外光半導體雷射、高溫及高功率微波電子元件上的應用，氮化鎵及其相關材料的研究目前在國際上與國內均受到極高度重視。與已被充分了解之砷化鎵及其相關材料為比較對象，氮化鎵具有較重之電子與電洞質量、較高之激子鍵結能量、及六邊型的晶體結構。為了解這些不同特性所造成之影響，本計畫研究氮化鎵及氮化銦鎵材料之載子動力、激子動力、與聲子動力特性。

## 三、結果與討論

在本計畫執行期限內，因受本計畫之經費贊助，完成下列事項(部分經費由台大補助)：

1. 帶尾載子動力學實驗：

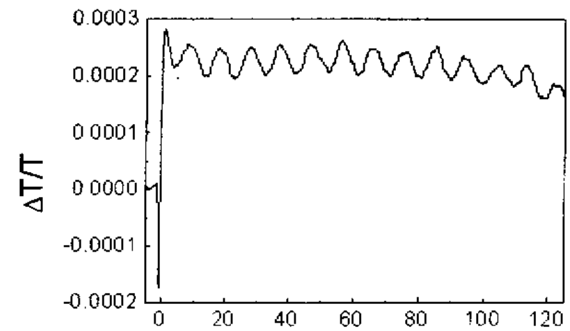
本實驗室利用 pump-probe 技術，在純氮化鎵材料中，發現氮化鎵材料之帶尾能態依能量高低而有截然不同之載子動力學表現。較近帶底之能態其載子動力學表現與能帶載子行為相同，而較遠帶底之帶尾能態則呈現 single-exponential 衰減。經與理論比較，較遠帶底之之載子動力學表現，發現是由聲子輔助穿隧效應所主導。發表論文請見計畫成果自評：論文 (A)3。

2. 載子擴散行為實驗：

本實驗室利用光學 pump-probe 技術，成功發展出量測二維載子擴散係數之量測方法，並應用於氮化銦鎵/氮化鎵量子井中之二維載子擴散係數量測。量測結果顯示，在氮化銦鎵/氮化鎵量子井中之二維載子(ambipolar)擴散係數極大，且隨量子井增後而急速增加。在 62Å 量子井中，其 ambipolar diffusion coefficient 為 $2700 cm^2/s$，較 bulk 值高出至少 1000 倍以上。實驗顯示氮化銦鎵/氮化鎵量子井中，具有"giant ambipolar diffusion"之特性。此特性是由於量子井中巨大之壓電場所致。發表論文請見計畫成果自評：論文(A)1、(B)I2、(B)I4、(B)I9。

3. 同調聲學聲子震盪實驗：

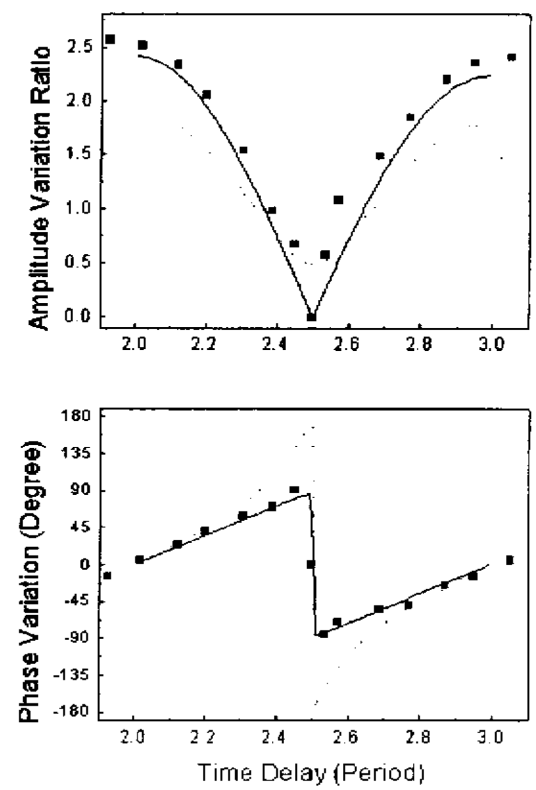
利用塊材壓電氮化鎵材料，成功以干涉方式產生同調聲學聲子震盪。此實驗為首次在塊材中，成功產生高頻同調聲學聲子震盪，如圖一所示，其震盪生命期超過 300 皮秒，為已知震盪中最長者。發表論文請見計畫成果自評：論文(A)5、(B)I8。




圖一：以干涉方式，在塊材氮化鎵材料中產生之同調聲學聲子震盪。

4. 聲子震盪之同調控制實驗：

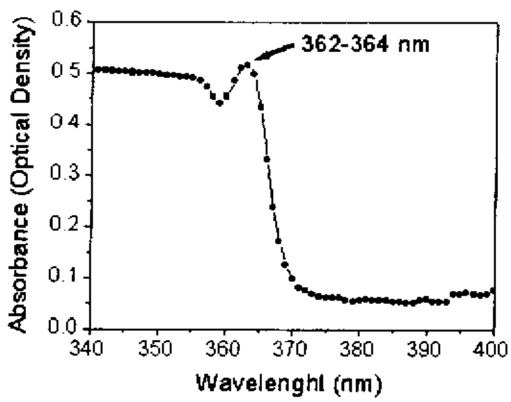
利用飛秒雷射脈衝，本實驗室首次完成聲子震盪之光學同調控制實驗。聲子震盪之大小與相位均可由脈衝控制而達成。在此實驗中，更發現了令人驚訝之聲子放大行為。圖二為聲子震盪之同調干涉實驗結果，實驗結果需加入聲子放大項，方能成功解釋。發表論文請見計畫成果自評：論文(A)2、(B)I1、(B)I3、(B)I7。



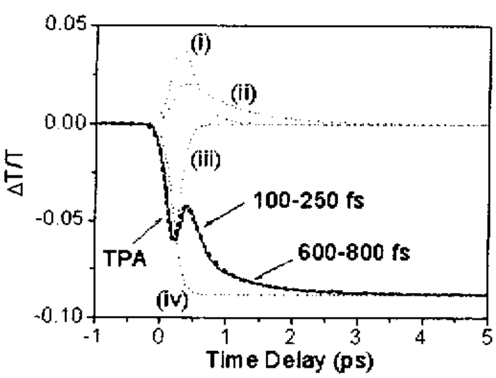

圖二：聲子震盪之同調干涉實驗結果。實線為考慮聲子放大行為，虛線為不考慮聲子放大行為。

5. 激子動力學行為研究：

本實驗室利用 pump-probe 技術，在純氮化鎵材料中，發現自由激子游離時間，在室溫時約在 100-250 飛秒左右。圖三為純氮化鎵材料在室溫時之吸收頻譜。363nm 之吸收峰及對應到自由激子的吸收。在 363nm 之飛秒穿透量測結果如圖四所示。量測可見四種反應。(i)自由激子游離(100-250 fs)、(ii)載子冷卻(600-800 fs)、(iii)雙光子吸收、(iv)bandgap renormalization。發表論文請見計畫成果自評：論文(A)6。




圖三：純氮化鎵材料在室溫時之吸收頻譜。363nm 之吸收峰及對應到自由激子的吸收。




圖四：純氮化鎵材料在室溫時，363nm 之飛秒穿透量測結果。量測可見四種反應： (i) 自由激子游離(100-250 fs)、(ii)載子冷卻(600-800 fs)、(iii)雙光子吸收、(iv) bandgap renormalization。

## 四、計畫成果自評

本計畫已完成當初預期之目標。在論文方面則已發表期刊論文共 5 篇，國際會議論文 10 篇，國內會議論文 3 篇，另有一篇論文已投稿尚在審查中。

(A) SCI 期刊論文

1. Y.-C. Huang, J.-C. Liang, C.-K. Sun, A. Abare, and S. P. DenBaars, "Piezoelectric-field enhanced lateral ambipolar diffusion coefficient in InGaN/GaN multiple quantum wells," *Applied Physics Letters* **78** (7), 928-930 (2001).
2. C.-K. Sun, J.-C. Liang, A. Abare, and S. P. DenBaars, "Coherent optical control of acoustic phonon oscillations in InGaN/GaN multiple-quantum-wells," *Applied Physics Letters* **78** (9), 1201-1203 (2001).
3. C.-K. Sun, J.-C. Liang, X.-Y. Yu, S. Keller, U. K. Mishra, and S. P. DenBaars,. "Studies of Carrier Dynamics in Unintentionally Doped GaN Bandtail States" *Applied Physics Letters* **78** (18), 2724-2726 (2001).
4. C.-K. Sun, S.-W. Chu, S. P. Tai, S. Keller, A. Abare, U. K. Mishra, and S. P. DenBaars," Mapping piezoelectric field distribution in Gallium Nitride with scanning second-harmonic-generation microscopy," *J. Scanning Microscopies* **23** (3), 182-192, **invited paper** (2001).
5. Y.-K. Huang, G.-W. Chern, C.-K. Sun, Y. Smorchkova, S. Keller, U. Mishra, and S. P. DenBaars, "Generation of coherent acoustic phonons in strained GaN thin film," *Applied Physics Letters* 79 (20), 3361-3363 (2001).
6. Y.-C. Huang, G.-W. Chern, J.-C. Liang, C.-K. Sun, C.-C. Hsu, S. Keller, and S. P. DenBaars, "Femtosecond dynamics of exciton bleaching in bulk GaN at room temperature," submitted to *Applied Physics Letters*.

**(B) 研討會論文**

**I. 國際會議論文**

1. C.-K. Sun, J.-C. Liang, and H.-L. Chen, "Coherent control of semiconductor phonon oscillation," in Technical Digest of *The 8th Asia Pacific Physics Conference*, Taipei, TAIWAN, paper BC7 (2000); C.-K. Sun, J.-C. Liang, H.-L. Chen, Y.-K. Huang, A. Abare, and S. P. DenBaars, "Coherent control of semiconductor phonon oscillations," Proceedings of *the 8th Asia-Pacific Physics Conference -APPC2000*, pp. 247-249, World Scientific, Singapore (2001).
2. C.-K. Sun, Y.-C. Huang, J.-C. Liang, A. Abare, and S. P. DenBaars, "Piezoelectric-field modified 2D carrier diffusion behavior in InGaN/GaN quantum wells," in Technical Digest of *The 8th Asia Pacific Physics Conference*, Taipei, TAIWAN, paper BA5 (2000); C.-K. Sun, Y.-C. Huang, J.-C. Liang, A. Abare, and S. P. DenBaars, "Piezoelectric-field modified 2D

carrier diffusion behavior in InGaN/GaN quantum wells," Proceedings of *the 8th Asia-Pacific Physics Conference -APPC2000*, pp. 132-134. World Scientific, Singapore (2001).

3. C.-K. Sun, J.-C. Liang, Y.-K. Huang, H.-L. Chen, Y.-C. Huang, A. Abare, and S. P. DenBaars, "Optical coherent control and coherent amplification of phonon oscillations in InGaN/GaN multiple quantum wells," Proceedings of *2nd International Photonics Conference*, Hsinchu, TAIWAN, paper W-S2-B002, Vol. **1**, pp. 71-73 (2000).

4. Y.-C. Huang, J.-C. Liang, C.-K. Sun, A. Abare, and S. P. DdenBaars, "Huge 2D carrier diffusion constant/mobility observed in InGaN/GaN multiple-quantum-wells," Proceedings of *2nd International Photonics Conference*, Hsinchu, TAIWAN, paper W-S1-B003, Vol. **1**, pp. 33-35 (2000).

5. Y.-K. Huang, C.-K. Sun, Y. Smorchkova, S. Keller, and S. P. DenBaars, "Observation of coherent acoustic phonon oscillations in bulk gallium nitride," Proceedings of *2nd International Photonics Conference*, Hsinchu, TAIWAN, paper W-S4-B001, Vol. **1**, pp. 68-70 (2000).

6. C.-K. Sun, J.-C. Liang, Y.-L. Huang, Y.-C. Huang, X.-Y. Yu, S. Keller, and S. P. DenBaars, "Femtosecond carrier dynamics in GaN," in Technical Digest of *Ultrafast Phenomena in Semiconductor V Symposium, Photonics West*, San Jose, CA, paper SPIE 4280-01, **invited speaker** (2001); in *Proceedings of SPIE*, Vol. **4280**, pp. 1-8 (2001).

7. C.-K. Sun, "Toward the realization of the first phonon laser," Workshop on Spectroscopy and Optoelectronics, Shanghai, China, **invited speaker** (2001).

8. C.-K. Sun, Y.-K. Huang, Y. Smorchkova, S. Keller, and S. P. DenBaars, "Observation of coherent acoustic phonon oscillations in bulk gallium nitride," in Technical Digest of *Quantum Electronics and Laser Science Conference (CLEO/QELS'2001)*, Baltimore, MD, USA, paper QThI3, pp. 202-203 (2001).

9. Y.-C. Huang, C.-K. Sun, A. Abare, S. Keller, and S. P. DenBaars, "Observation of giant ambipolar diffusion coefficient in thick InGaN/GaN multiple-quantum-wells," in Technical Digest of *Conference on Laser and Electro-Optics (CLEO/QELS'2001)*, Baltimore, MD, USA, paper CTuW4, pp. 241-242 (2001).

10. C.-K. Sun, Y.-K. Huang, G.-W. Chern, "Realization of phonon laser with femtosecond technology," in Technical Digest of *Ultrafast Phenomena in Semiconductors VI, Photonic West*, San Jose, CA, USA (2002).

**II. 國內會議論文**

1. C.-K. Sun and Y.-K. Huang, "Toward the realization of the first SASER," *The Annual Meeting of PSROC*, paper Db1 (2001); 物理雙月刊 **23** (1), pp. 84-85 (2001).

2. Y.-K. Huang, G.-W. Chern, and C.-K. Sun, "Coherent gain and threshold behavior of phonon lasing in InGaN/GaN MQW," *Optics and Photonics Taiwan'01*, Kaohsiung, Taiwan ROC.

3. G.-W. Chern, Y.-C. Huang, J.-C. Liang, C.-K. Sun, C.-C. Hsu, S. Keller, and S. P. DenBaars, "Exciton ionization dynamics in bulk GaN," *Optics and Photonics Taiwan'01*, Kaohsiung, Taiwan ROC.

**(C)其他(雜誌、國內期刊)**

1. Chi-Kuang Sun,"氮化鎵材料之非線性光學性質量測,"工程科技通訊,Vol. **43**, pp. 57-61 (2000).