III族氮化物半导体极化调控

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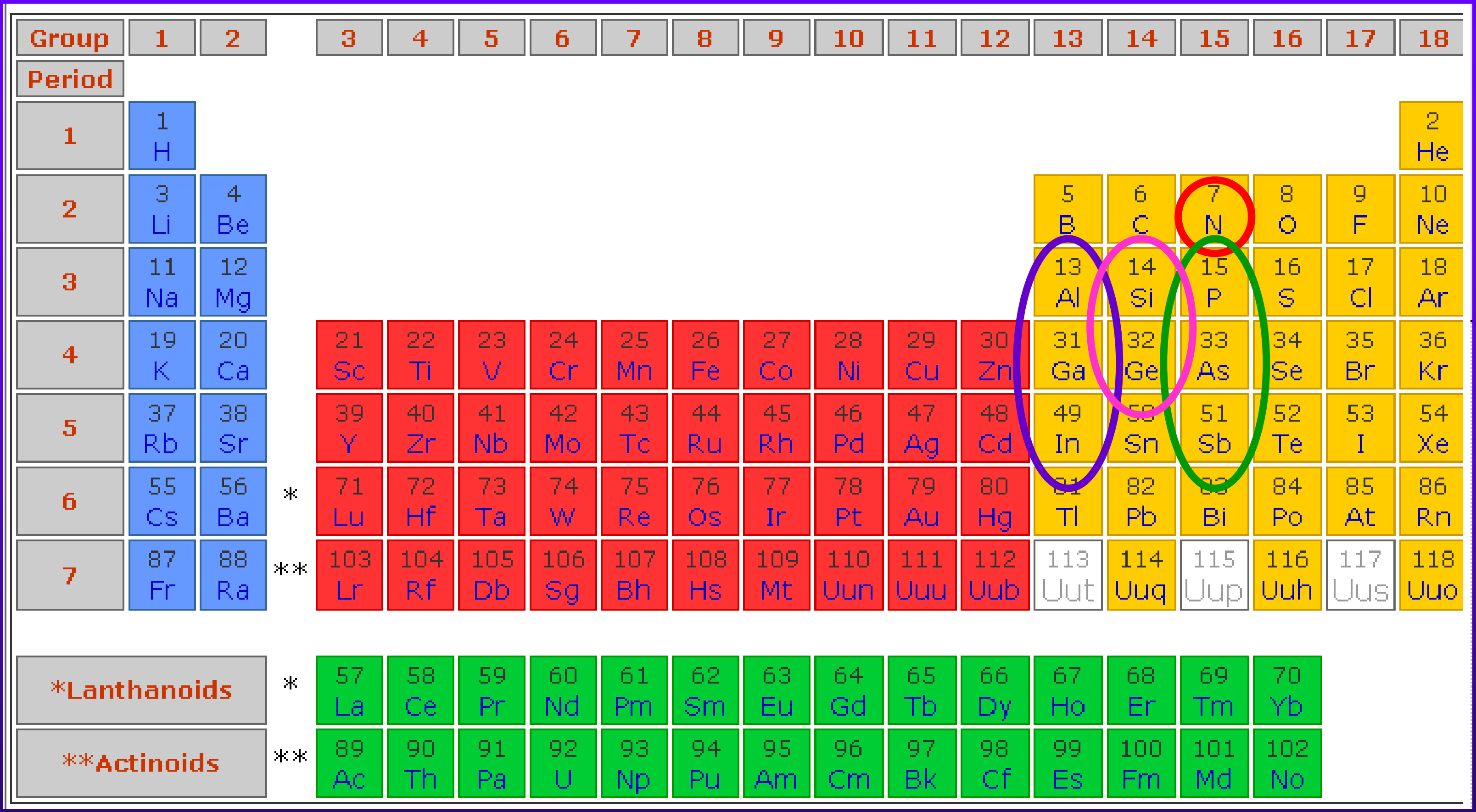
主要内容

- III族氮化物半导体简介
- 非极性面III族氮化物半导体量子阱材料与LED器件
- 其它极化调控器件
- 小结

什么是III族氮化物半导体?



Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun	111 Uuu	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

半导体材料使用历史的简要回顾

- 第一代半导体材料，以Si、Ge为代表
  - 集成电路的主要材料，占当前整个半导体产品的百分之九十五
  - 技术上最成熟，代表人类物质文明的最高水平
  - 广泛应用于计算机和各种电子产品
- 第二代半导体材料，以GaAs、InP等材料为代表
  - 光电子器件，LED和LD
  - 光通信
  - 微波功率器件和电路
- 第三代半导体材料，目前以III族氮化物、SiC为代表
  - 短波光电子器件，蓝、绿光LED，蓝紫光LD，紫外光电探测器件
  - 高温电子器件
  - 高功率微波器件
  - 高场高功率电力电子器件

当前主要的宽带隙半导体有：

（1）III族氮化合物（1.9-6.2 eV）

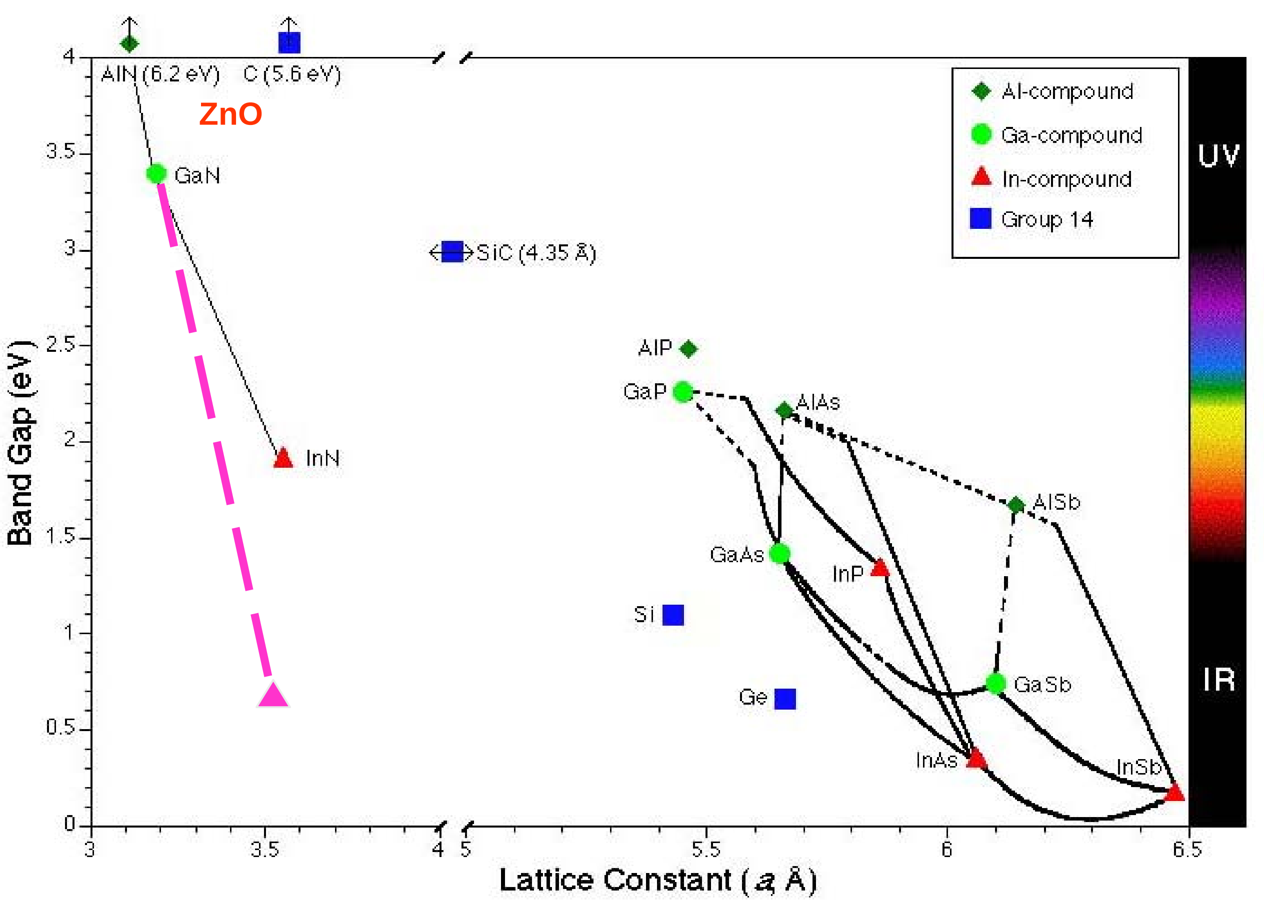
GaN	(3.4 eV)
InN	(1.9 eV,0.7eV)
AlN	(6.2 eV)
InGaN	(1.9 - 3.4 eV)
AlGaN	(3.4 - 6.2 eV)

（2）ZnO基氧化物半导体 （2.8 – 4.0 eV）

ZnO，ZnMgO，ZnCdO

（3）宽禁带Ⅳ族化合物

SiC	（2.4-3.1 eV）
金刚石薄膜	（5.5 eV）


AlN (6.2 eV)
C (5.6 eV)
ZnO
GaN
SiC (4.35 Å)
InN
AlP
GaP
AlAs
AlSb
GaAs
InP
Si
Ge
GaSb
InAs
InSb
Al-compound
Ga-compound
In-compound
Group 14
UV
IR
Band Gap (eV)
Lattice Constant (a Å)
0
0.5
1
1.5
2
2.5
3
3.5
4
3
3.5
4
5
5.5
6
6.5

第三代

第一、二代

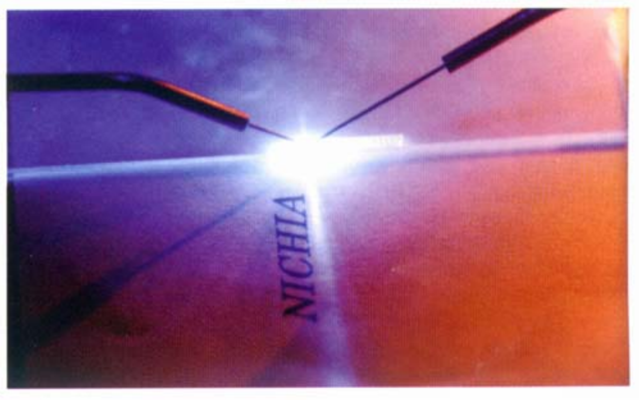
Ⅲ族氮化物半导体发展动向

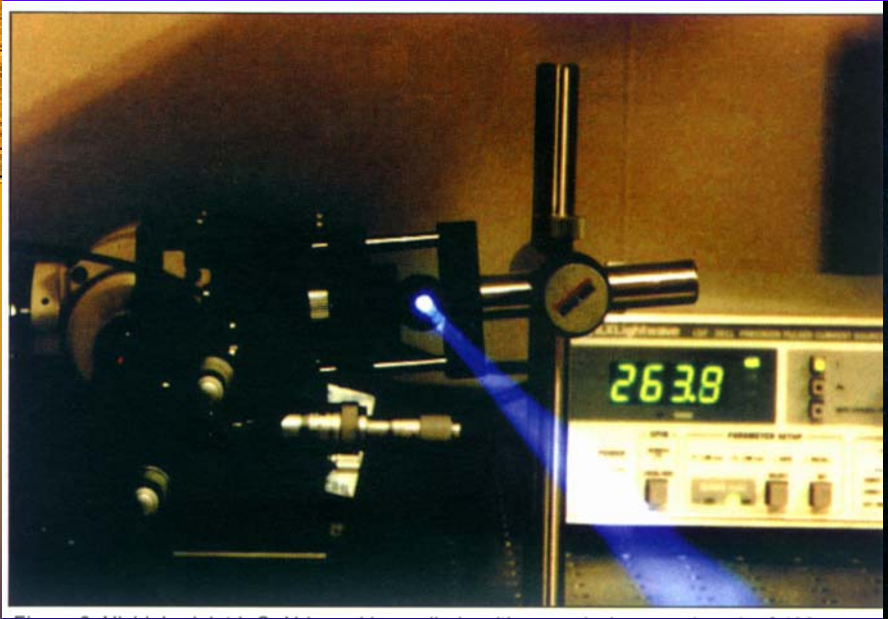
◆基于“宽带隙”，开拓“高温区”、“大功率”与“短波段”半导体新技术领域；

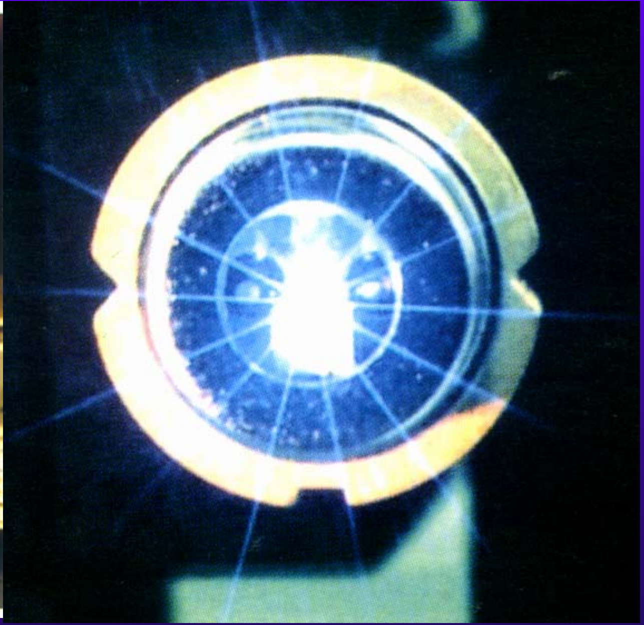
◆基于“低维结构子能带”又进入“中红外”技术领域；

◆基于“强压电性”，进入声表面波和传感器及微系统等技术领域。

III族氮化物蓝紫光激光二极管







III族氮化物紫外探测器

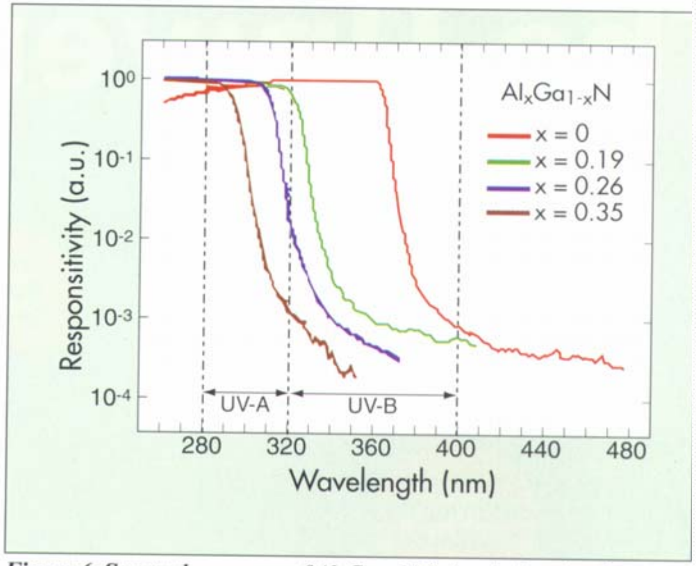


Figure 6. Spectral response of $Al_xGa_{1-x}N$ Schottky barrier detectors.

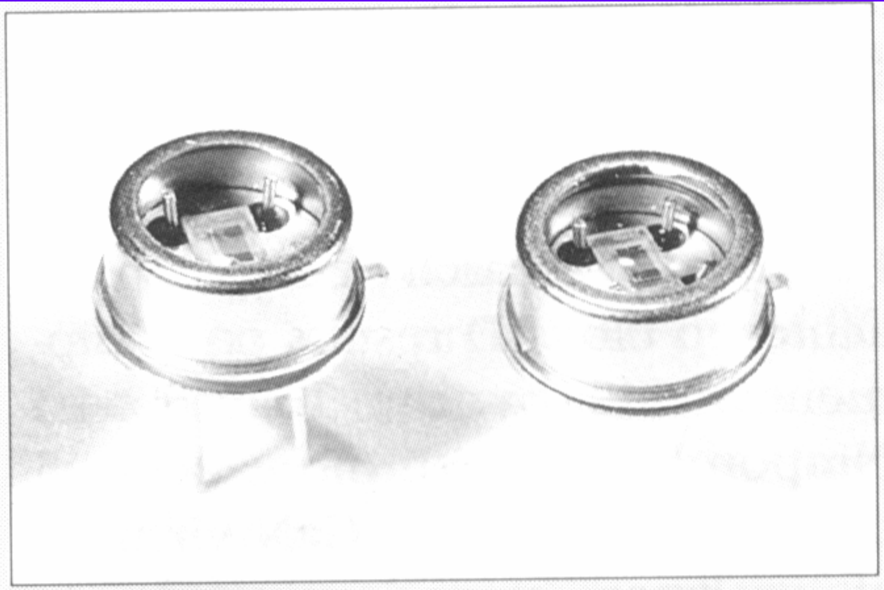
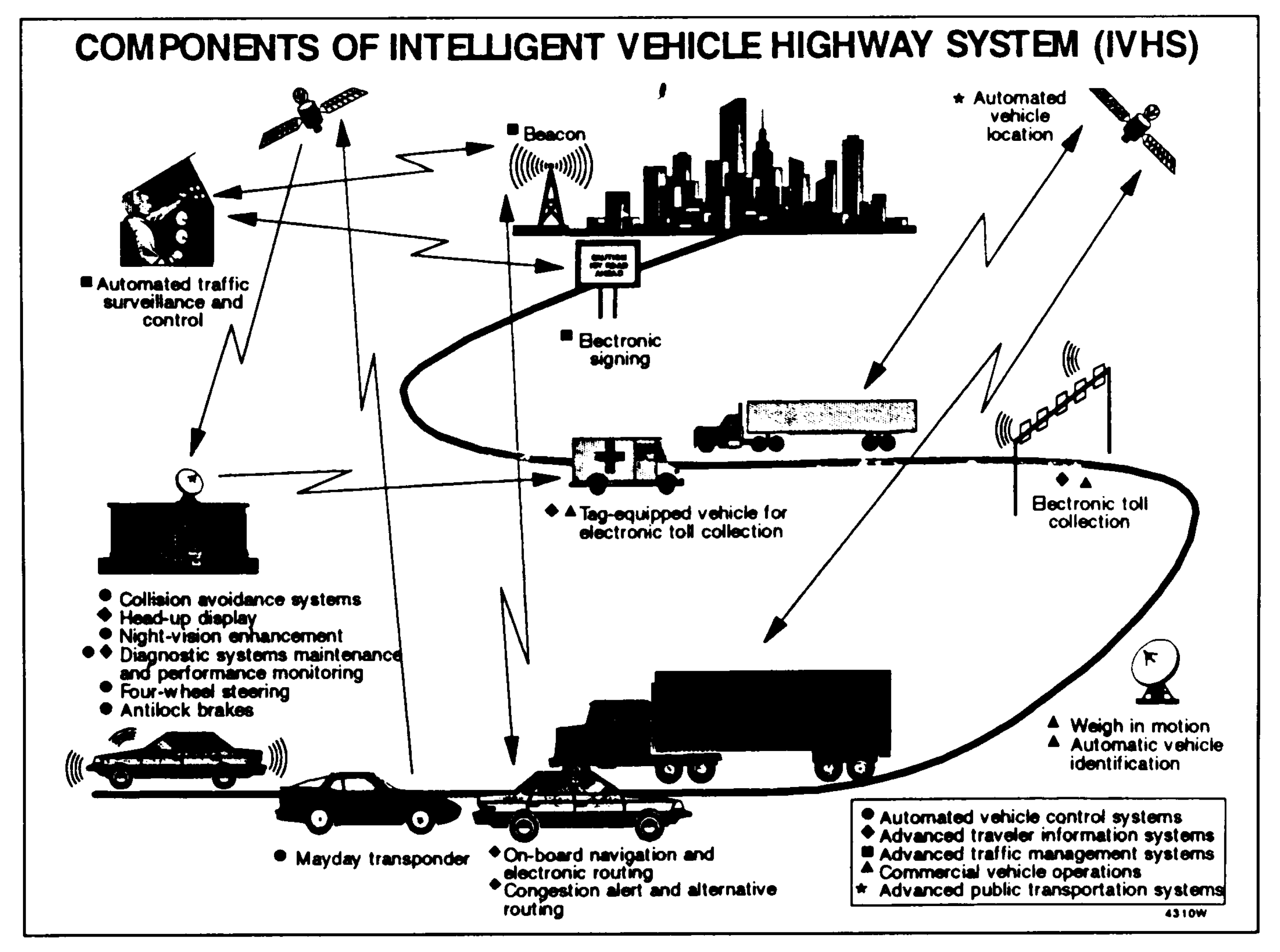


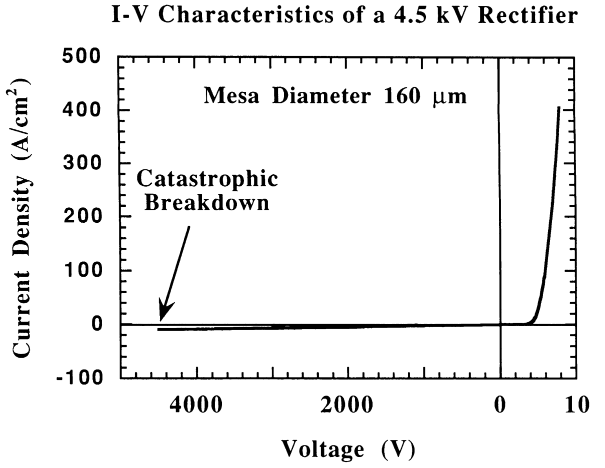
Figure 2. 2500S series of high responsivity

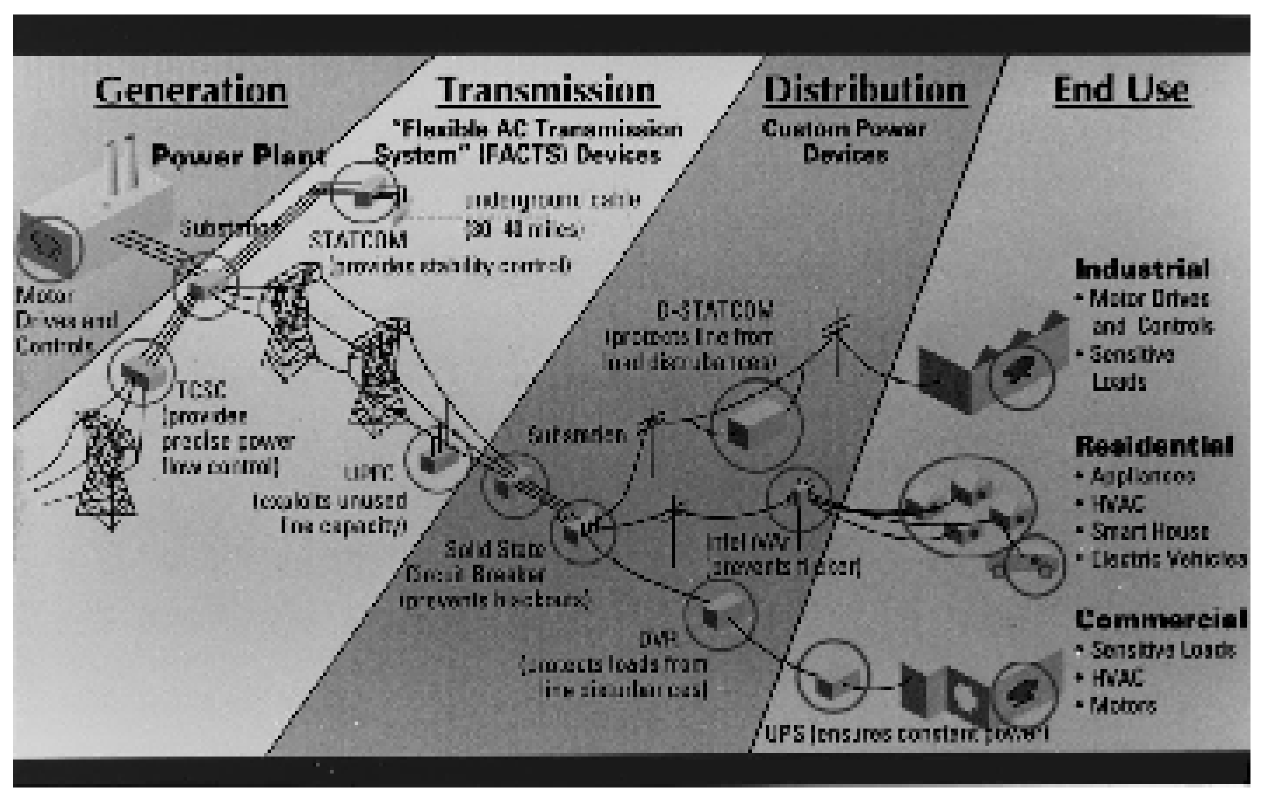
III族氮化物微波大功率器件



COMPONENTS OF INTELLIGENT VEHICLE HIGHWAY SYSTEM (IVHS)

宽禁带半导体高场电力电子器件





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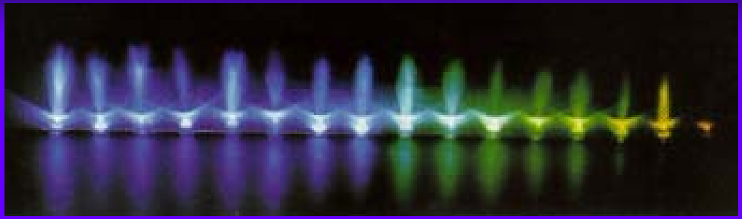
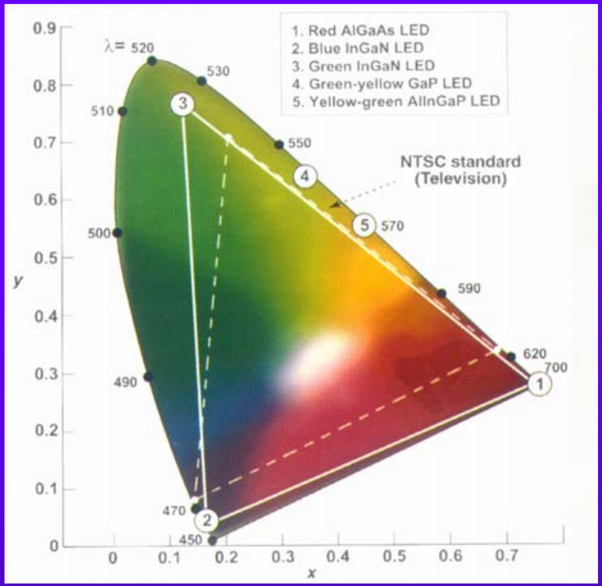
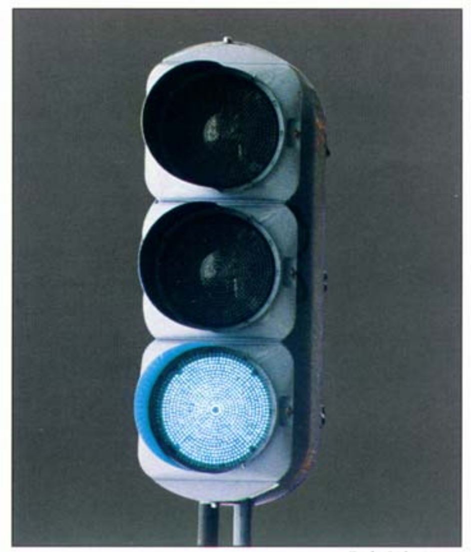
III族氮化物蓝绿光发光二极管及其应用

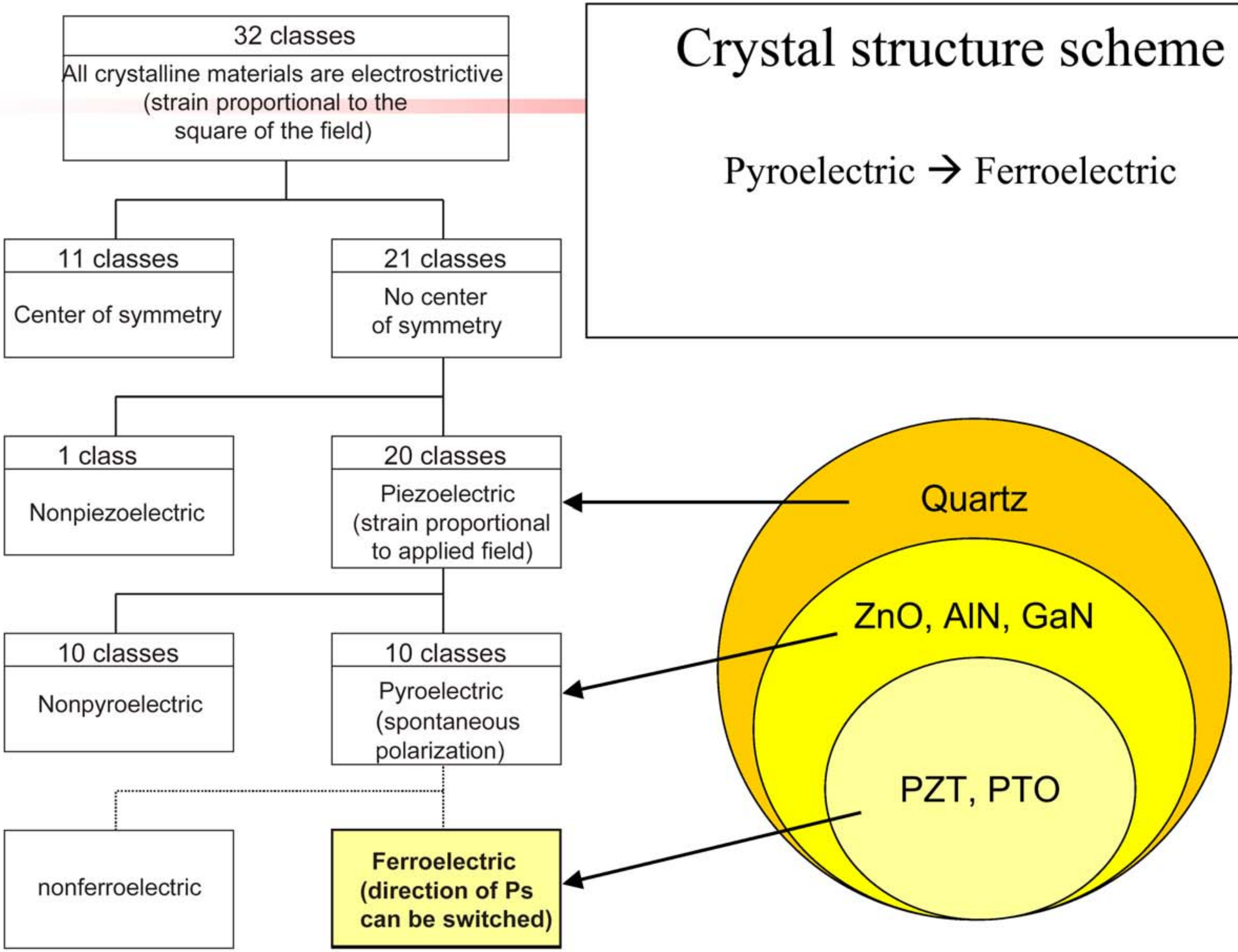






Crystal structure scheme

Pyroelectric → Ferroelectric



32 classes
All crystalline materials are electrostrictive (strain proportional to the square of the field)

11 classes
Center of symmetry

21 classes
No center of symmetry

1 class
Nonpiezoelectric

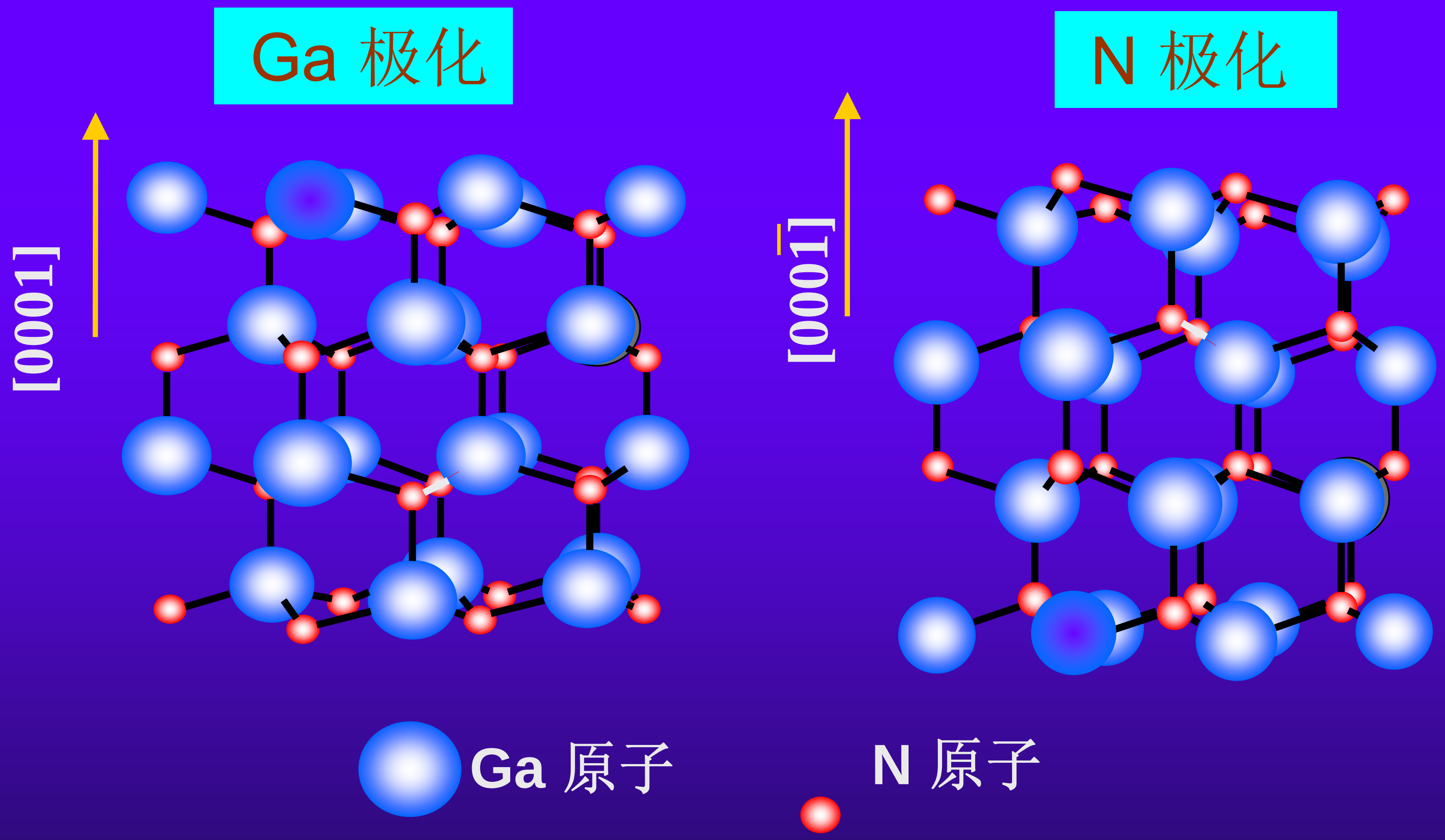
20 classes
Piezoelectric (strain proportional to applied field)

10 classes
Nonpyroelectric

10 classes
Pyroelectric (spontaneous polarization)

nonferroelectric

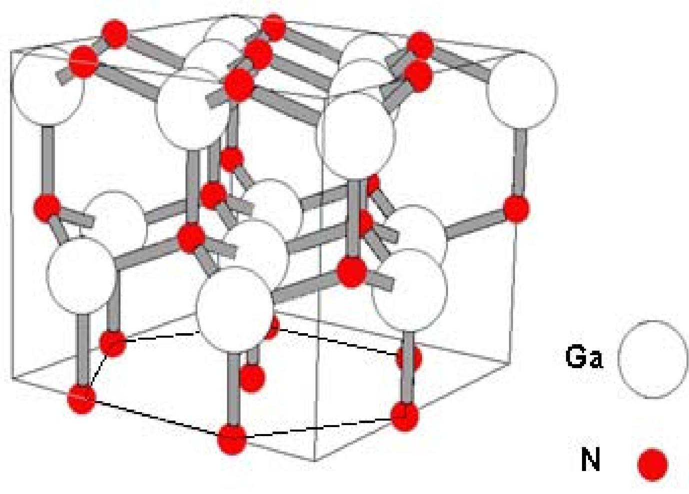
Ferroelectric (direction of Ps can be switched)

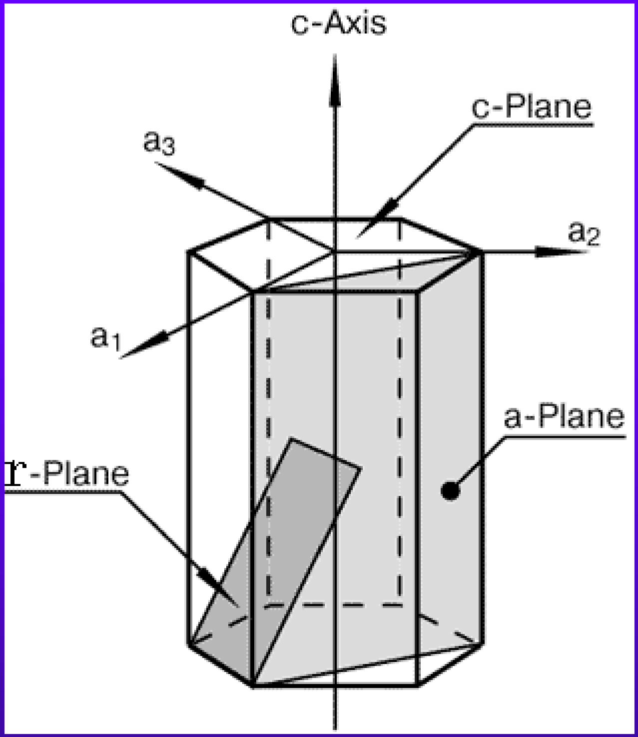

Ga 极化

N 极化

C面GaN有源层，非中心对称结构，存在极化效应

解决办法：M面和a面GaN中无极化





$c - plane(0001) \qquad a - plane(11\bar{2}0)$

$r - plane(1\bar{1}02) \qquad m - plane(10\bar{1}0)$

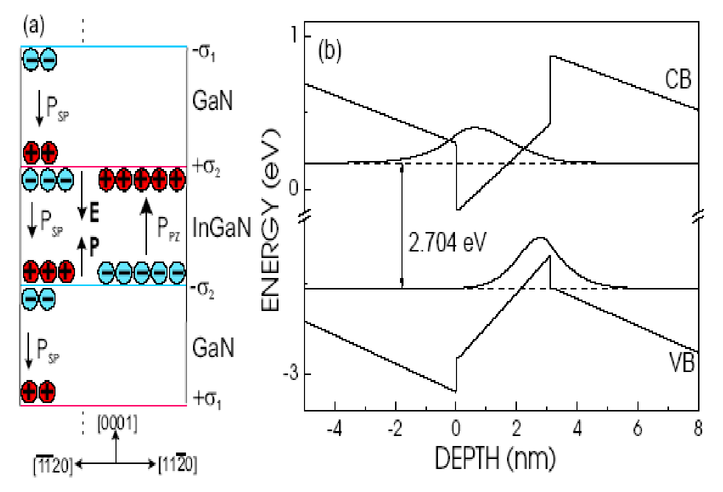
$n - plane(11\bar{2}3) \qquad s - plane(10\bar{1}1)$

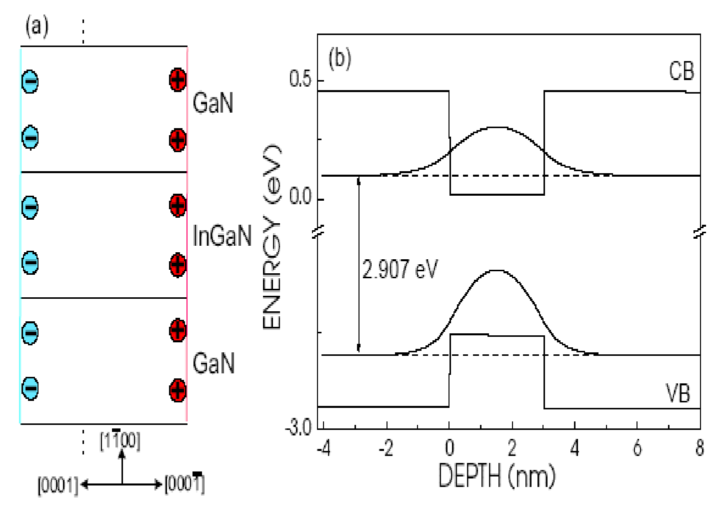
宽禁带半导体的极化规律、控制和极化诱导能带工程

- 自发极化与压电极化
- 极化设计
- 极化控制
- 衬底对极化的调控
- 极化诱导能带工程的应用
    - 非极化InGaN/GaN量子阱和高发光效率LED
    - 极化增强AlGaN/GaN异质界面二维电子气
    - 极化增强高灵敏度紫外光电探测器
    - 极化诱导空穴沟道场效应晶体管

非极性面III族氮化物量子阱与LED

极化对C/M面 GaN/InGaN 的能带影响





极化电场方向平行生长方向，造成能带倾斜，使电子与空穴波函数不再完全重叠

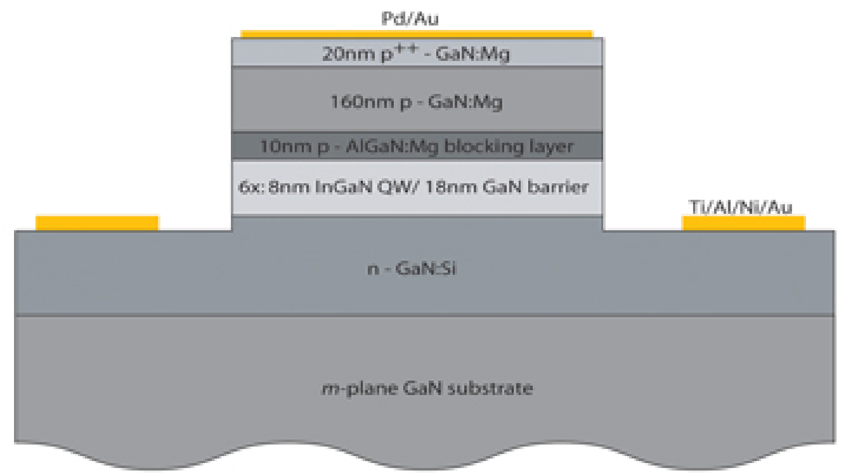
极化电场方向平行于外延膜的界面方向，沿载流子输运方向量子阱的能带是平带。

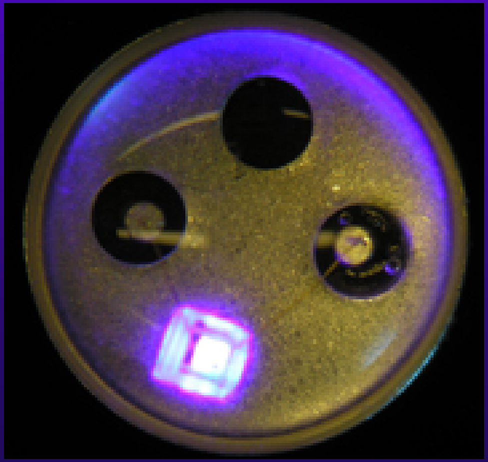
GaN($\bar{1}$100) :在生长方向没有极化电场

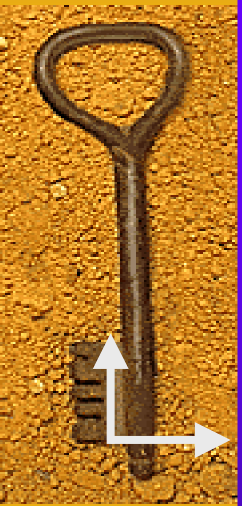
→ 有利于辐射复合效率的提高

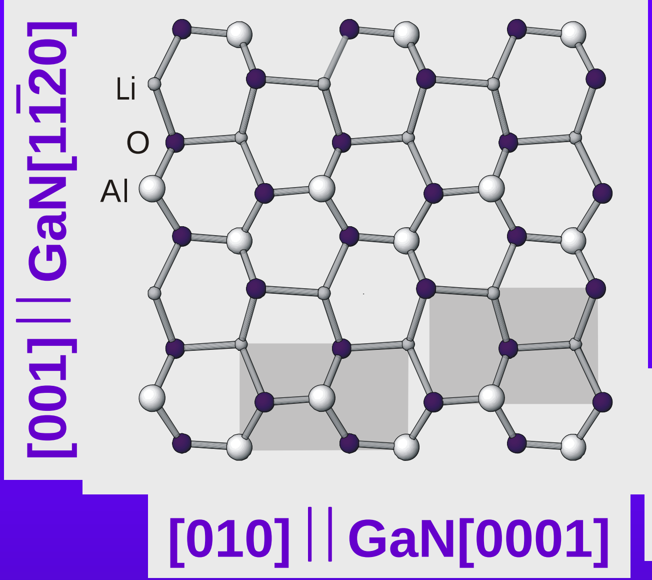
非极性面III族氮化物量子阱和LED已经取得重要突破

- 今年5月美国加大圣芭芭拉分校报道了m面GaN衬底上高量子效率LED，300μm x 300μm 管芯20mA驱动电流下402nm紫外光输出功率28mW，外量子效率达45.4% ，160mA下210mW，200mA下250mW，外量子效率依然高达41%。
- 今年1月同一实验室已经报道了m面III族氮化物激光二极管的激射。







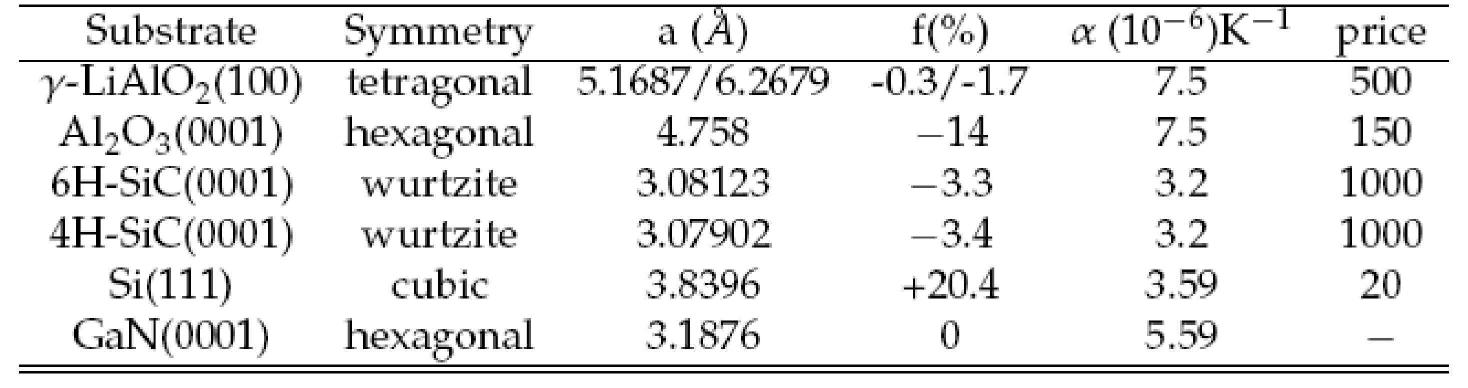


Substrate: γ-$LiAlO_2$(100):

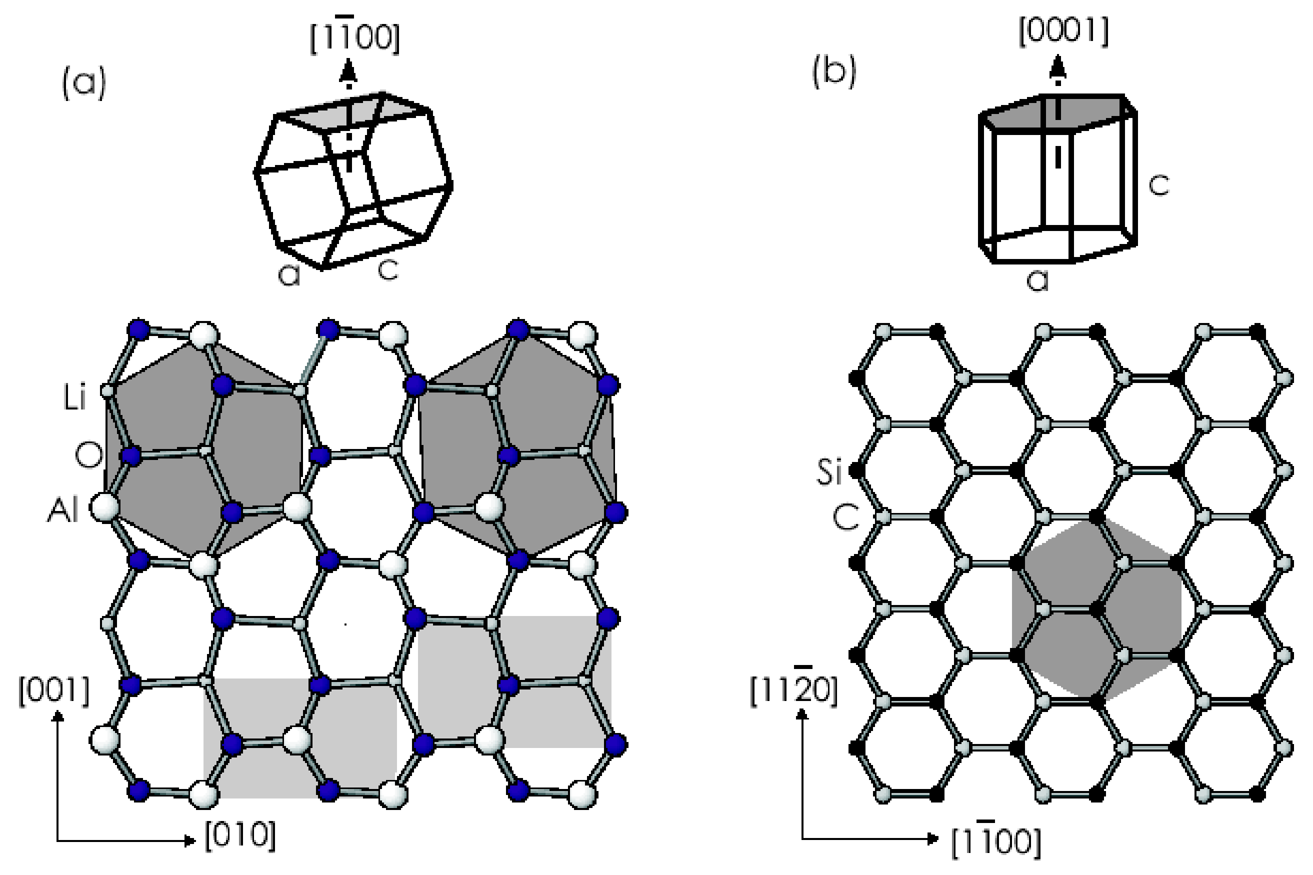
[010]: $a_{LiAlO_2} \approx c_{GaN}$ → 0.3%

[001]: $c_{LiAlO_2} \approx 2\, a_{GaN}$ → 1.7%

GaN与LiAlO2(100)衬底的晶格失配比与蓝宝石的失配小，从理论上讲容易得到高质量的GaN材料。



Substrate	Symmetry	a (Å)	f(%)	$\alpha\ (10^{-6})K^{-1}$	price
γ-$LiAlO_2$(100)	tetragonal	5.1687/6.2679	-0.3/-1.7	7.5	500
Al_2O_3(0001)	hexagonal	4.758	−14	7.5	150
6H-SiC(0001)	wurtzite	3.08123	−3.3	3.2	1000
4H-SiC(0001)	wurtzite	3.07902	−3.4	3.2	1000
Si(111)	cubic	3.8396	+20.4	3.59	20
GaN(0001)	hexagonal	3.1876	0	5.59	–


(a)
[1$\bar{1}$00]
a
c
Li
O
Al
[001]
[010]
(b)
[0001]
c
a
Si
C
[11$\bar{2}$0]
[1$\bar{1}$00]

The m-plane GaN films and InGaN/GaN multiple-quantum-well light-emitting diodes materials were grown on (100)$LiAlO_2$ by LP-MOCVD using TMG, TMIn and NH_3 as Ga , In and N source respectively,nitrogen and hydrogen as carrier gas.

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The samples were evaluated by means of

- X-ray diffraction (XRD)
- Polarized Raman scattering
- Atomic force microscope (AFM)
- Optical absorption and reflection
- Photoluminescence
- Electroluminescence
- I-V measurement.

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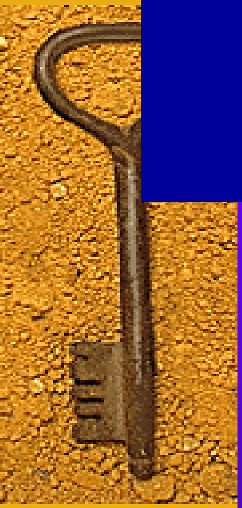
Results and discussion

1 Nonpolar m-plane GaN on LiAlO$_2$

2 InGaN/GaN heterostructures on LiAlO$_2$

3 InGaN/GaN multiple quantum wells LEDs on LiAlO$_2$

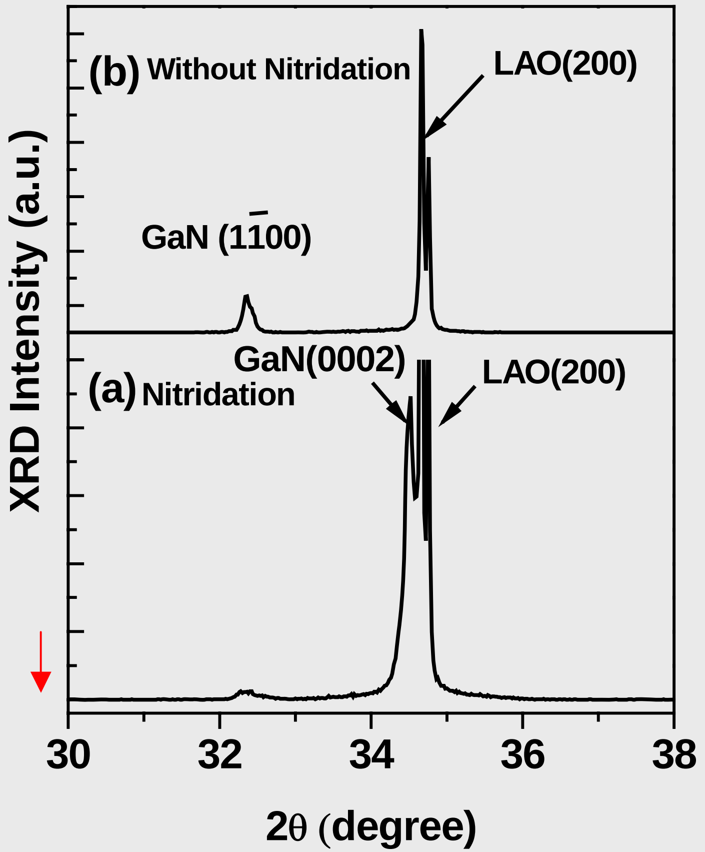
Nonpolar m-plane GaN on LiAlO2（100） substrates



The effect of growth condition on the phase purity of GaN epilayer

- Nitridation of LAO substrate
- Buffer growth temperature

The effect of the Nitridation of LAO substrate on the Phase Purity of GaN Epilayer



Growth condition:

(a) Nitridation, 850°C,150s，

850°C N2 2400s

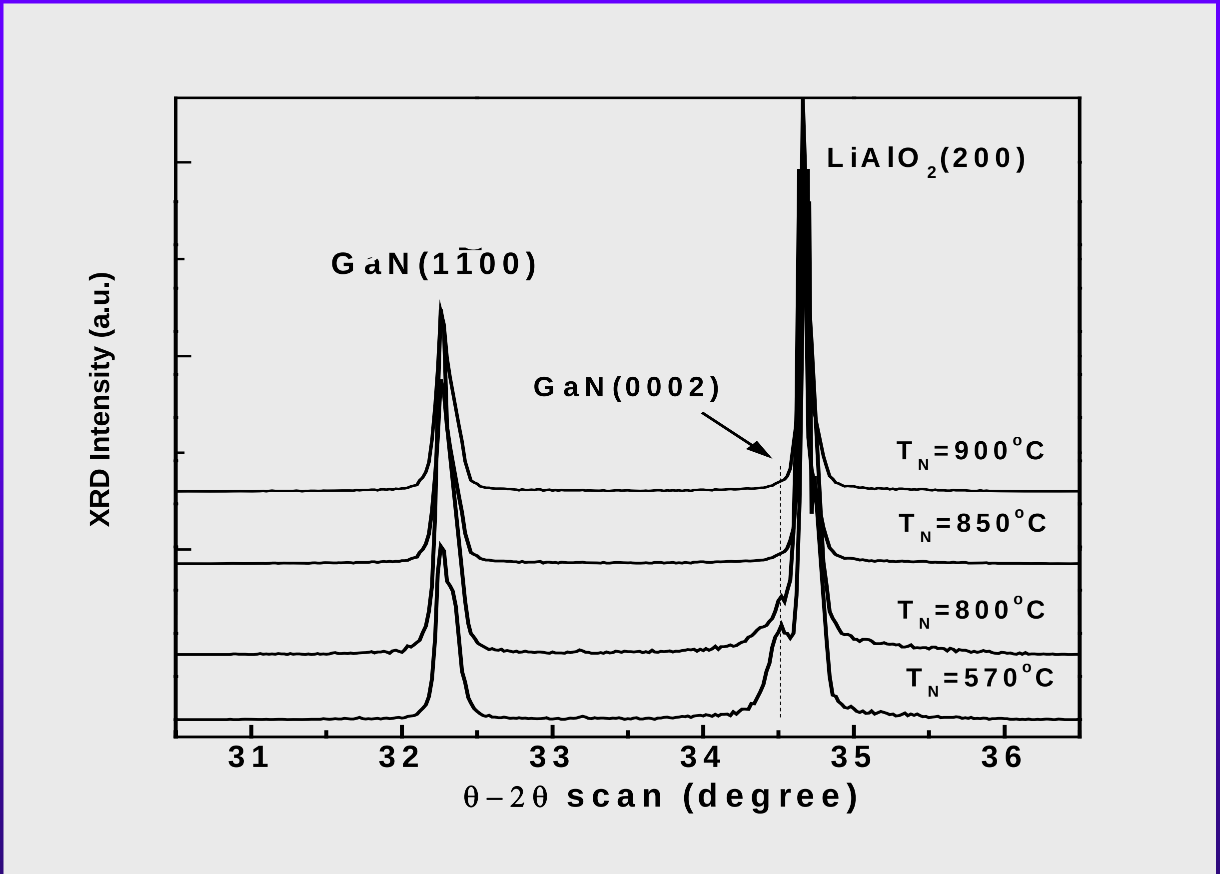
(b) Without nitridation,

850°C, 2400s。

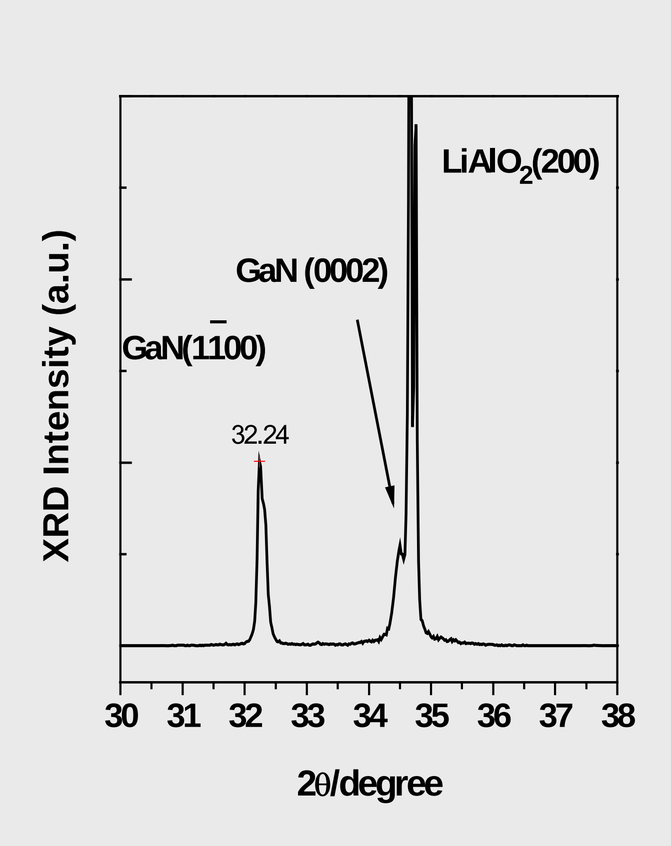
The X-ray diffraction patterns of samples with and without nitridation of the LAO substrate.

- The nitridation of LAO is inclined to the formation of C-plane GaN and is harmful to phase purity of m-plane GaN
- The nitridation of the LAO substrate leads to the reconstruction of the surface and to the formation of a thin layer of C-plane AlN.

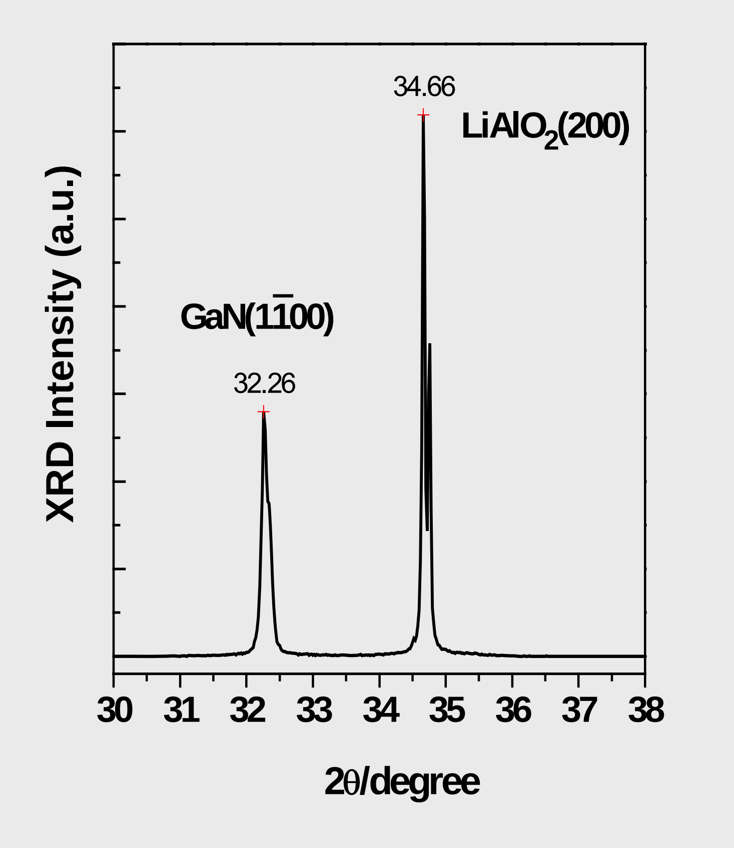
The Effect of Buffer Growth Temperature on The Phase Purity of GaN Epilayer



The X-ray diffraction patterns of samples grown at different buffer growth temperature.

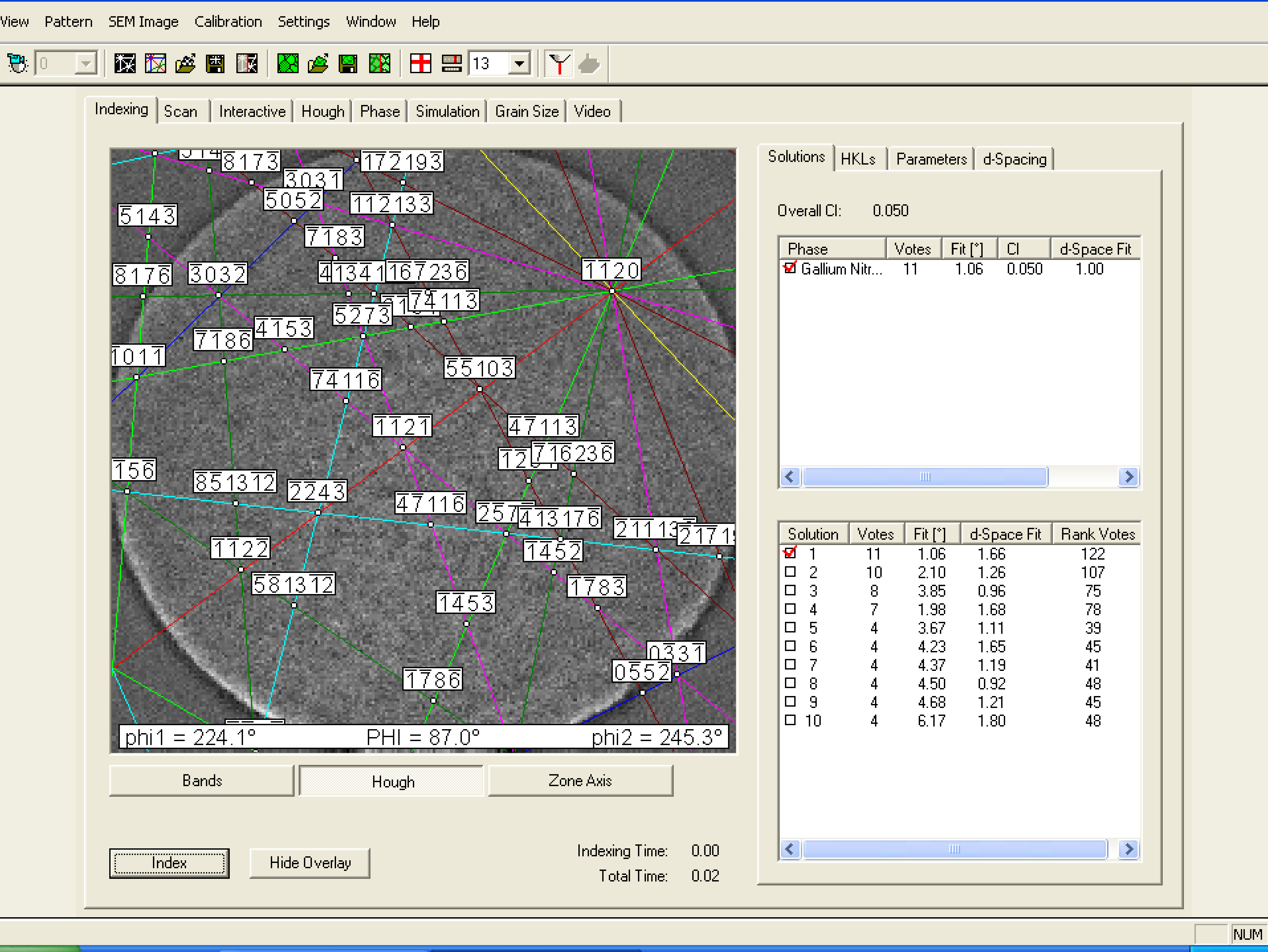


$T_B=570^0C$, $T_G=1050^oC$, t=2400s



$T_B=850^0C$, $T_G=1050^oC$, t=2400s

Results indicates that we obtain pure M-plane GaN film on LAO (100) with nucleation at 850 oC



phi1 = 224.1° PHI = 87.0° phi2 = 245.3°

Overall CI: 0.050

Phase	Votes	Fit [°]	CI	d-Space Fit
☑ Gallium Nitr...	11	1.06	0.050	1.00

Solution	Votes	Fit [°]	d-Space Fit	Rank Votes
☑ 1	11	1.06	1.66	122
☐ 2	10	2.10	1.26	107
☐ 3	8	3.85	0.96	75
☐ 4	7	1.98	1.68	78
☐ 5	4	3.67	1.11	39
☐ 6	4	4.23	1.65	45
☐ 7	4	4.37	1.19	41
☐ 8	4	4.50	0.92	48
☐ 9	4	4.68	1.21	45
☐ 10	4	6.17	1.80	48

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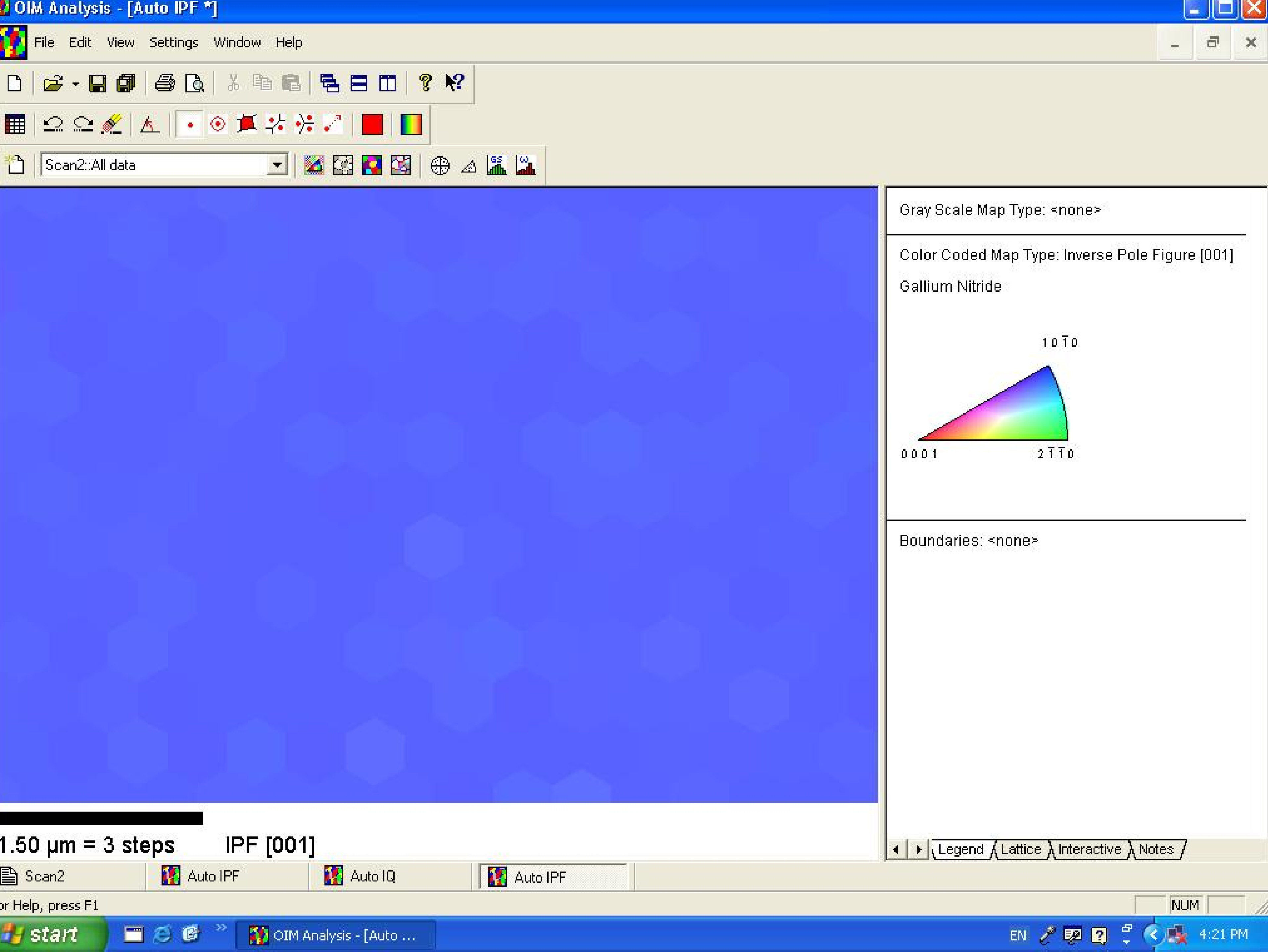


Gray Scale Map Type: <none>

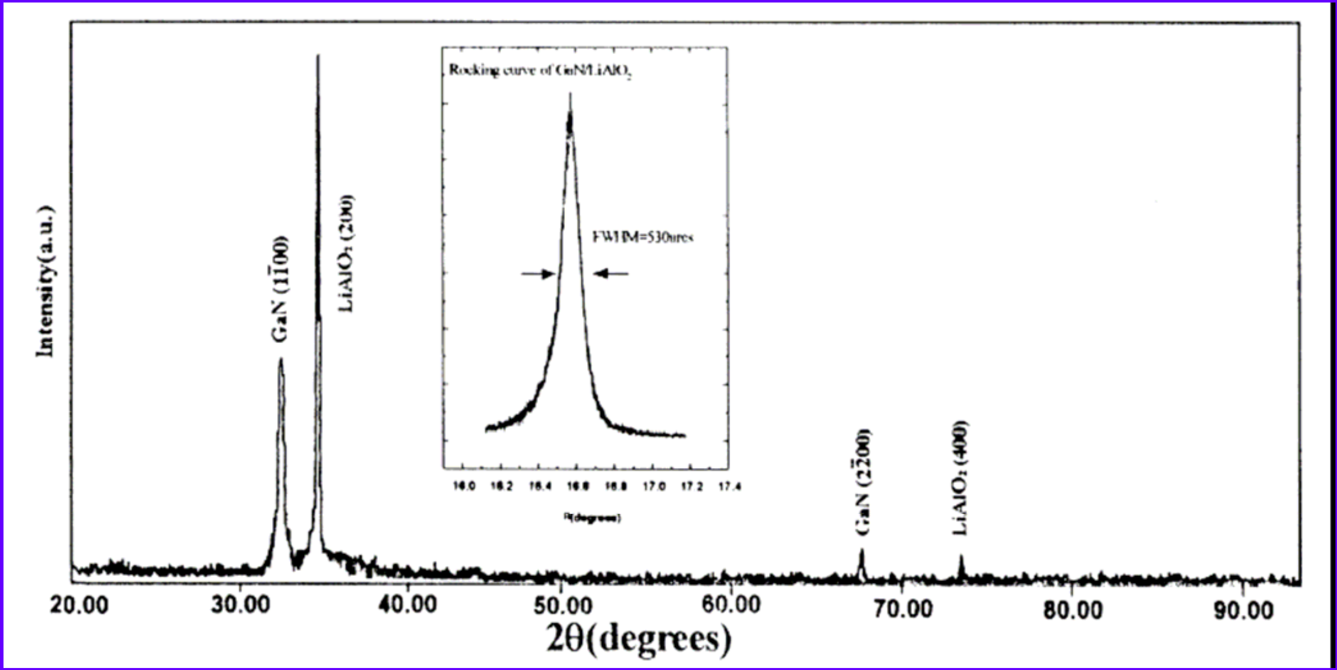
Color Coded Map Type: Inverse Pole Figure [001]

Gallium Nitride

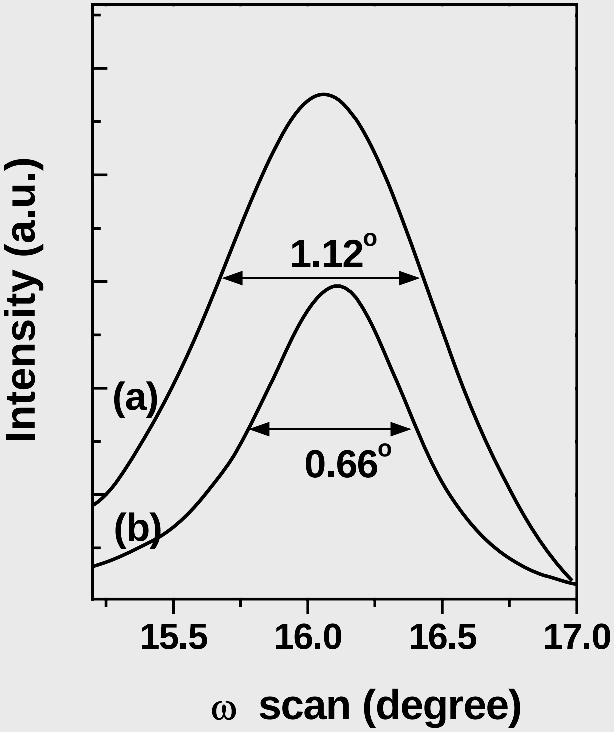
Boundaries: <none>

1.50 μm = 3 steps IPF [001]

- we conclude that growth at relatively higher buffer temperature can avoid c-phase GaN forming and be in favor of fabricating single-crystal m-plane GaN.



The effect of carrier gas on the quality of GaN epilayer



T_G=1050^{0}C

N_2 and H_2 as carrier gas respectively

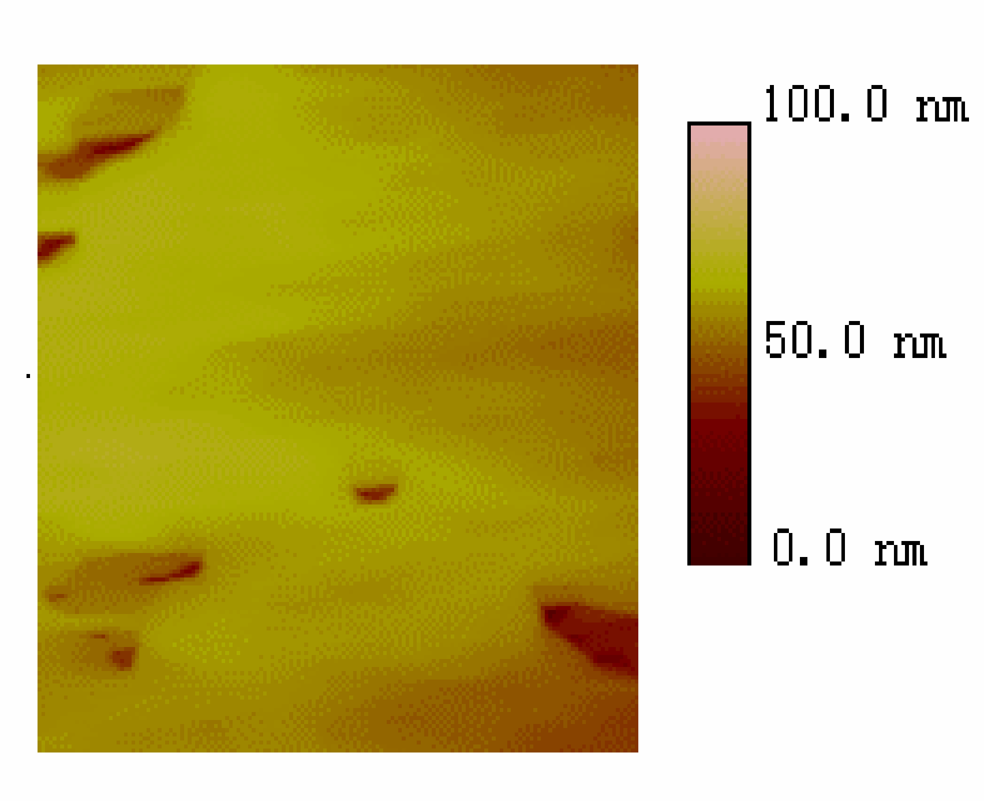
(a) N_2 as carrier gas, FWHM=1.12°

(b) H_2 as carrier gas, FWHM=0.66°

The rocking curve of GaN epilayer with vary carrier gas

Optimizing growth condition: LP-MOCVD

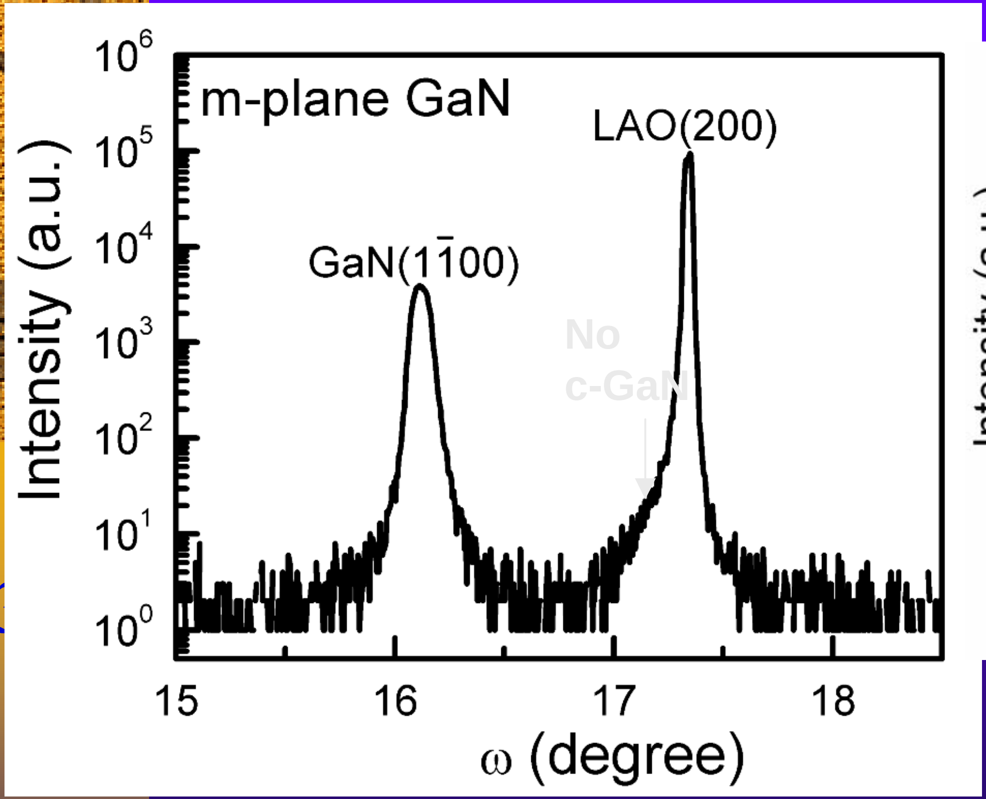
- Two-step growth method
- $T_N=850\ ^{o}C \sim 900\ ^{o}C$, N_2
- $T_G=1050^{0}C$, H_2
- Without Nitridation (LAO)

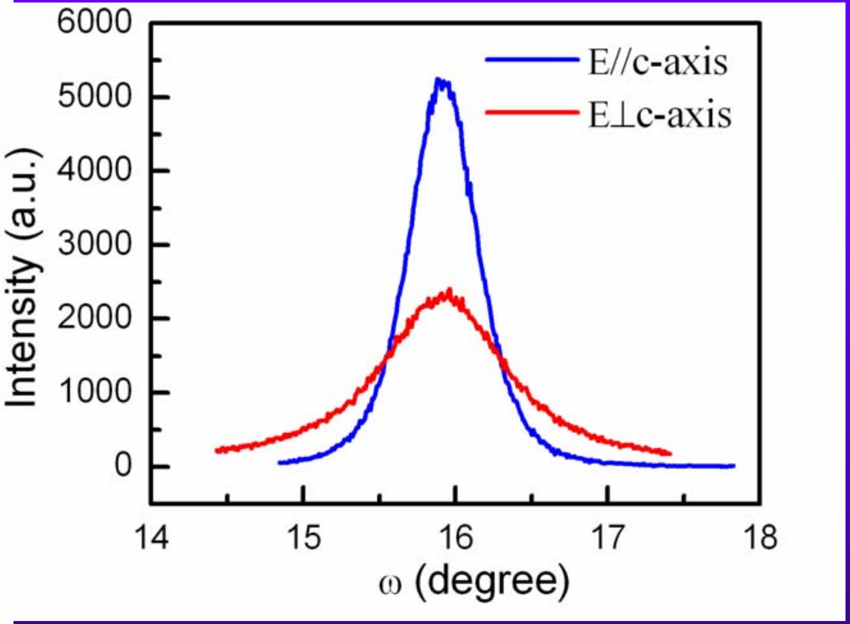


RMS roughness about 7nm.

Figure 3 2X2 μ m^2 AFM surface micrographs of GaN grown on LAO (T_N=850^{0}C, T_G=1050^{0}C)

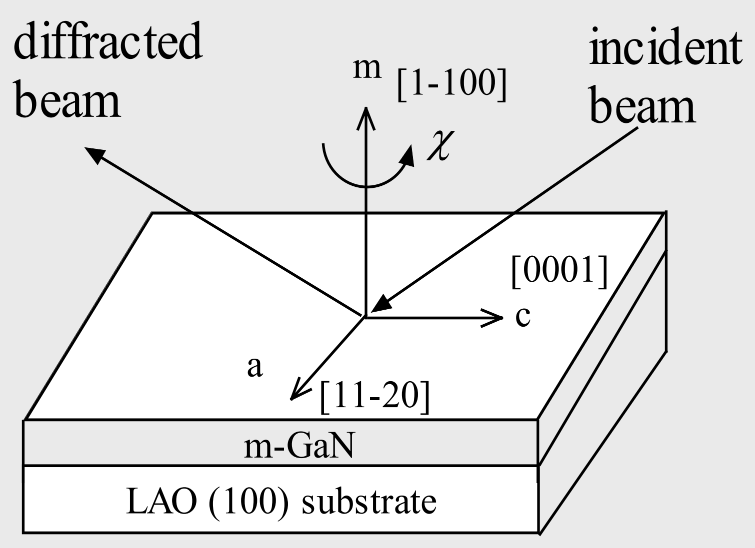
高分辨XRD ω~2θ扫描

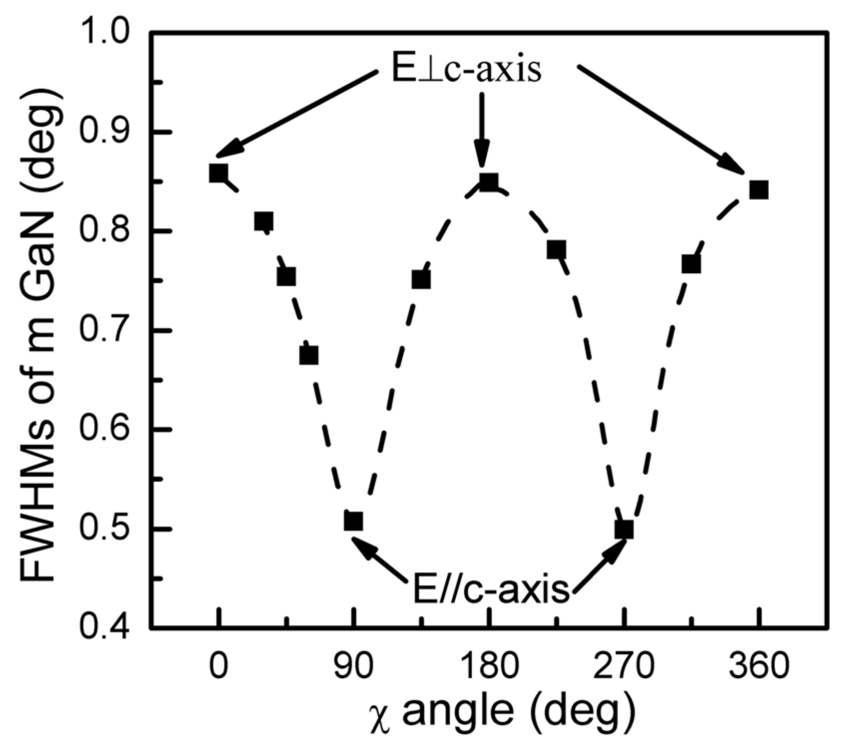




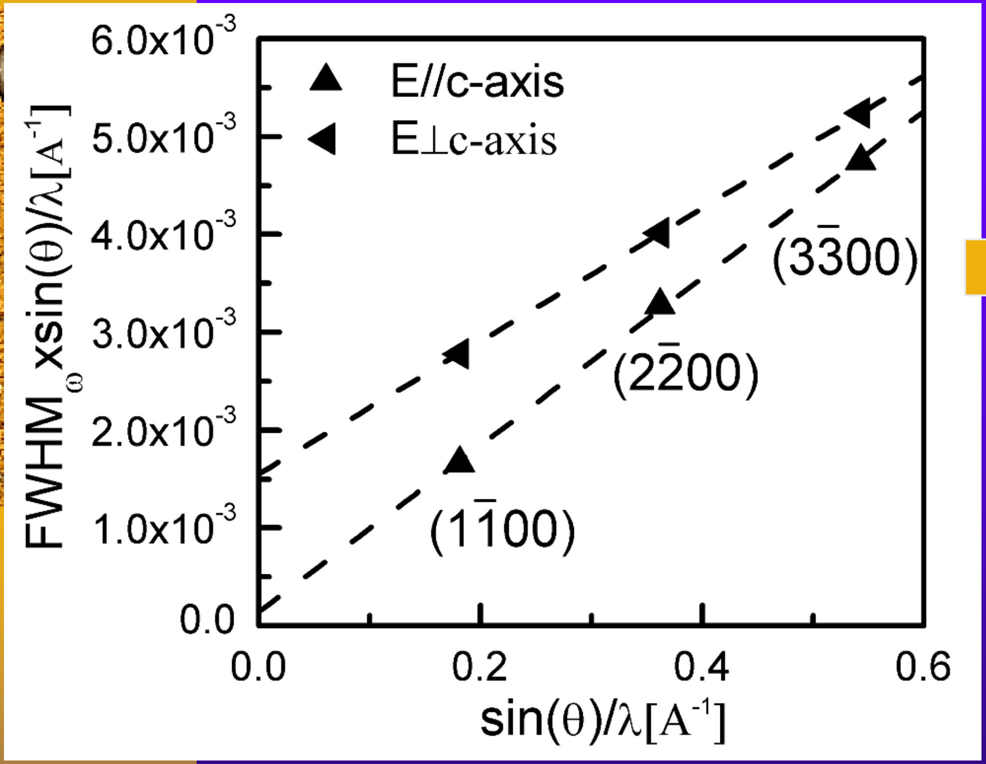
我们发现摇摆曲线的半峰宽在面内的两个方向明显差异。

摇摆曲线半峰宽随面内角χ变化



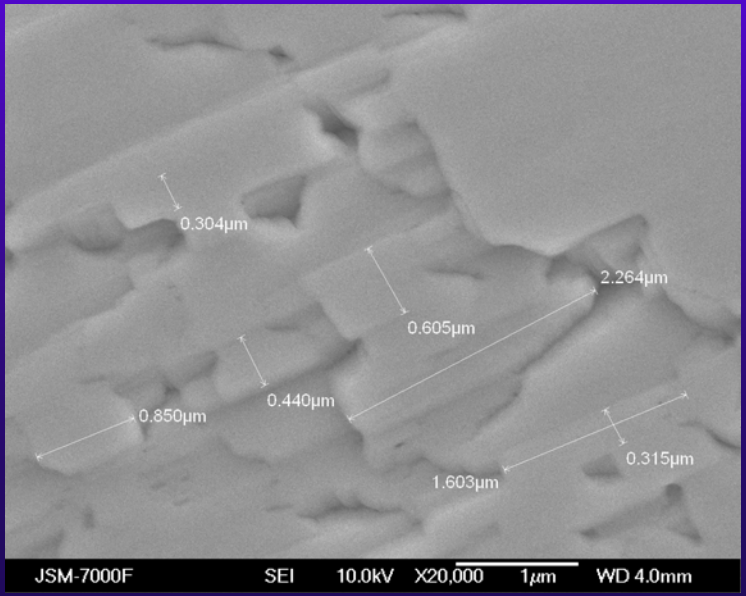


Williamson-Hall plot



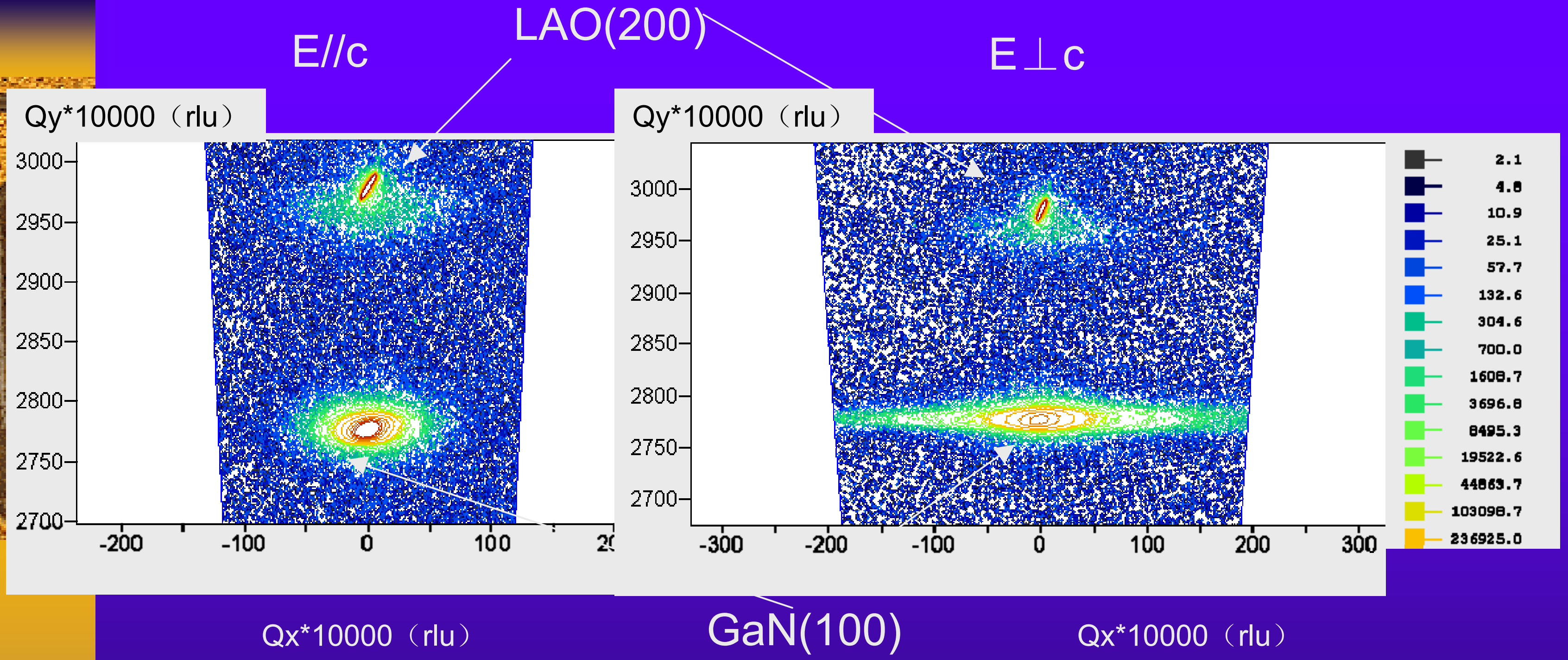
从W-H图，我们得出两个方向的tilt和lateral correlation length是不一样的。

	E//c	E⊥c
tilt	0.39°	0.48°
LC	300nm	30nm



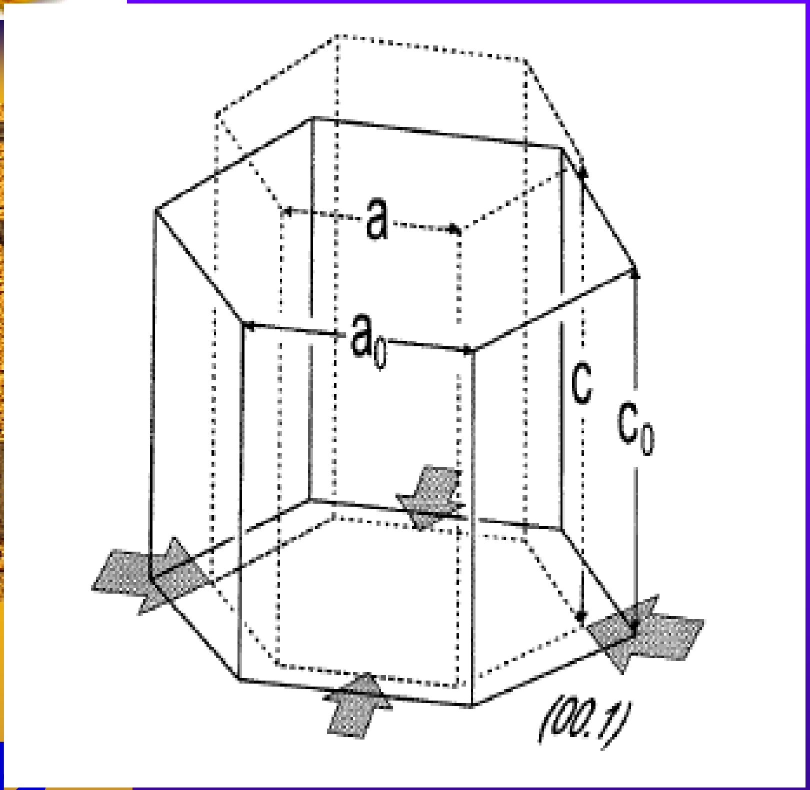
SEM形貌比较

GaN对称面(100)倒易空间map



上图表明，m-GaN(1$\bar{1}$00)在倒空间中的展宽当X射线的电场矢量E与c轴平行或垂直时是不一样的，说明了结构的各向异性。起源是GaN面内的a和c轴方向上tilt和lateral correlation length有差别，其数值已由Williamson-Hall plot 分析。

c-GaN应变分析



生长在C-sap or SiC的GaN面内受双轴压应力

c-GaN面内的应变是各向同性的，因此：

$$\epsilon_{\|}=\epsilon_{xx}=\epsilon_{yy}$$

$$\epsilon_{\perp}=\epsilon_{zz}$$

根据六角结构的对称性，可得

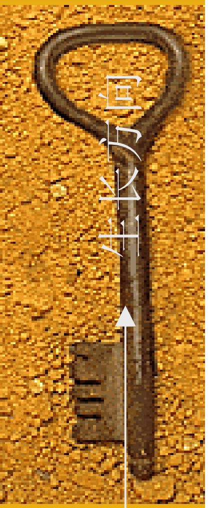
$$\begin{pmatrix}\sigma_{\|}\\ \sigma_{\perp}\end{pmatrix}=\begin{pmatrix}C_{11}+C_{12} & C_{13}\\ 2C_{13} & C_{33}\end{pmatrix}\begin{pmatrix}\epsilon_{\|}\\ \epsilon_{\perp}\end{pmatrix}$$

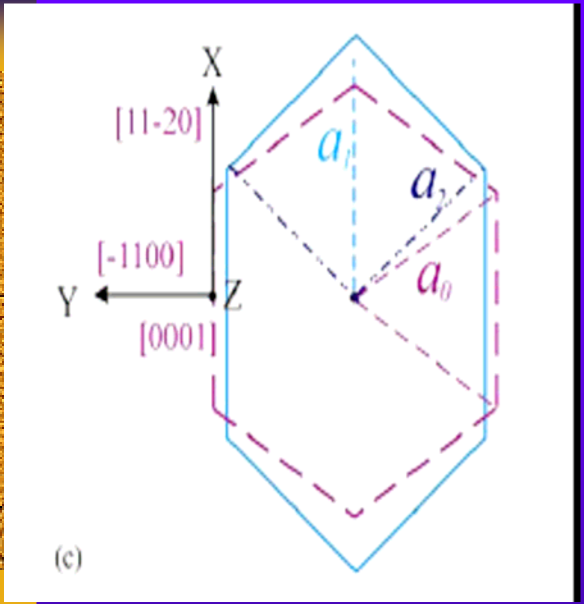
Z方向上是没有应力的，$\sigma_{\perp}=0$，所以：

$$\frac{\epsilon_{\perp}}{\epsilon_{\|}}=-2\frac{C_{13}}{C_{33}}$$

对于c-GaN，我们采用X射线手段只测对称面(0002)的晶格常数c，就可得ε_{zz}，从而算得面内的应变ε_{xx}。

m-GaN的应力分析





m-GaN的六角形产生形变后，

$$a1 \neq a2$$

同时：

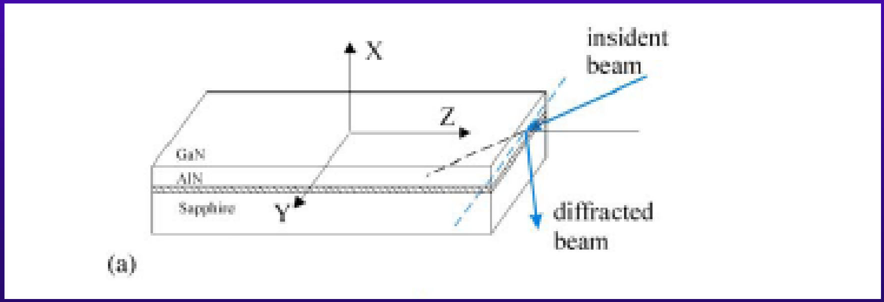
$$\varepsilon_{xx} \neq \varepsilon_{yy}$$

根据六角结构的对称性，只能得到：

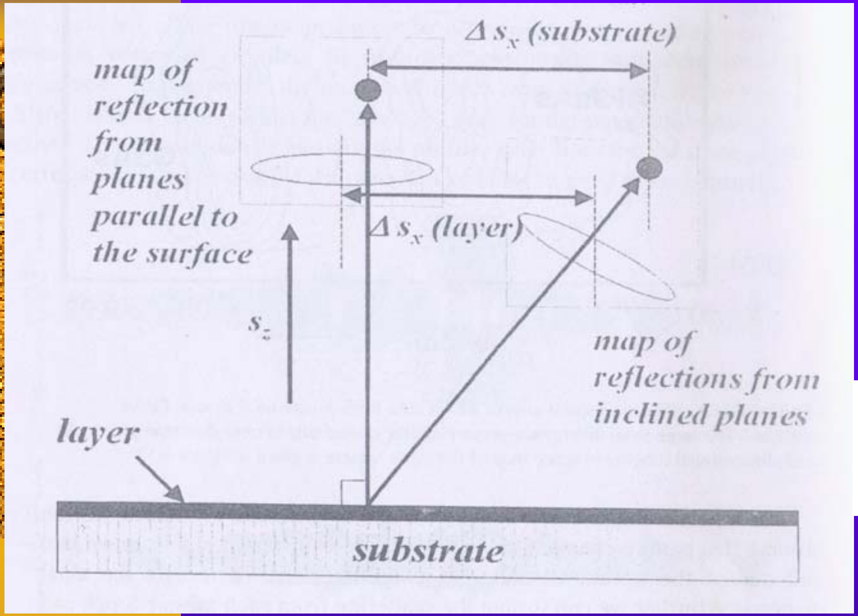
$$\epsilon_{yy} = \frac{-C_{12}\epsilon_{xx} - C_{13}\epsilon_{zz}}{C_{11}}$$

X射线测GaN(100)，能够得到 ε_{yy}，但是确定不了ε_{xx}和 ε_{zz}

GaN有足够厚，我们采用edge-geometry测样品侧面。



采用倒易空间方法分析



倒易空间方法可以精确的独立的确定面内外的晶格常数、应变。

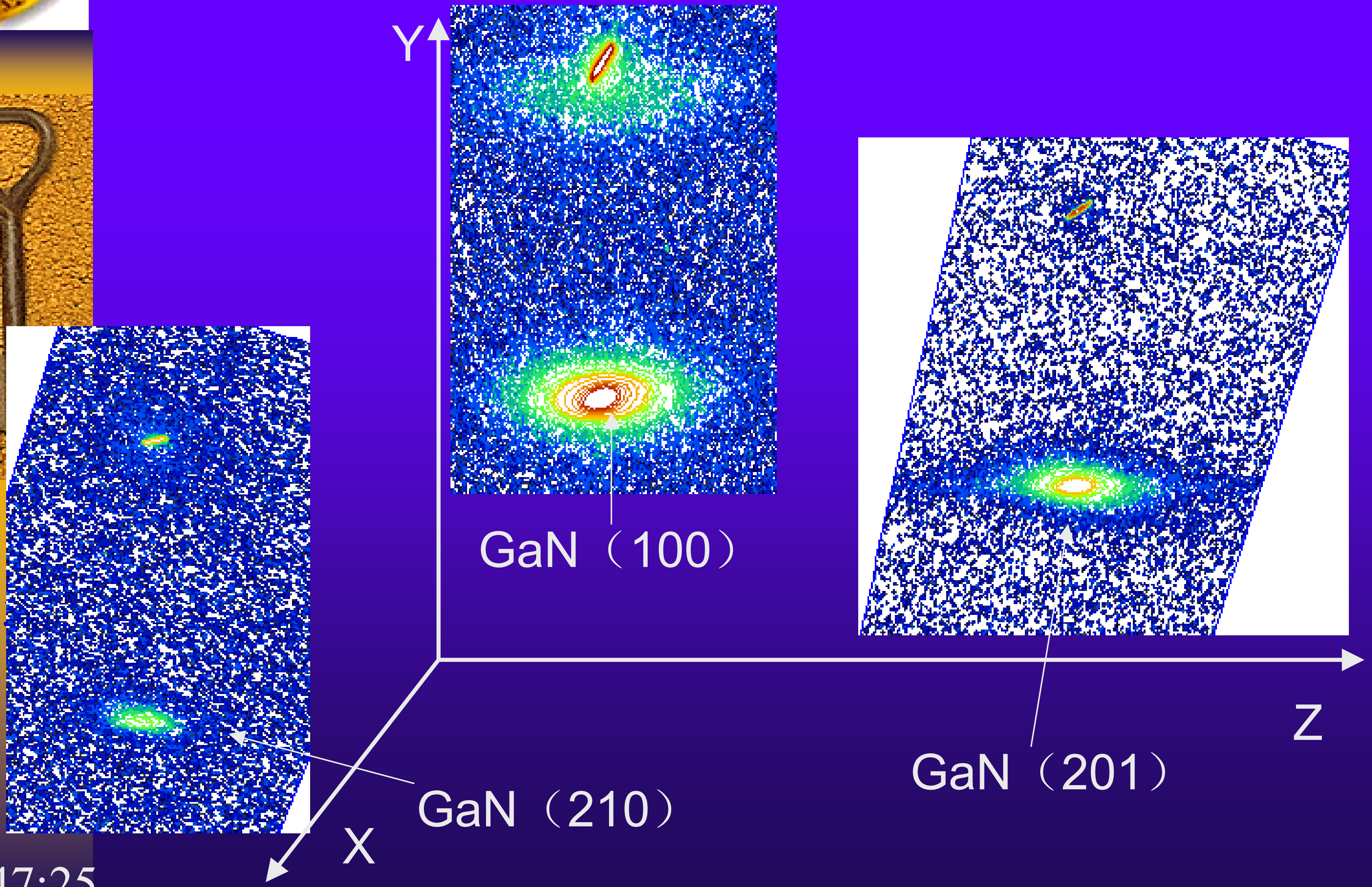
$$d_z = \frac{1}{s_z} = \frac{\lambda}{\{\sin\omega_{0\,0\,0\,2} + \sin(2\omega'_{0\,0\,0\,2} - \omega_{0\,0\,0\,2})\}}.$$

$$d_x = \frac{1}{s_x} = \frac{\lambda}{\{\cos\omega_{0\,1\,\bar{1}\,5} - \cos(2\omega'_{0\,1\,\bar{1}\,5} - \omega_{0\,1\,\bar{1}\,5})\} - \{\cos\omega_{0\,0\,0\,2} - \cos(2\omega'_{0\,0\,0\,2} - \omega_{0\,0\,0\,2})\}}$$

这样就可以得到各个方向的应变：

$$strain = \varepsilon_{xx} = \{\frac{d_x - \{d_x\}_{relax}}{\{d_x\}_{relax}}\}$$

GaN倒易空间图



结果分析

	ω (°)	2θ(°)	d(A)	ε(%)
Y(100)	16.1220	32.2315	2.7750	0.48%
X(210)	28.0558	94.8192	3.1568	-1.009%
Z(201)	20.1778	70.3156	5.1742	-0.19%

结果表明Y方向（即生长方向）产生压应变，面内X，Z方向产生张应变。

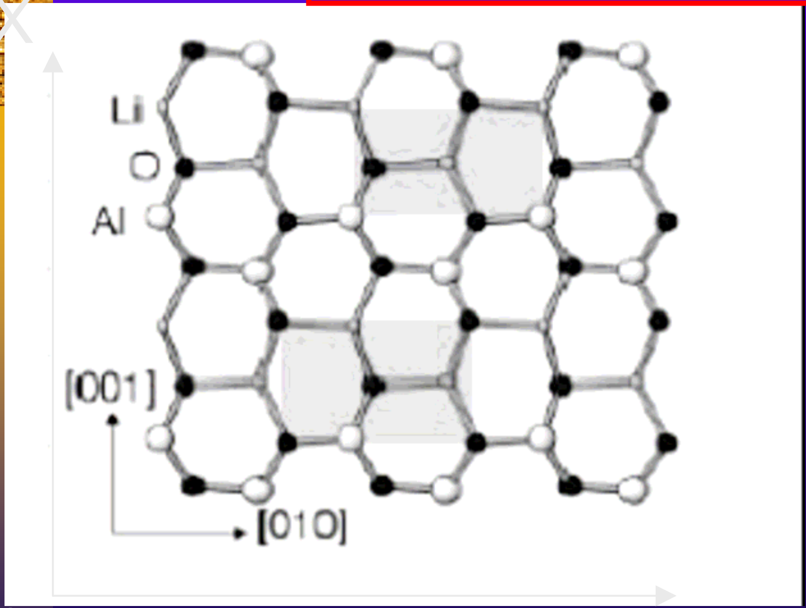
应变来源分析

来源

晶格失配 $f_x=0.3\%$

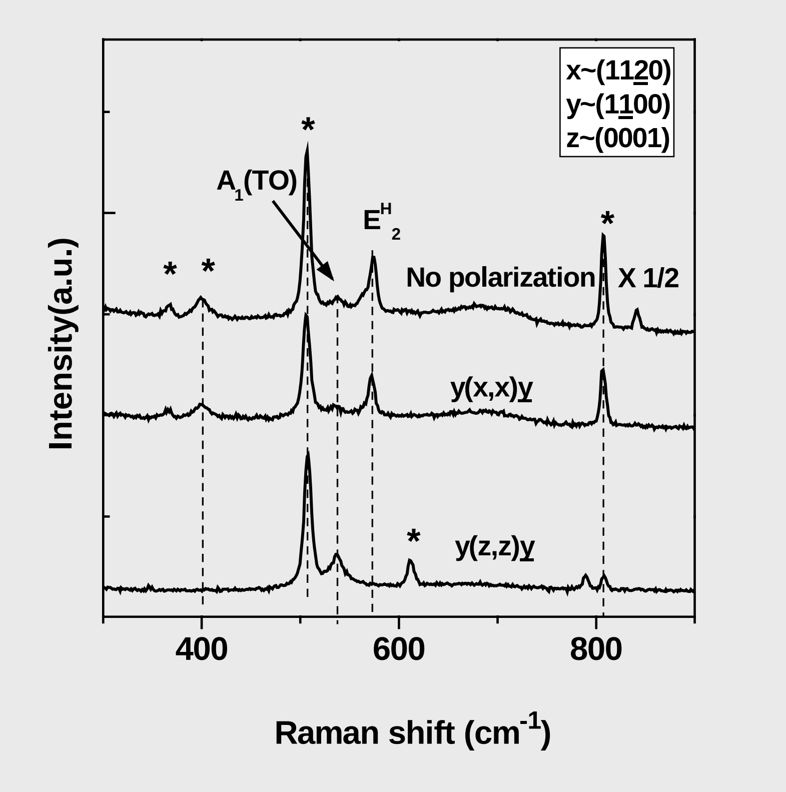
$f_z=1.7\%$

	GaN	LAO	热失配率
热膨胀系数（$10^{-6}/K^{-1}$）	$\alpha_Z=3.17$	$\alpha_Z=10.21$	69％
	$\alpha_x=5.59$	$\alpha_x=16.86$	67％



我们认为产生的主要来源是晶格失配，而在两个方向上的热失配差别不大。

Polarized Raman spectra of m-GaN



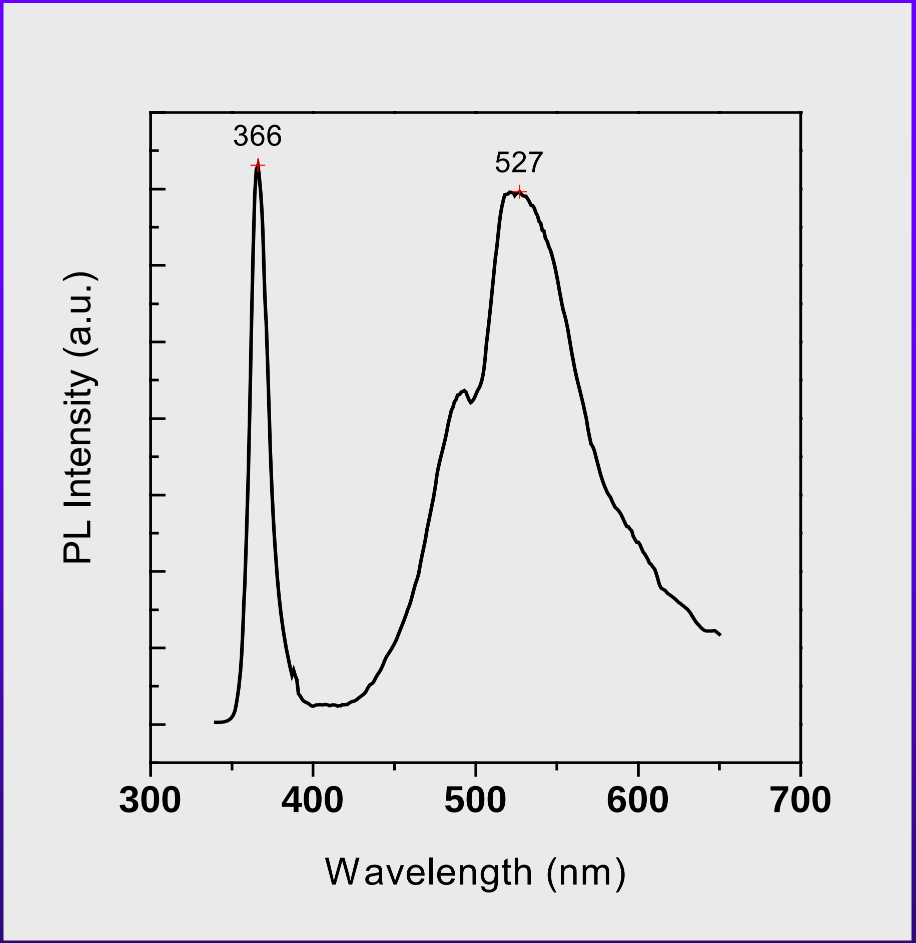
E$_2$(high) is not observable, confirming that the GaN film is a good single crystal

E$_2$(high) locates at 574cm^{-1}, blue-shifted 5cm^{-1}, indicating that compressive strain existing in the GaN film

(peaks with * come from LAOsubstrate)

Polarized Raman spectra confirm the in-plane anisotropy of the GaN film

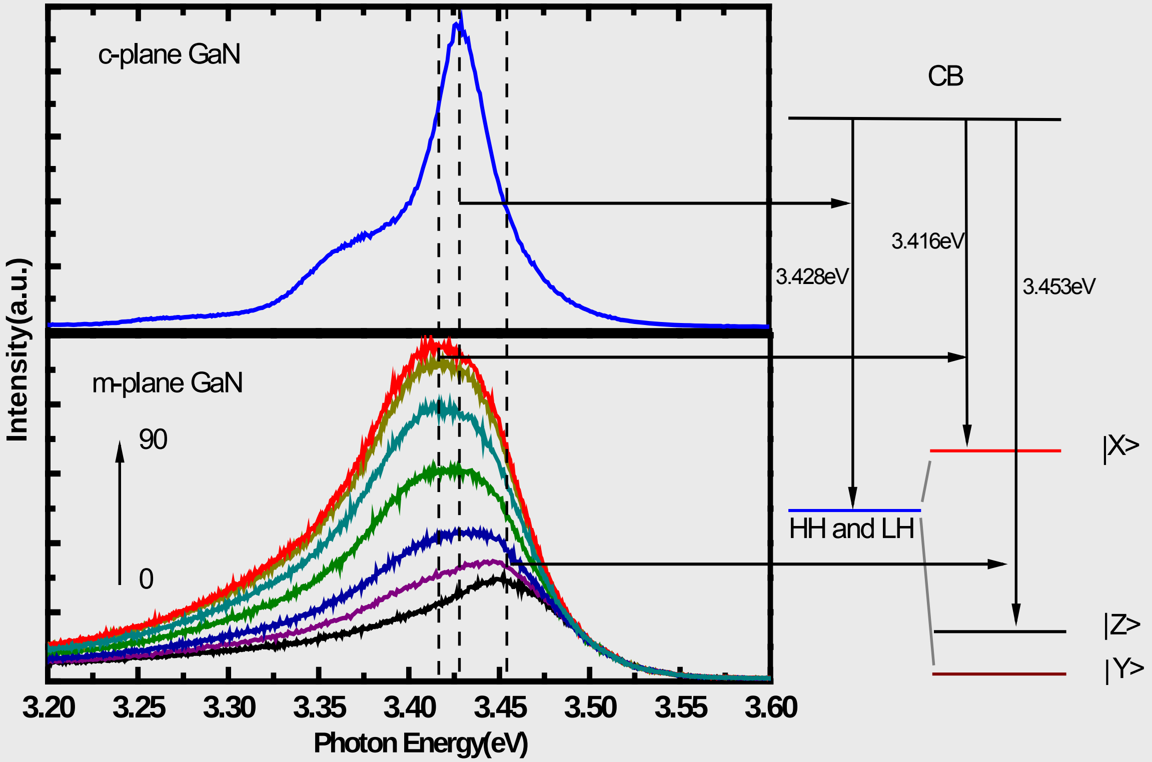
PL spectra of M-planeGaN



366nm～near band edge emission (NBE)

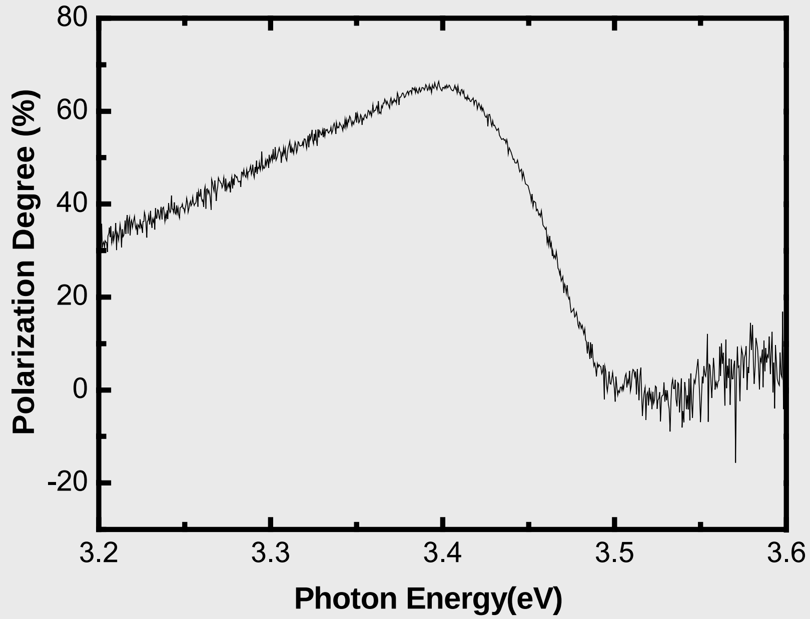
527nm～ yellow band emission

偏振PL谱



- 偏振PL谱表现了能带分裂的结果
- 同时给出｜x>带与｜z>在Γ点的能量差为37meV

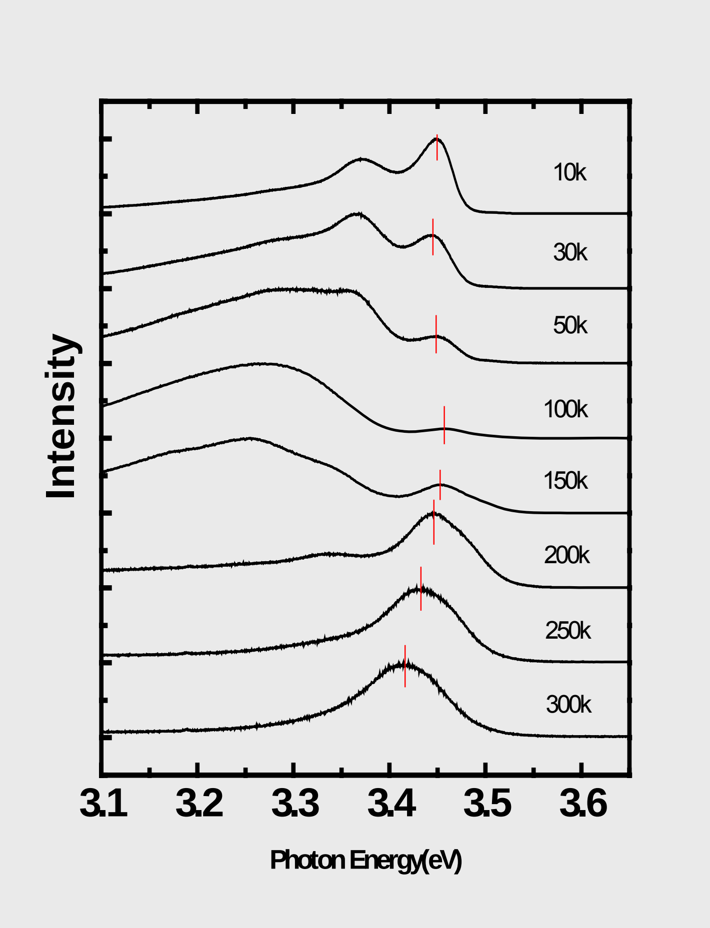
偏振度

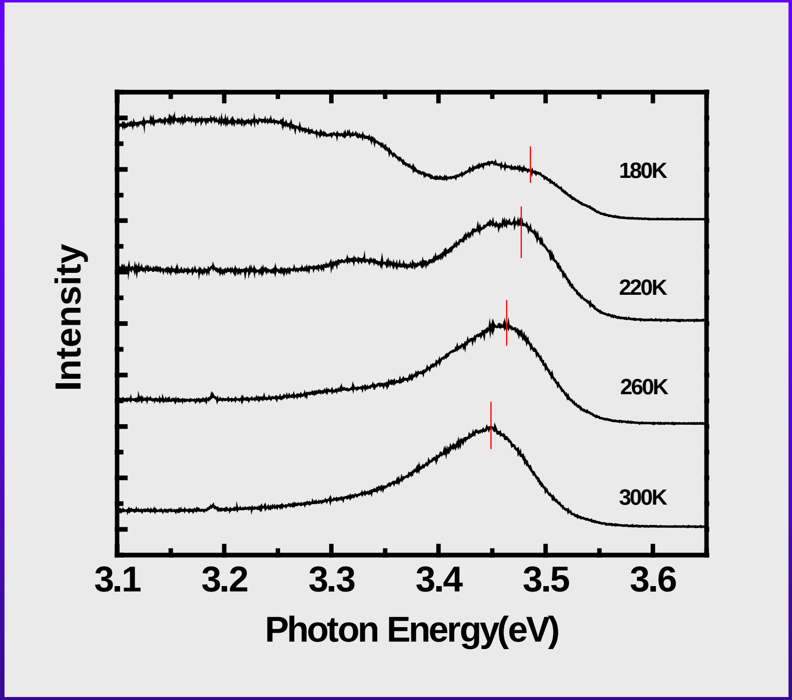


$$\rho = \frac{I_{E\perp c} - I_{E\parallel c}}{I_{E\perp c} + I_{E\parallel c}}$$

采用垂直腔表面发射的激光器产生E‖x的偏振光将是性能比较优化的。

变温PL谱

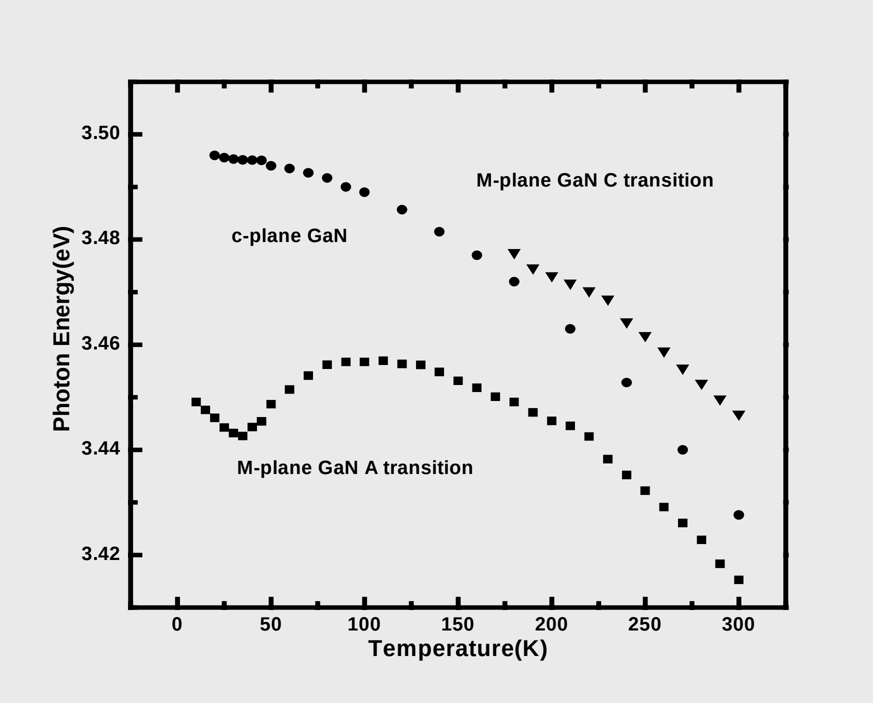




A跃迁变温谱

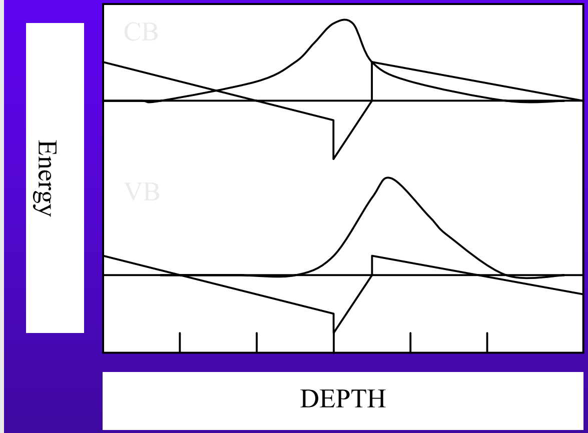
C跃迁变温谱

变温PL峰移



跃迁能量随温度的变化

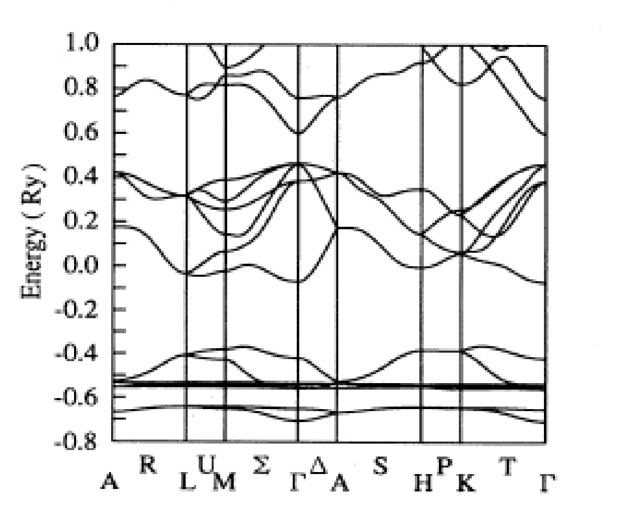
- S型变化原因：缺陷



- 空穴激活能：9meV

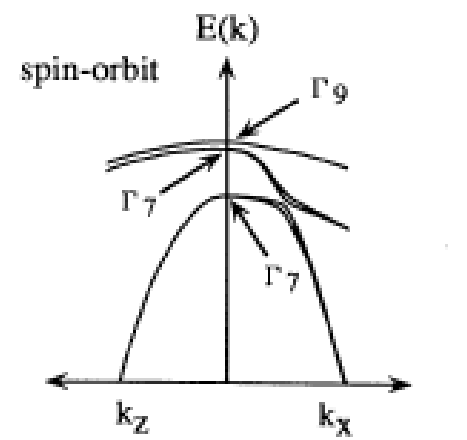
无应力作用下GaN能带

重空穴带 |x±iy>
轻空穴带
晶场劈裂带 |z>



Ga和N的s态电子

N 2p态电子

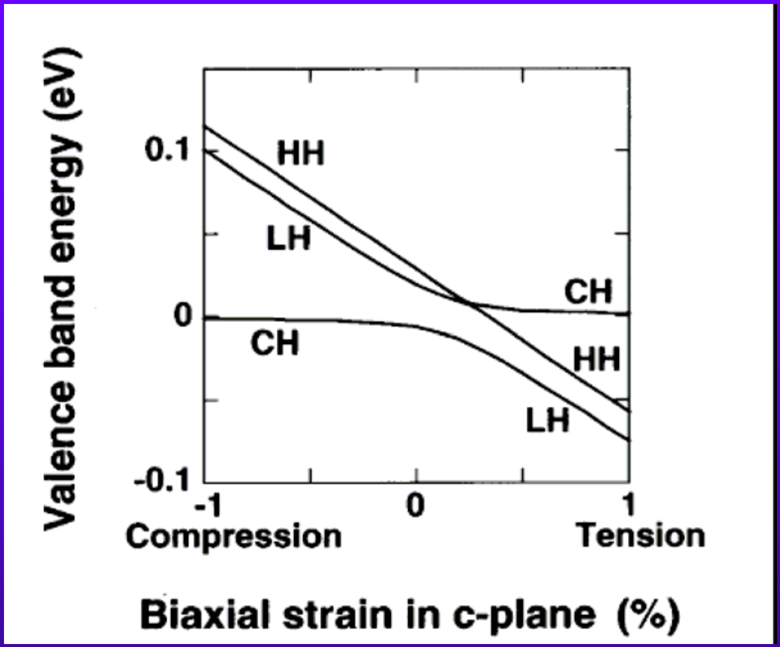


GaN能带图

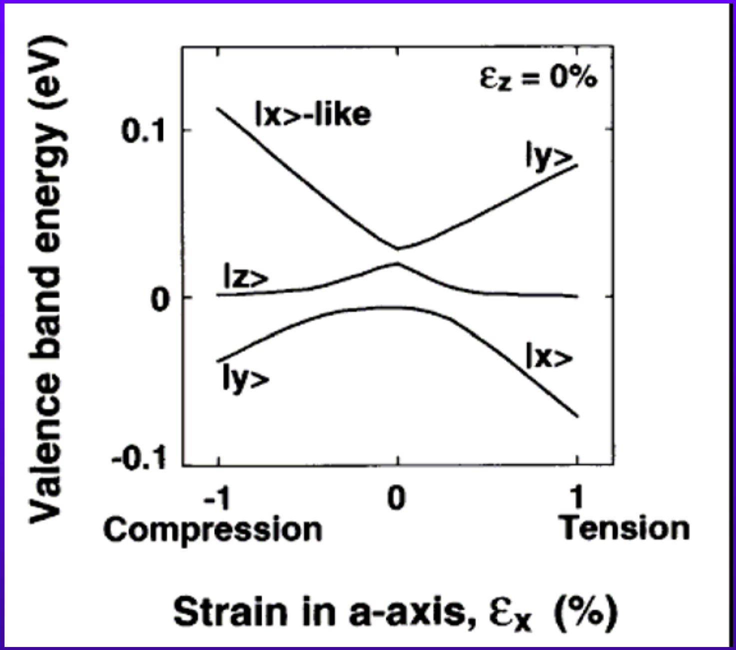
考虑电子自旋的价带顶能带

M. Suzuki et. al, Phys. Rev. B., 52(11): 8132 (1995)

应力作用下价带顶能带



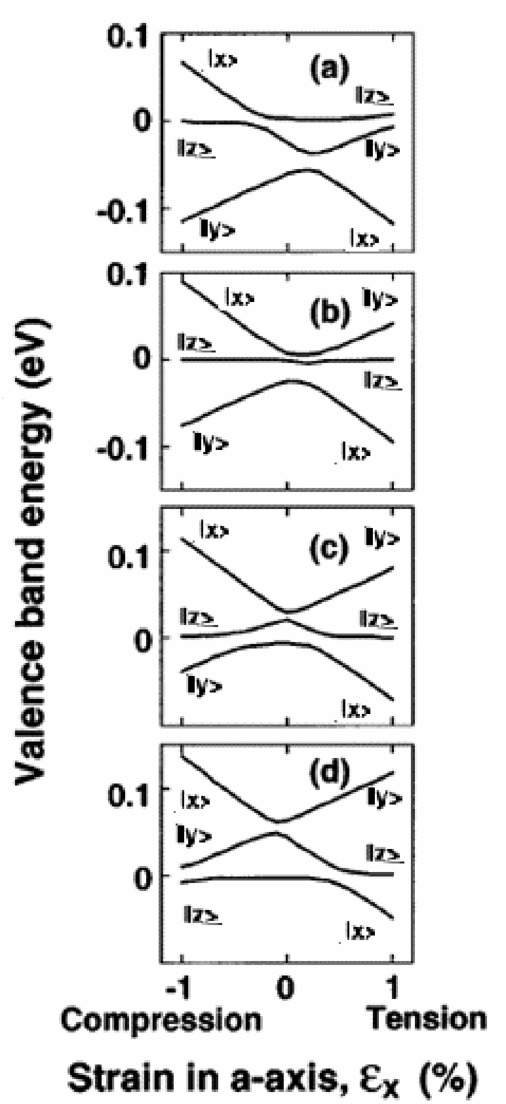
C面各向同性应力作用下



C面各向异性应力作用下

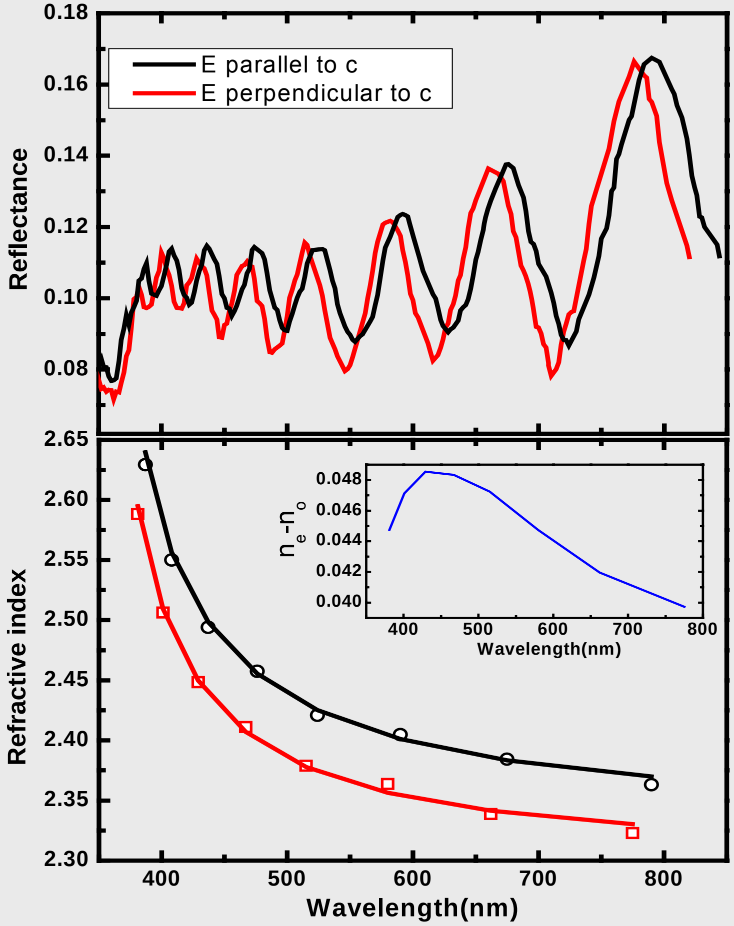
K. Domen, et al. Appl. Phys. Lett. 70(8), 24 (1997).

应力作用下价带顶能带



- (a) ε_z=-1%
- (b) ε_z =-0.5%
- (c) ε_z =0%
- (d) ε_z =0.5%

偏振反射谱



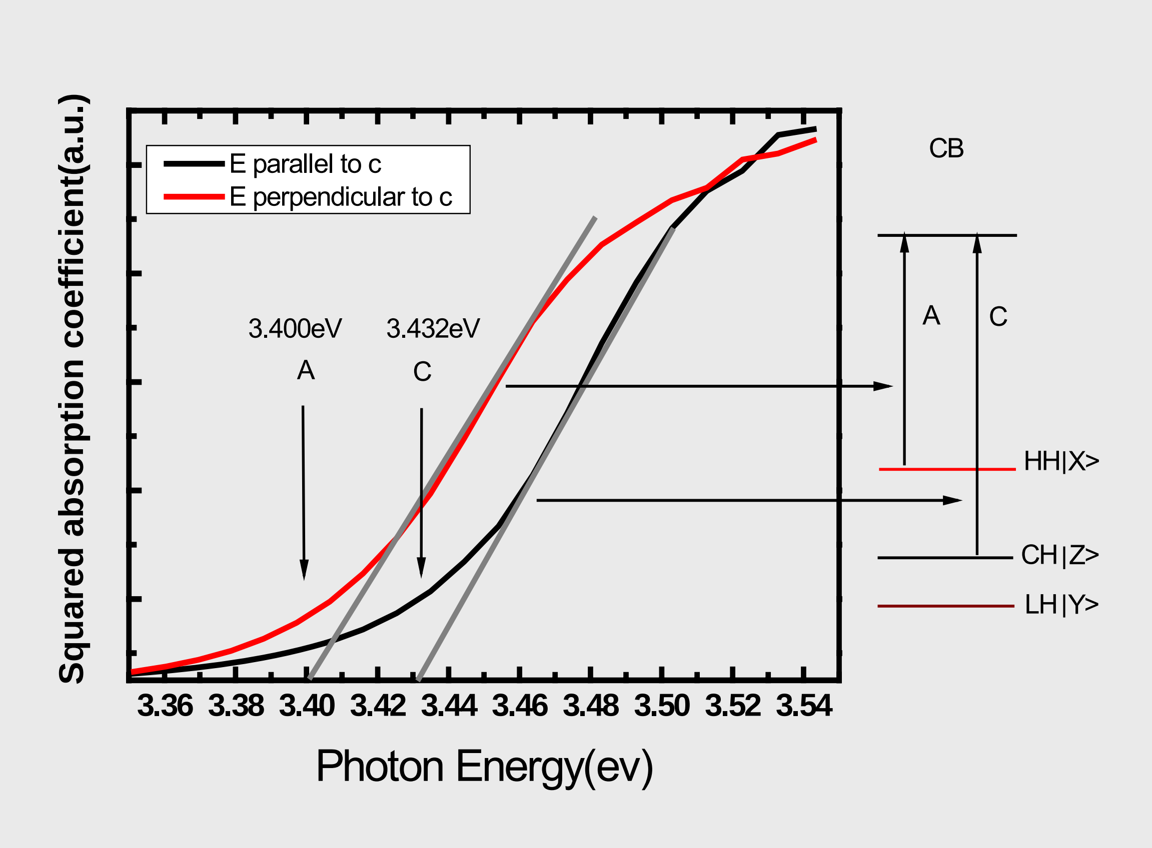
两个不同偏振方向的反射谱的干涉峰位存在明显的偏移

$$n^2(\lambda) = \varepsilon_\infty + \frac{a_1}{\lambda^2 - b_1^2} + \frac{a_2}{\lambda^2 - b_2^2}$$

$$\varepsilon_{\infty \mathrm{P}} = 5.480$$

$$\varepsilon_{\infty \perp} = 5.324$$

偏振吸收谱



拟和公式:

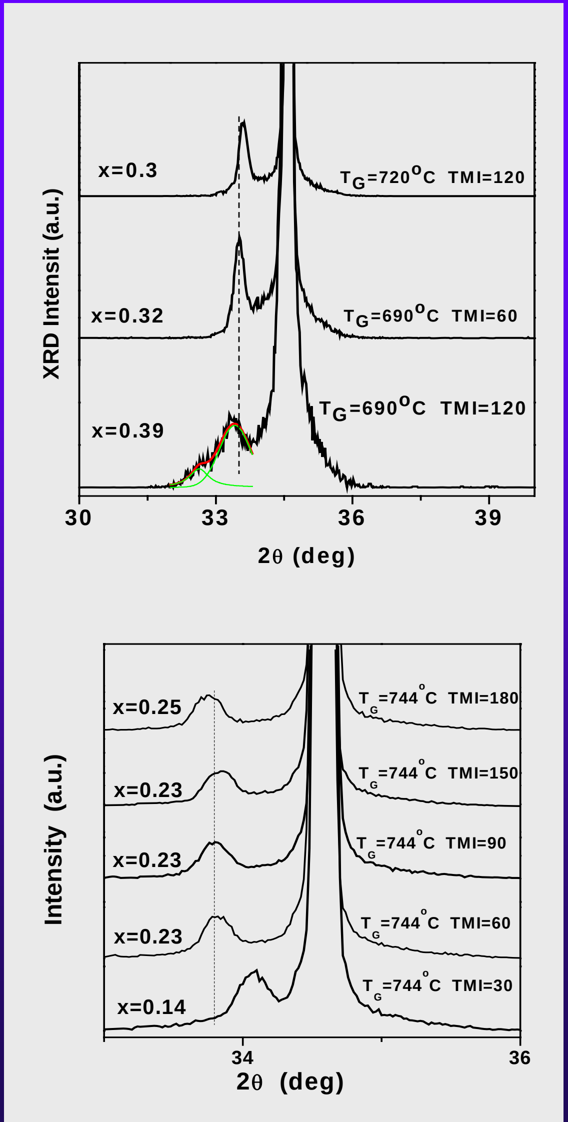
$$\alpha(h\upsilon) = A(h\upsilon - E_g)^{1/2}$$

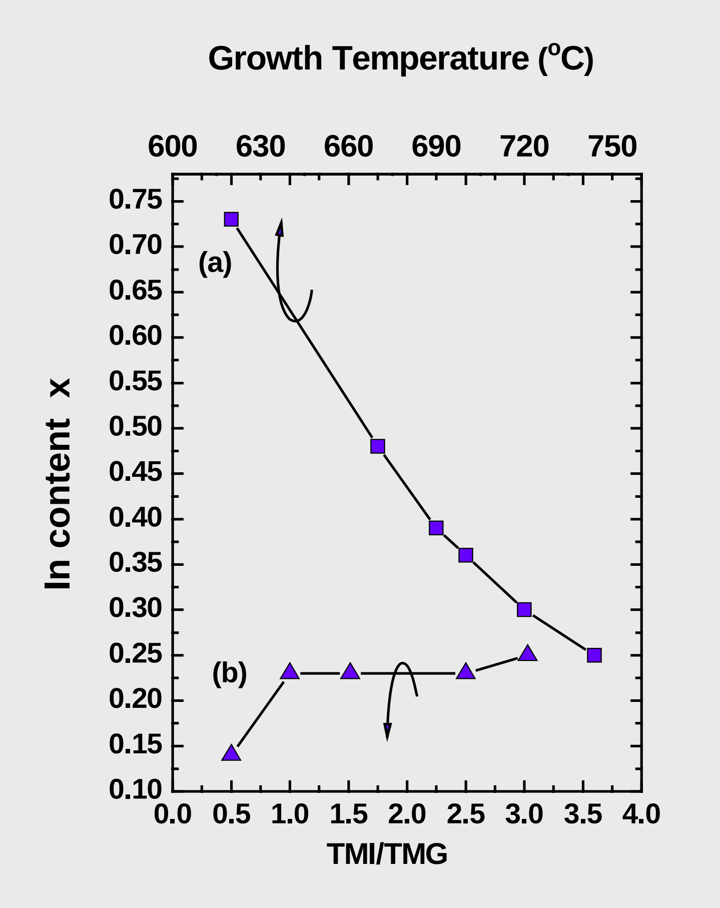
两个偏振方向的有效禁带宽度的差为

32meV

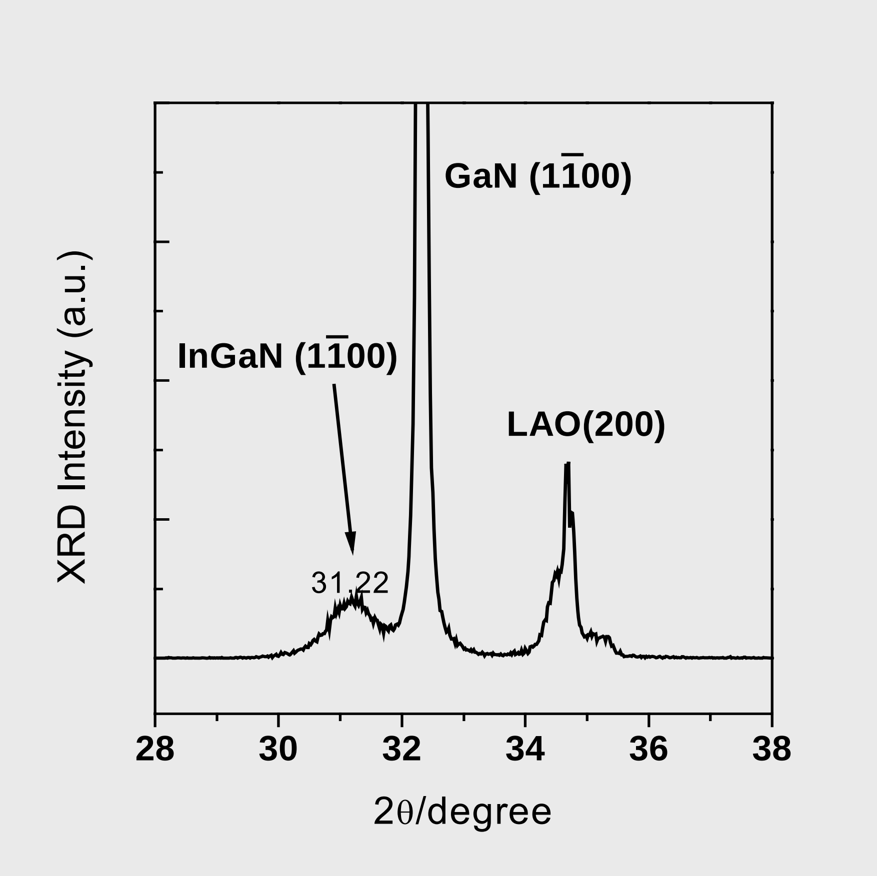
nonpolar m-plane InGaN/GaN heterostructures

The effect of the TMI and growth temperature on In-content in InGaN grown on LAO



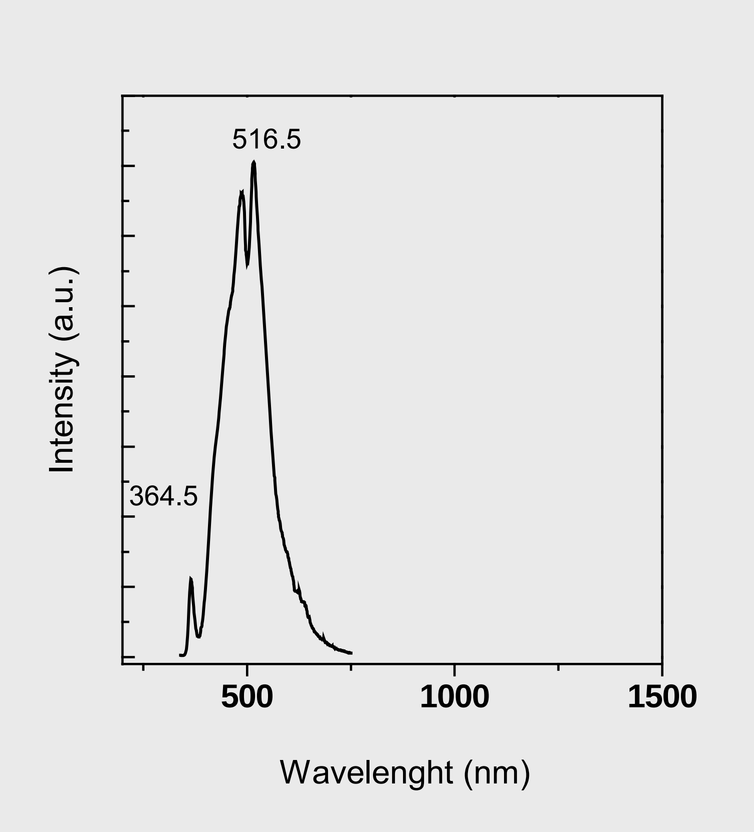


The X-ray diffraction patterns of InGaN/GaN hetrostructure grown on the LAO substrate.



In-content ~ 0.3

PL spectra of InGaN/GaN MQWs grown on LAO



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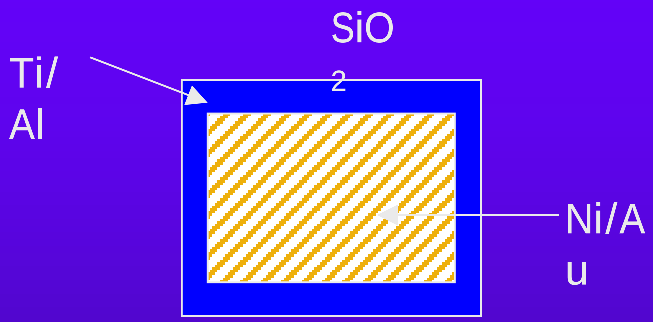
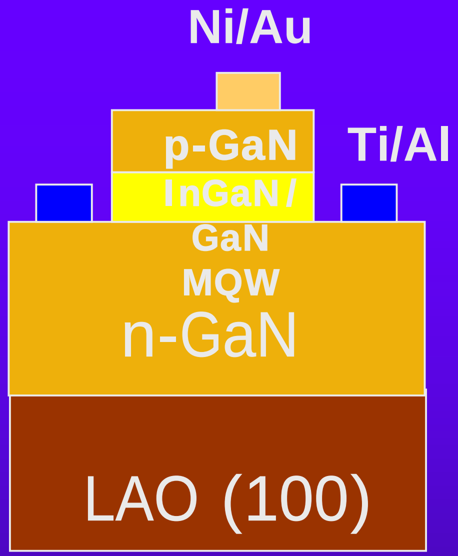
Period:5 ($In_{0.3}Ga_{0.7}N$/GaN) Quantum Wells

m-plane InGaN/ GaN MQWs LED

Schematic digram of InGaN/GaN MQWs LED



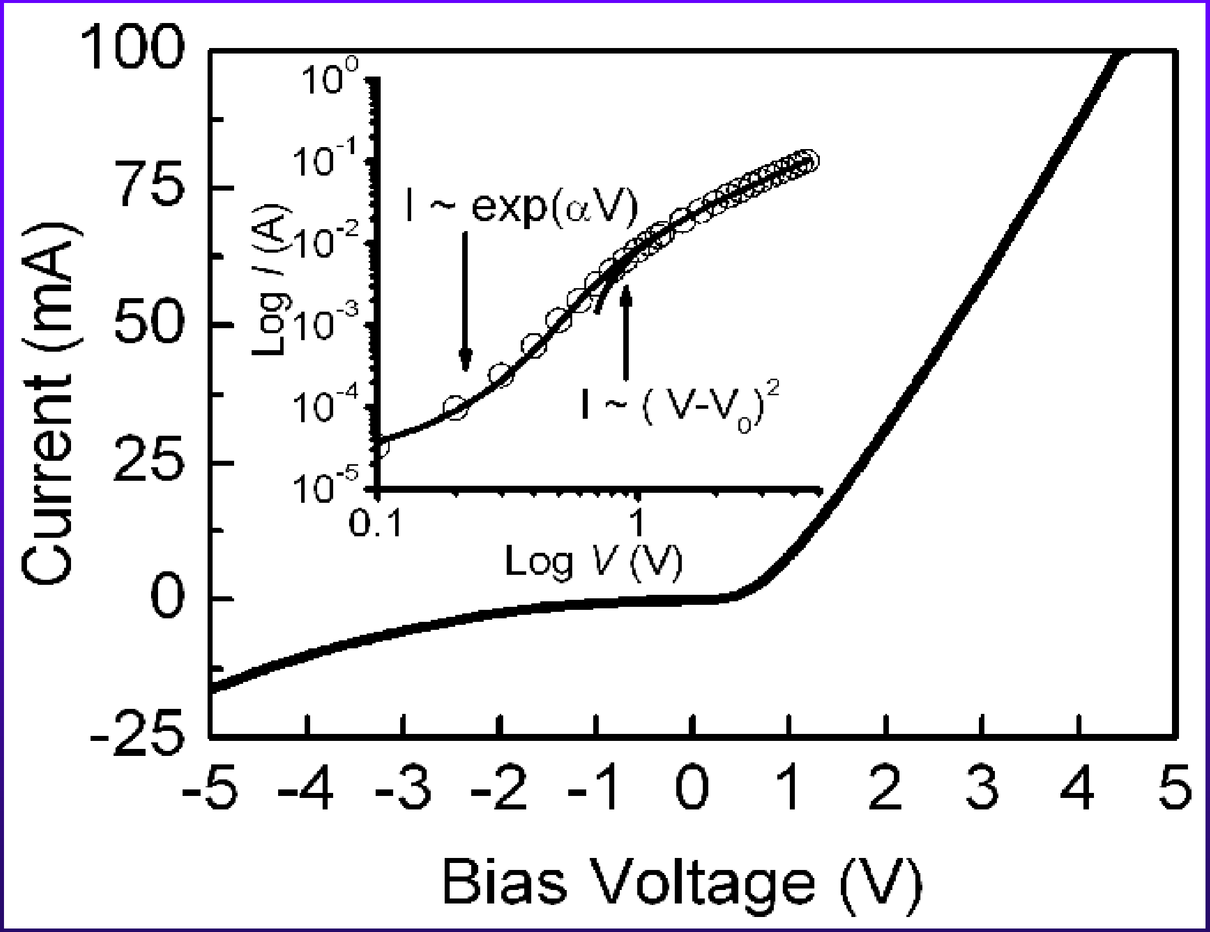


Chip size
80um×80um、
200um×200um
400um×400um、
800um×800um

N-GaN：1.2um
InGaN/GaN MQW P=5
P-GaN：200nm
N type contact, Ti/Al

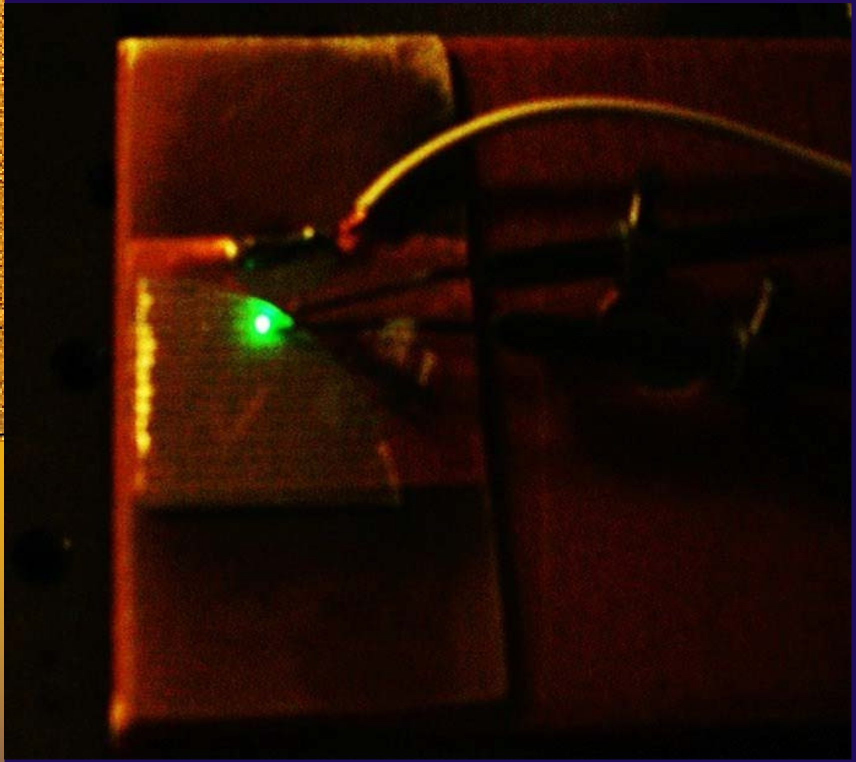
P type contact ,Ti/Au

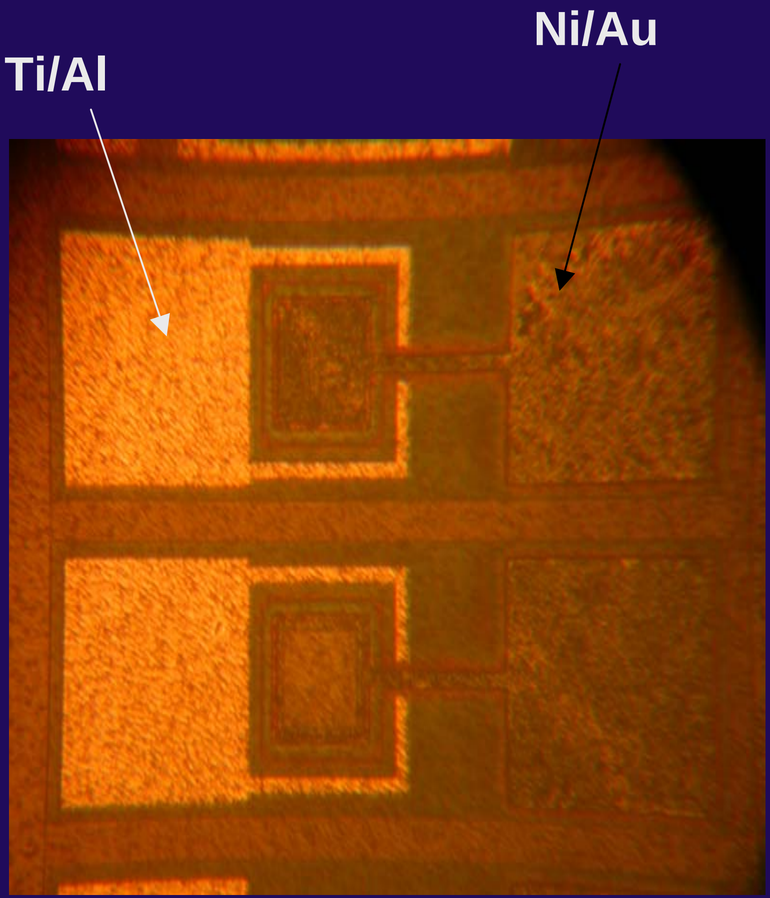
I-V curve of non-polar InGaN/GaN LED at RT



n=4.2 for small bias

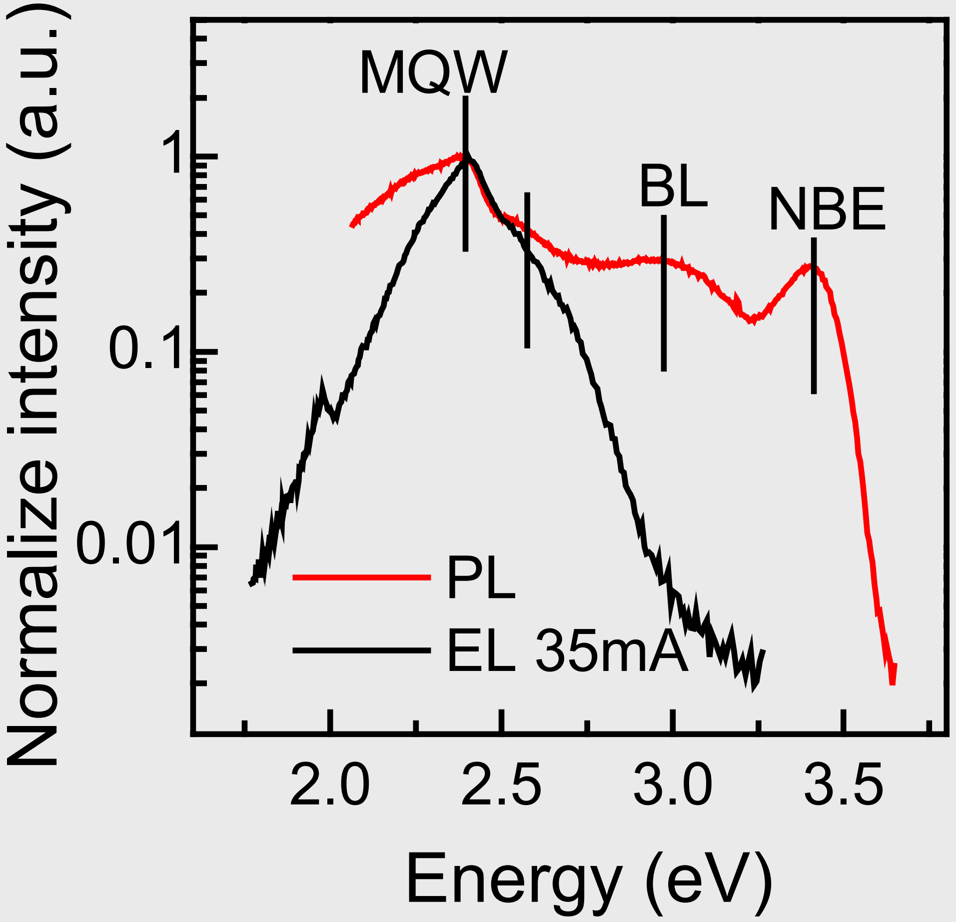
EL of M-plane InGaN/GaN MQWs LED



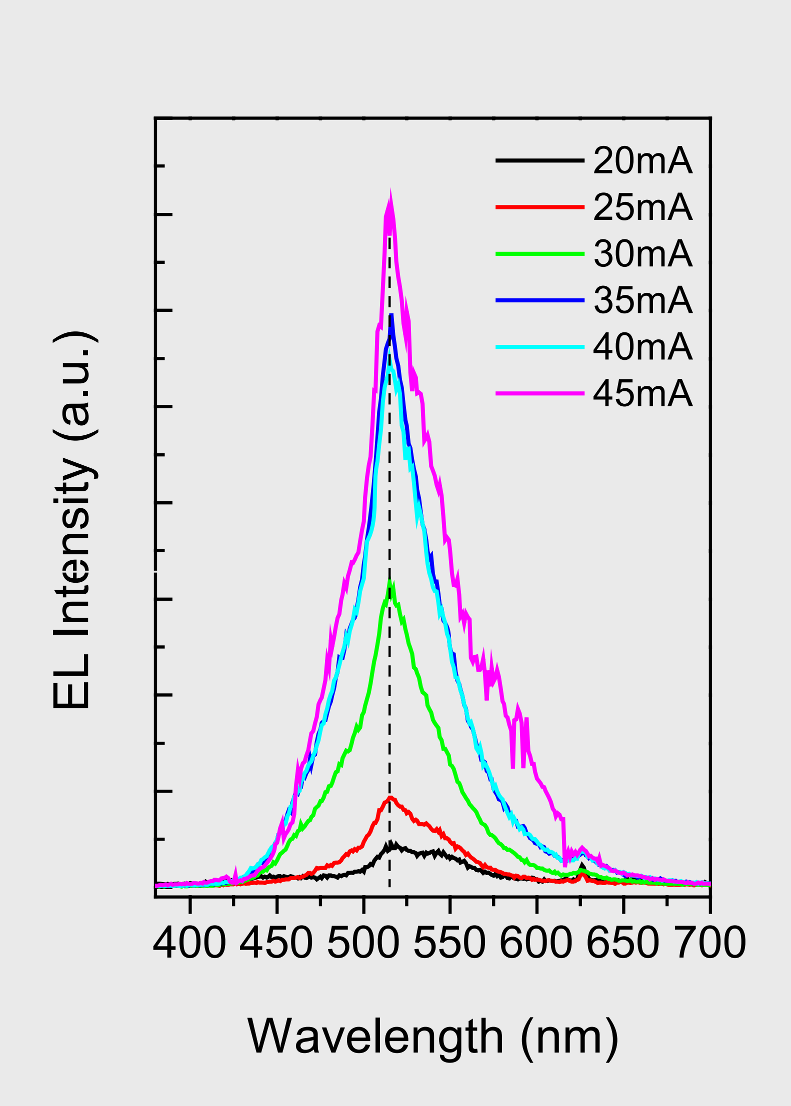


14:47:25

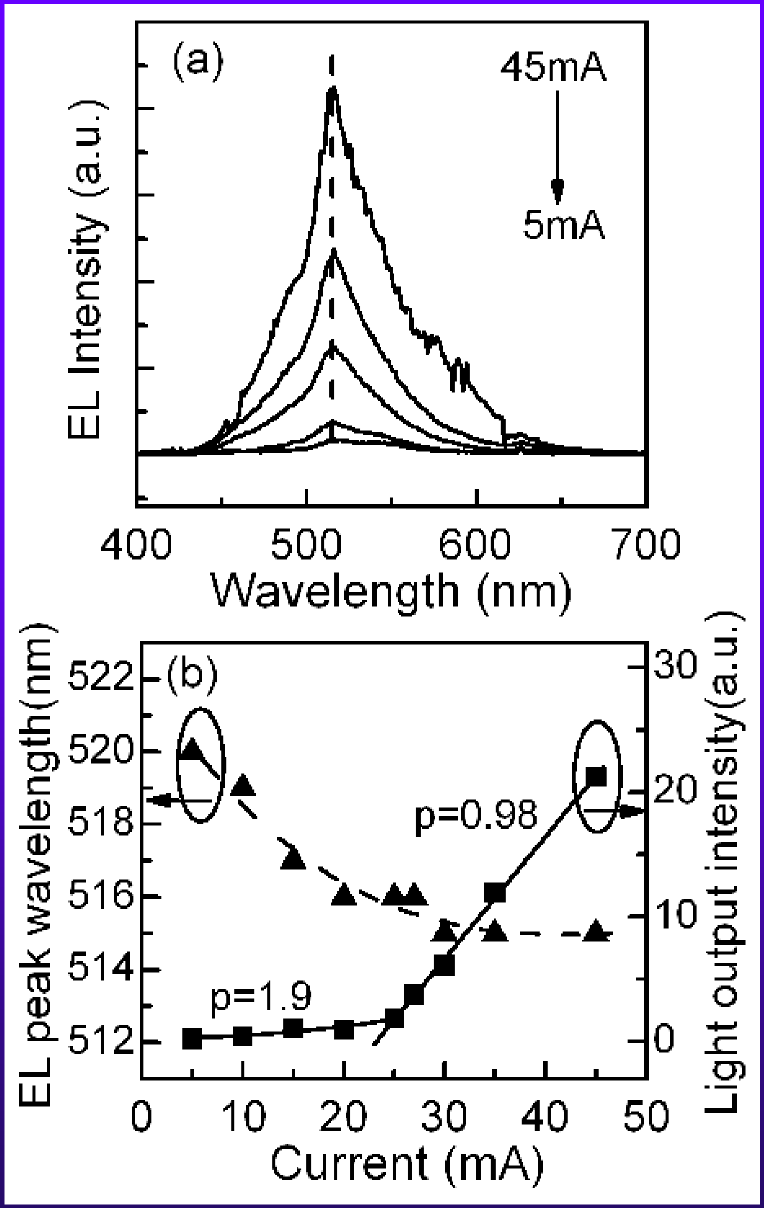
Comparison of EL spectrum to PL spectrum



EL spectra of m-plane InGaN/GaN LED



absence of polarization induced electric fields in the m-plane quantum wells



$$L = cI^{p}$$

P=0.98 for I>25mA

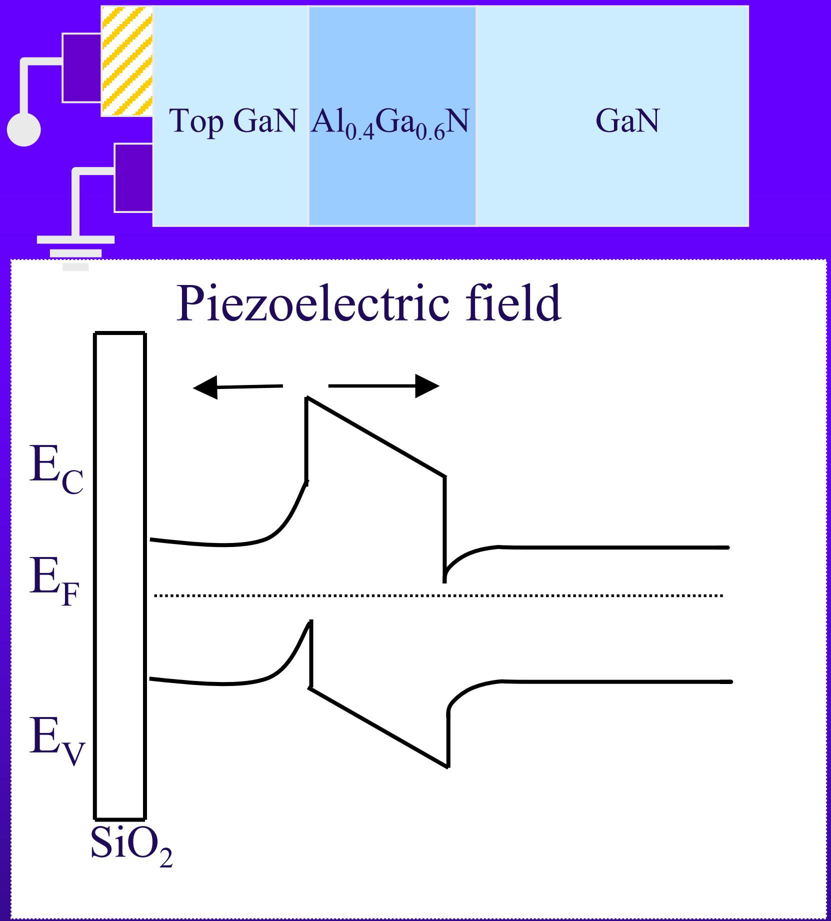
极化诱导能带工程及其在器件设计中的应用

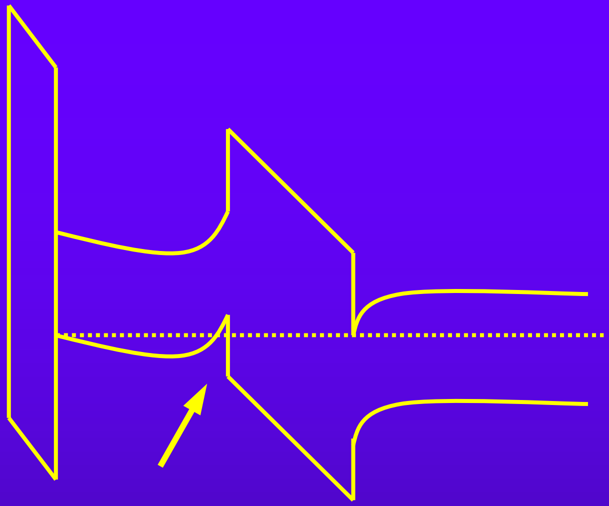
GaN/AlGaN/GaN p沟MIS-HFET

基于GaN/AlGaN/GaN双异质结中的压电极化效应对异质结能带的调制， GaN/AlGaN界面上产生空穴阱，在栅压的共同作用下，可以实现*p*型反型层,进而提出、发展了GaN/AlGaN/GaN双异质结P沟MIS-FET器件。

发表在：Mater.Res.Sci.Proc. Vol.622,T2.9-34922(2001)

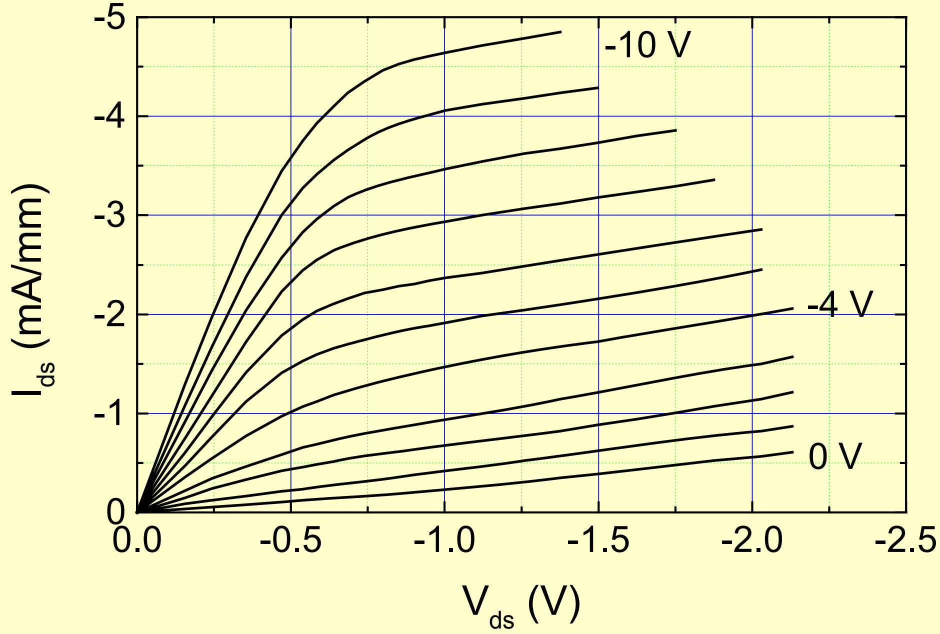
Appl.Phys.Lett. 79(21)3530(2001)





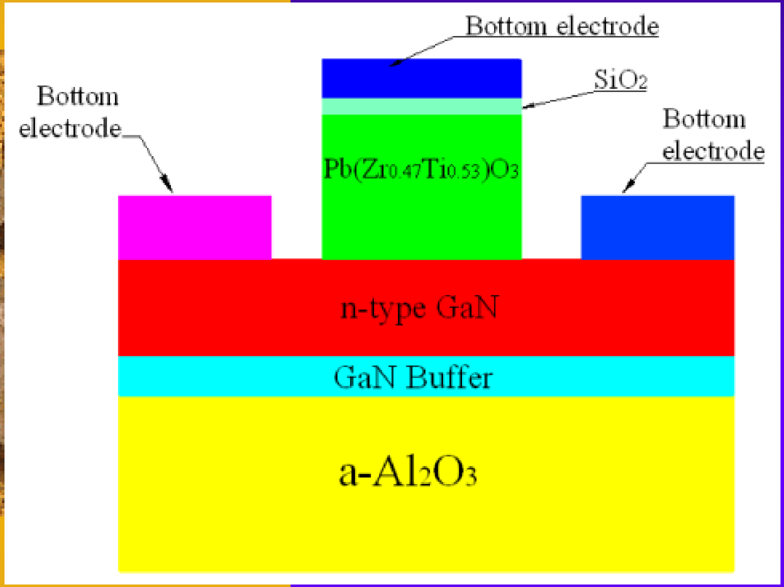
hole accumulation

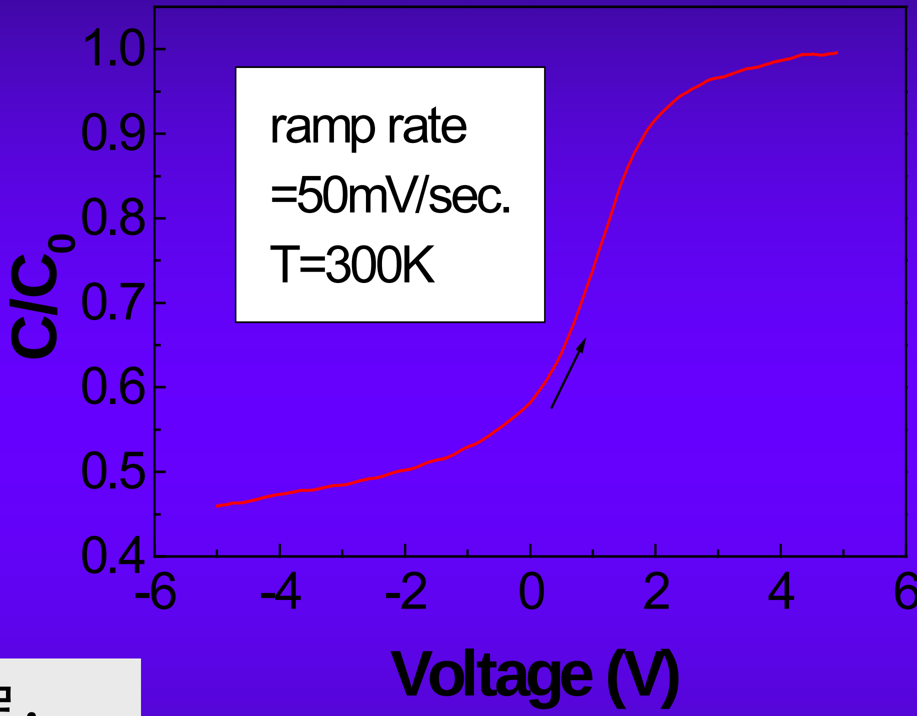
栅压作用下异质结构能带变化，左：零栅压；右：负栅压



2DHG MISFET output characteristics
bias：0~ -10 V，step：-1 V,

金属-铁电体-GaN 的 M-F-S 异质结构

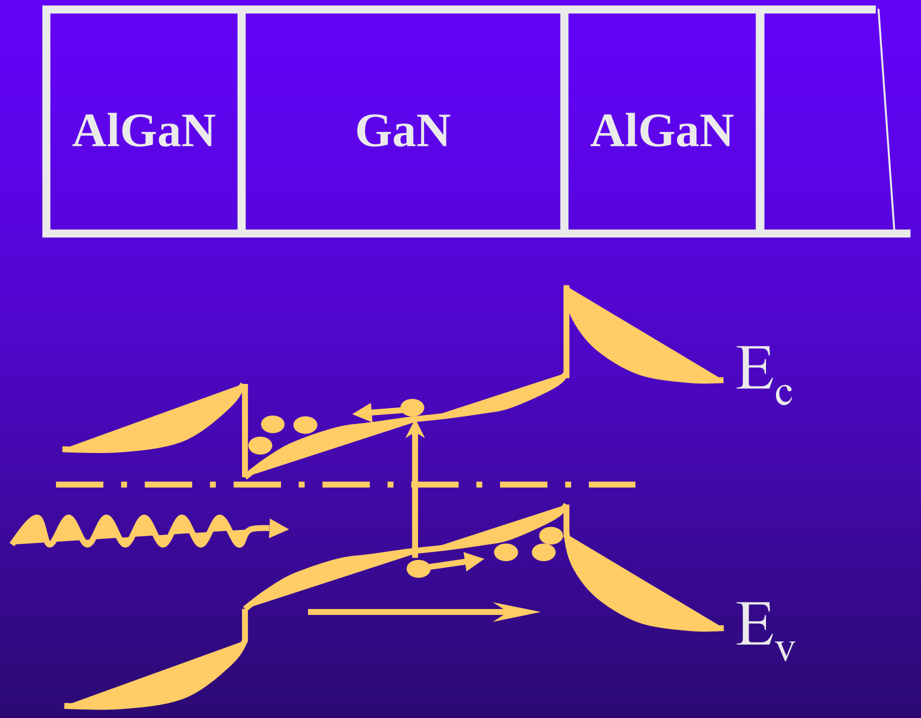


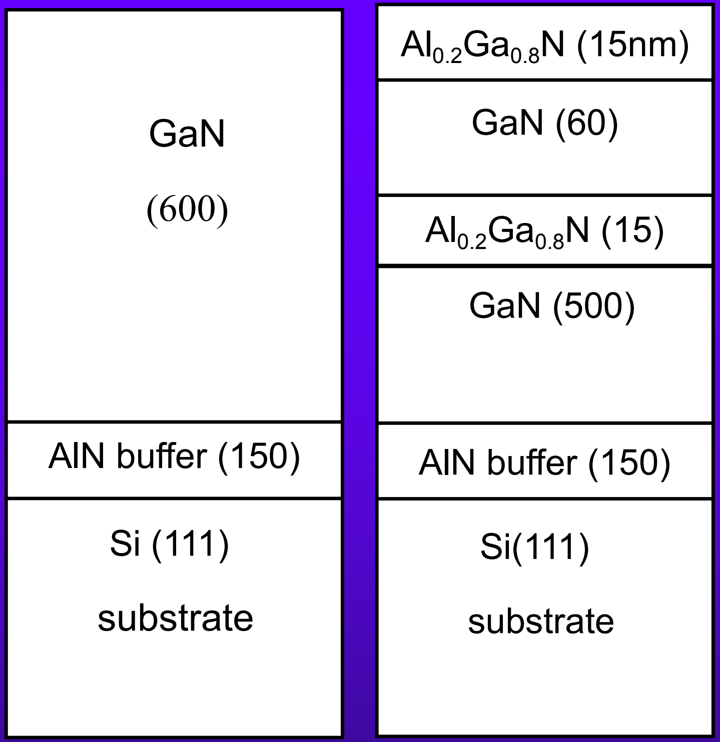


PZT：作为MIS结构的栅介质层；
极化场调制GaN表面能带弯曲

以SiO_2为栅的常规MIS结构，即使加80V反向偏压也难以实现反型，以PZT为栅的MFS结构，可在-5V下实现反型。

AlGaN/GaN/AlGaN紫外探测器





GaN

(600)

AlN buffer (150)

Si (111)

substrate

$Al_{0.2}Ga_{0.8}N$ (15nm)

GaN (60)

$Al_{0.2}Ga_{0.8}N$ (15)

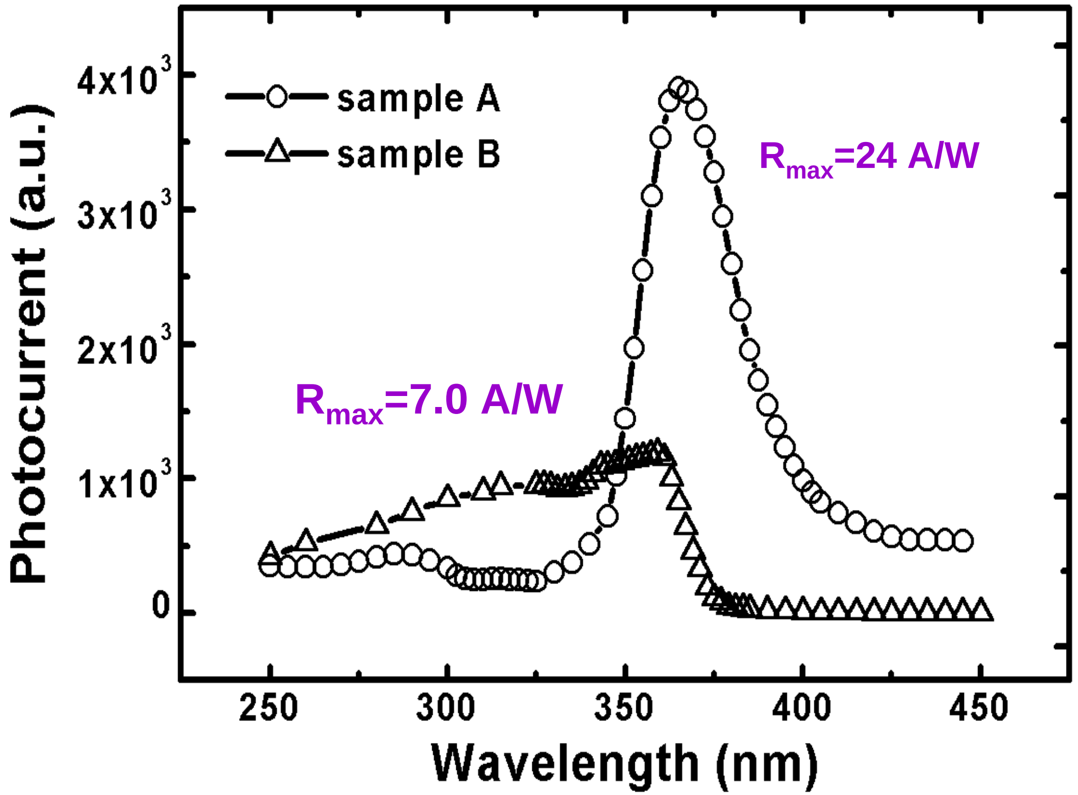
GaN (500)

AlN buffer (150)

Si(111)

substrate

(a) monolayer (b) multilayer



sample A
sample B
R_{max}=24 A/W
R_{max}=7.0 A/W
Photocurrent (a.u.)
0
1×10^3
2×10^3
3×10^3
4×10^3
250
300
350
400
450
Wavelength (nm)

$Al_{0.22}Ga_{0.78}N/GaN/Al_{0.22}Ga_{0.78}N$双异质结探测器

AlGaN/GaN界面

自发极化
压电极化

形成
2DEG

电子-空穴对
空间分离
减少复合

提高
载流子
迁移率

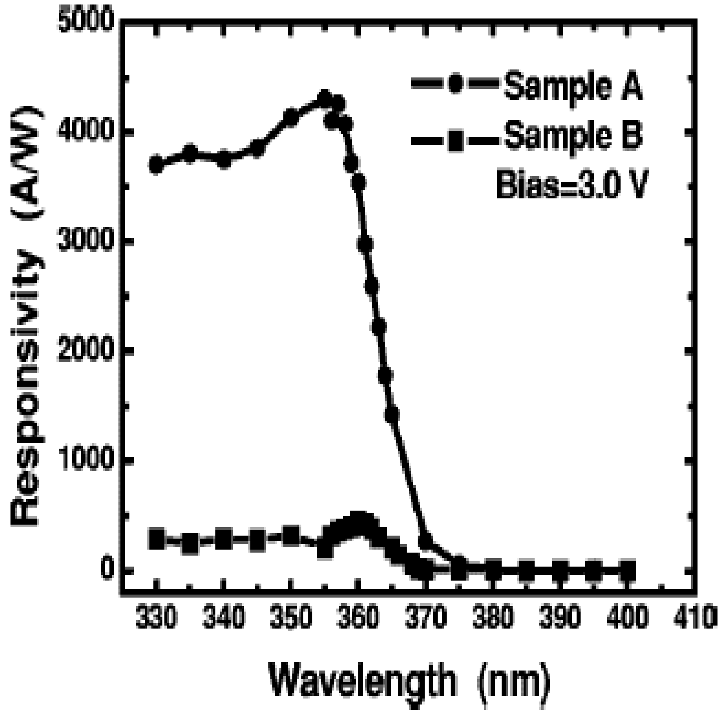


FIG. 3. Spectral response of the $Al_{0.22}Ga_{0.78}N/GaN/Al_{0.22}Ga_{0.78}N$ heterostructure photodetector (sample A) and the GaN monolayer structure photodetector (sample B) under 3.0 V bias.

AlGaN/GaN/AlGaN
AlN/GaN
异质结构探测器:
峰值响应度
比GaN探测器提高约
10、12倍(3V偏压)
最高达4300A/W

小结

- 研究了极化对III族氮化物半导体能带的调控，重点研究了
  - $LiAlO_2$（100）衬底上非极性m面GaN薄膜和InGaN/GaN量子阱的MOCVD外延技术，生长出高质量的m面GaN薄膜和InGaN/GaN量子阱
  - 非极性m面GaN薄膜的结构与能带性质，尤其是m面特殊对称性破缺和应变结构引人的各向异性和跃迁选择定则
  - 非极性面LED，证明生长方向极性的解除

- 通过对极化的设计，提出并实现了几种新的器件结构
  - 空穴沟道场效应晶体管
  - 铁电极化栅**MFS**结构
  - 高响应度紫外探测器

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