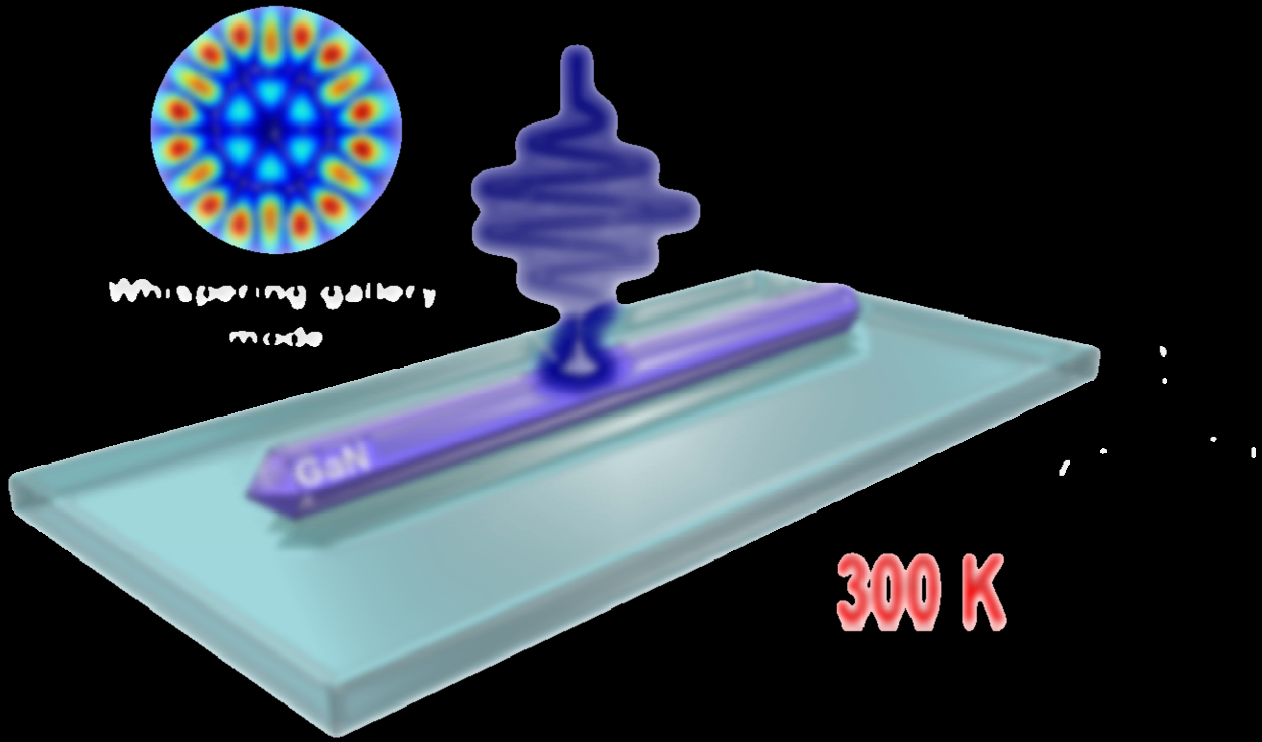
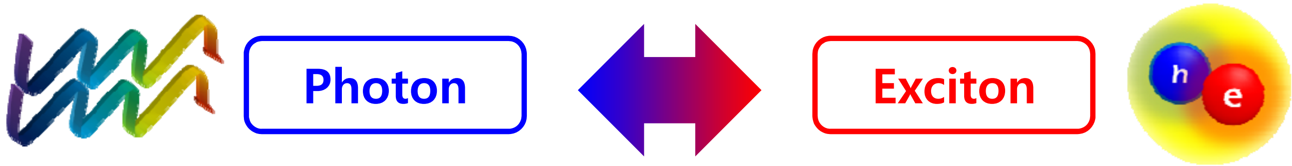
Whispering gallery polaritons in group III-nitride semiconductor wire



Hyun Gyu Song, *Su Hyun Gong and* ***Yong-Hoon Cho***
Department of Physics
Korea Advanced Institute of Science and Technology (KAIST)
Daejeon 305-701, Republic of Korea
Email: yhc@kaist.ac.kr

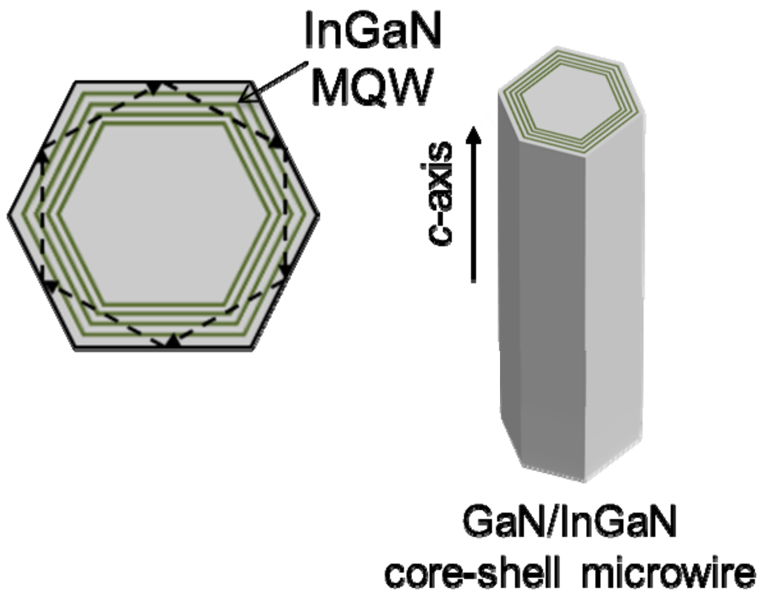
Contents

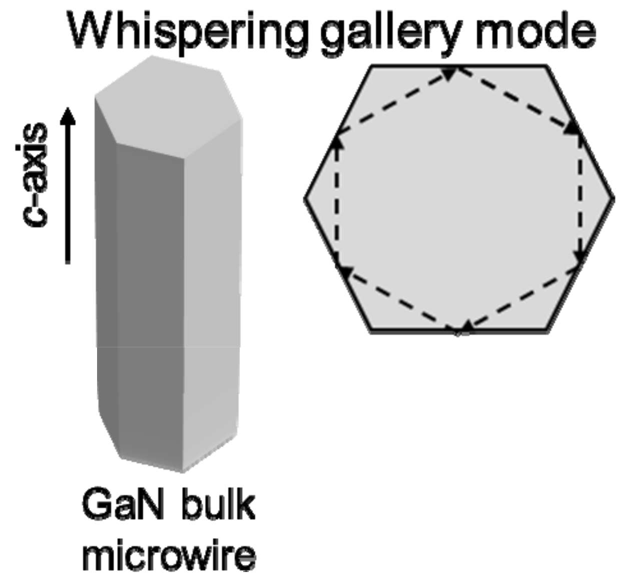


1. Introduction

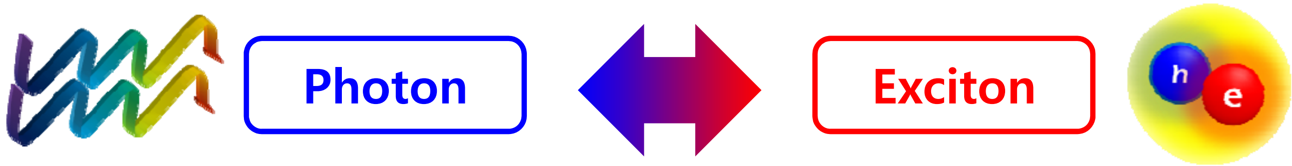
2. Giant Rabi-splitting of GaN/InGaN core-shell microwire

3. Summary





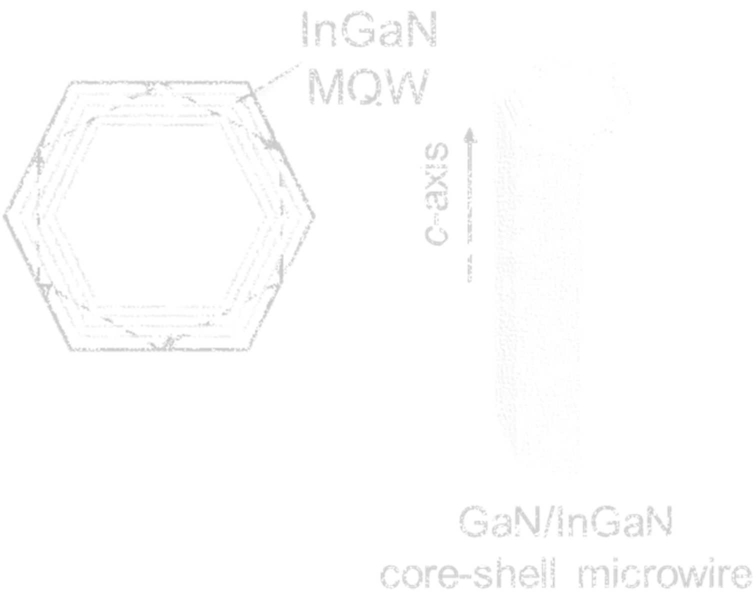
Contents

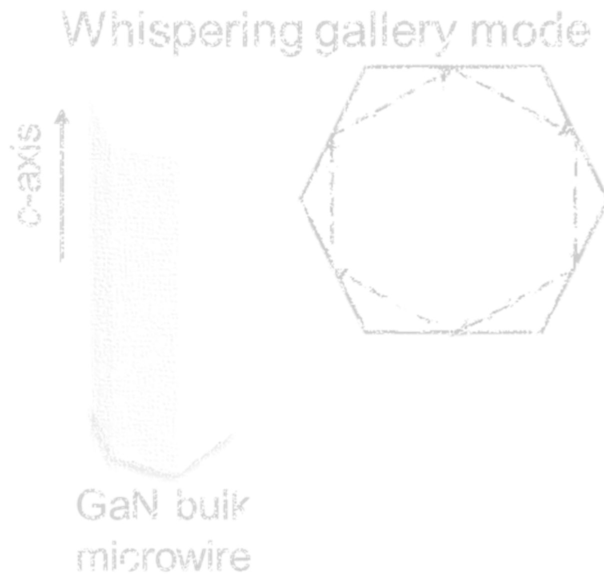


1. Introduction

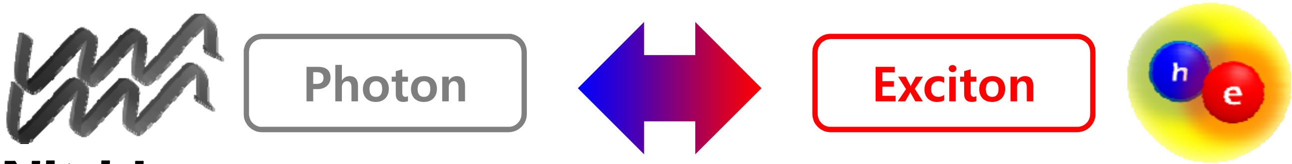
2. Giant Rabi-splitting of GaN/InGaN core-shell microwire

3. Ballistic propagation of polariton condensate for bulk GaN microwire

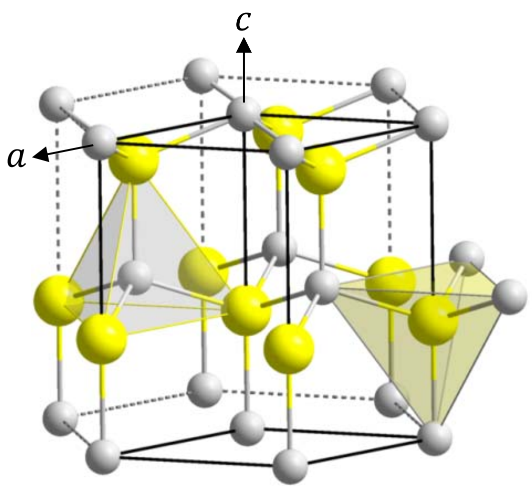




1. Introduction: Exciton in GaN

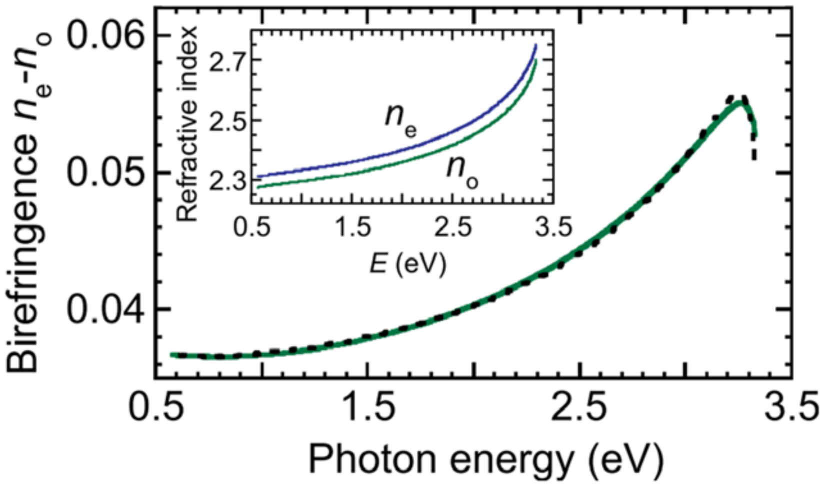


Gallium Nitride

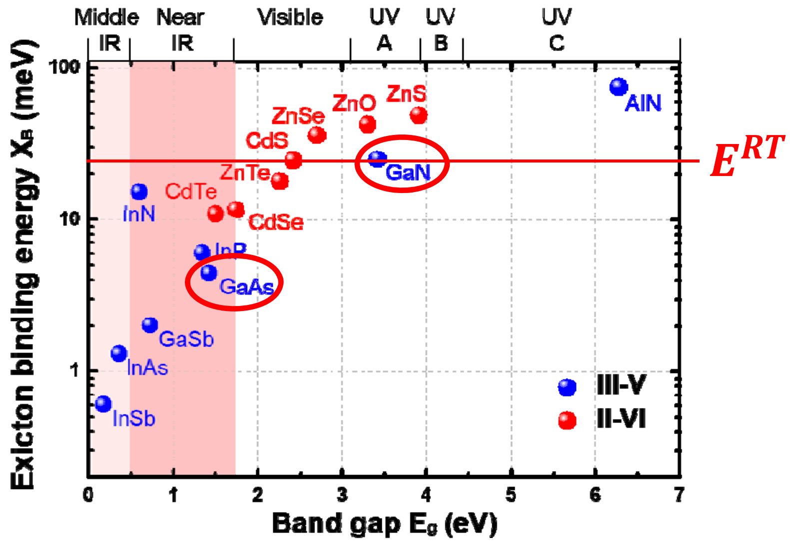


- Binary III/V direct band gap semiconductor
- Wurtzite crystal structure (a=3.18 Å, c=5.18 Å)
- **Uniaxial birefringence material for c-axis**
- **Tunability of wavelength with combining In, Al**
- Wide band gap: 3.4 eV (300 K, direct)
- **Large exciton binding energy : 26 meV (Bulk)**
- **Small Bohr radius : 3.4 nm**
- **High oscillation strength**

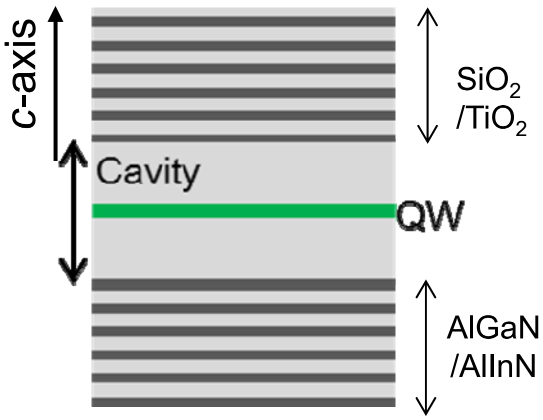
	II	III	IV	V	VI		
							He
		B	C	N	O	F	Ne
		Al	Si	P	S	Cl	Ar
Cu	Zn	Ga	Ge	As	Se	Br	Kr
Ag	Cd	In	Sn	Sb	Te	I	Xe
Au	Hg	Tl	Pb	Bi	Po	At	Rn



APL 107. 092104 (2015)

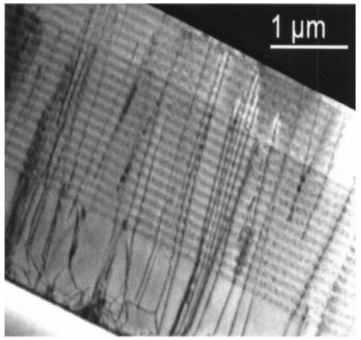


1. Introduction: Disadvantages of III-nitride planer cavity

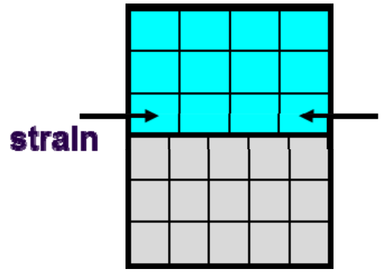


III-nitride cavity (planar cavity)

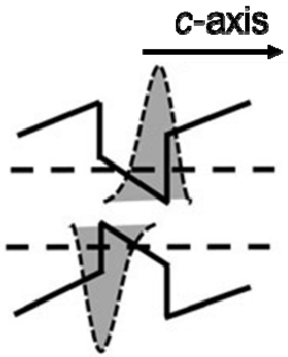
1) Low quality of Bragg mirror



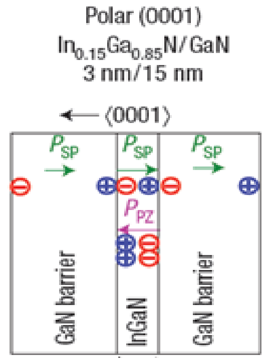
- Lattice misfit
- Thermal expansion coefficient misfit



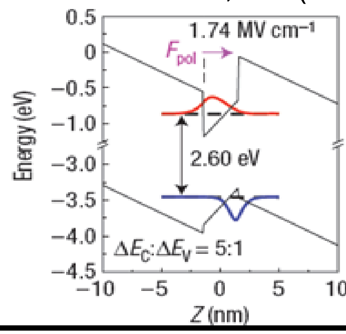
2) Large built-in field



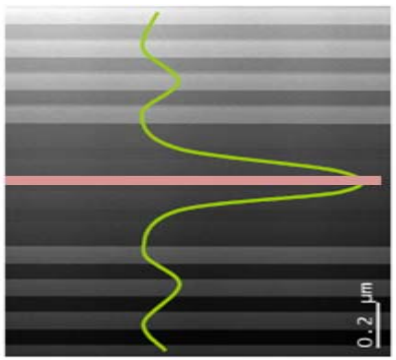
- Piezoelectric polarization : P_{PZ}



Nature Mater. 5, 810 (2006)

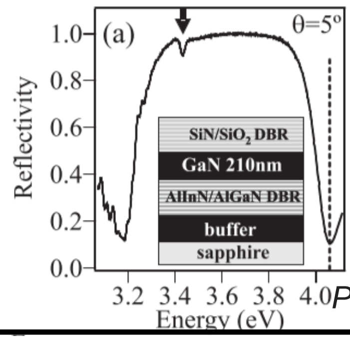


3) Small spatial overlap



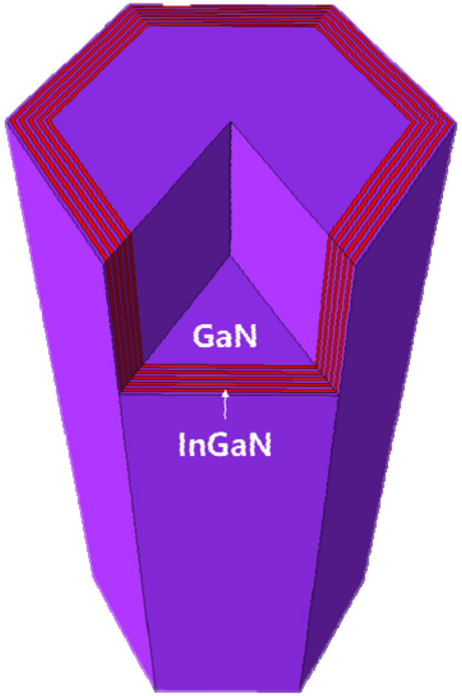
- 67 period of AlGaN/GaN QWs
- 210 nm GaN

PRB 80, 233301 (2009)



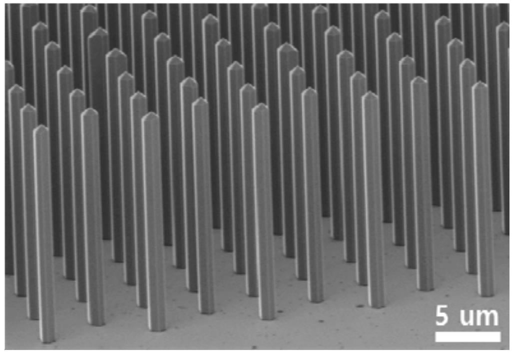
PRL 98, 126405 (2007)

1. Introduction: Advantage of wire structure for III-nitride system



GaN/InGaN
core-shell microwire

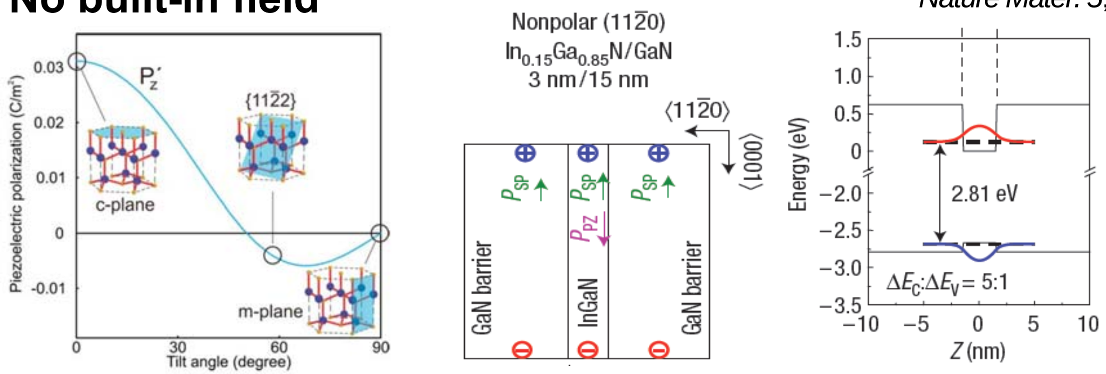
1) No Bragg mirror



- As-grown
- No complex fabrication
- Spontaneously formed hexagonal shape

2) No built-in field

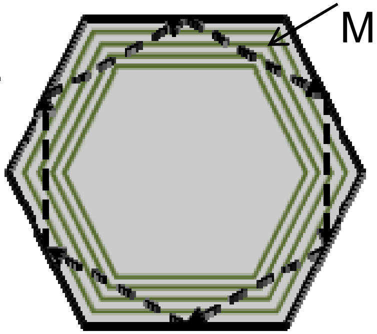
Nature Mater. 5, 810 (2006)



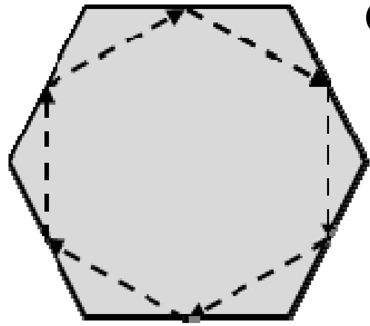
3) Large spatial overlap

InGaN
MQWs

Core-
shell



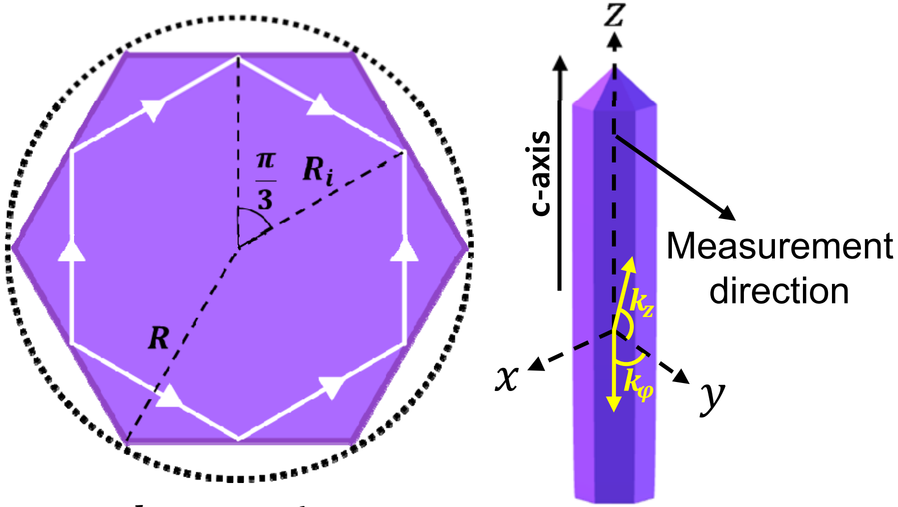
Bulk
GaN



1. Introduction : Whispering gallery mode in hexagonal wire

Photon ⟷ **Exciton**

✓ Whispering gallery (plane wave model)



$$E_{cav}(0) = \frac{hc}{n6R_i}\left[N + \frac{6}{\pi}\arctan\left(\beta\sqrt{3n^2-4}\right)\right]$$

PRL 93. 10 (2004)

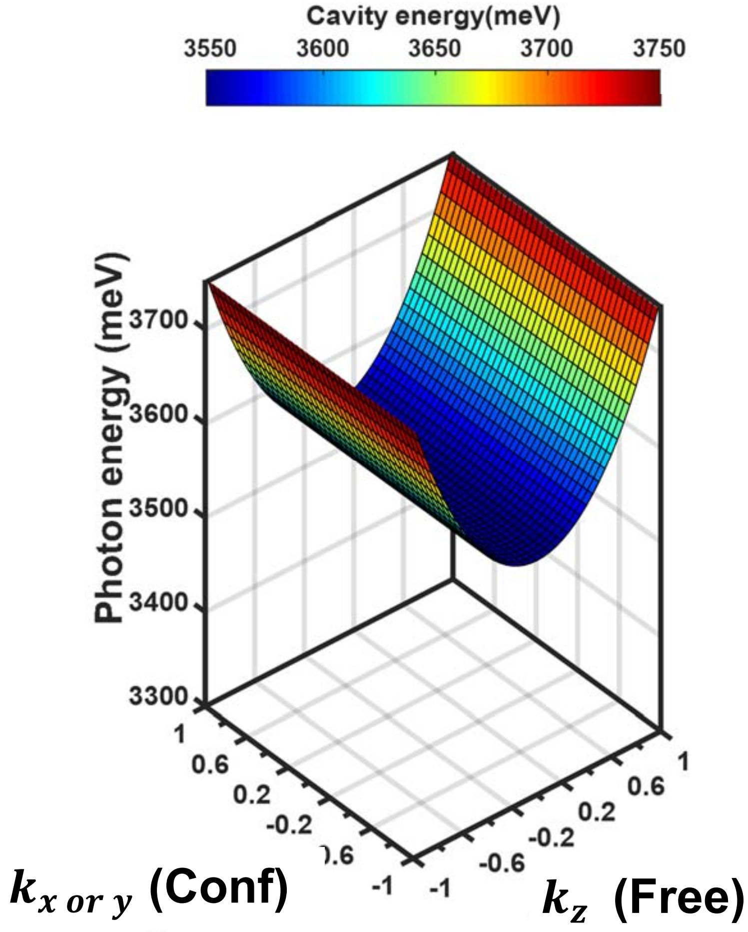
$$e^{\underbrace{i(kr-\varphi)}}$$

$kr - \varphi = 2\pi N$: Resonance

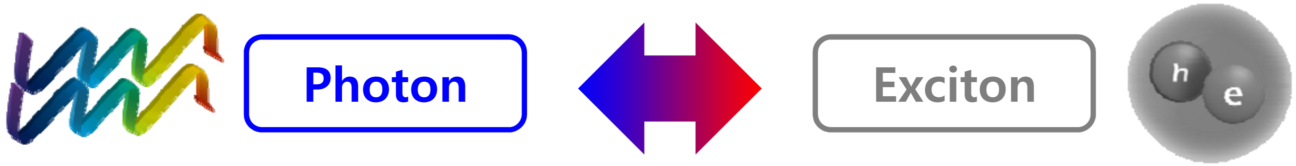
$$6 \times \frac{2\pi n}{\lambda_0} \times R_i = 2\pi N + 6 \times 2\arctan(\beta\sqrt{3n^2-4})$$

$$\underbrace{6}_{\text{Hexagonal}} \times [\underbrace{k \times R_i}_{\text{Optical path length}} - \underbrace{2\arctan(\beta\sqrt{3n^2-4})}_{\text{Negative phase shift}}] = 2\pi N$$

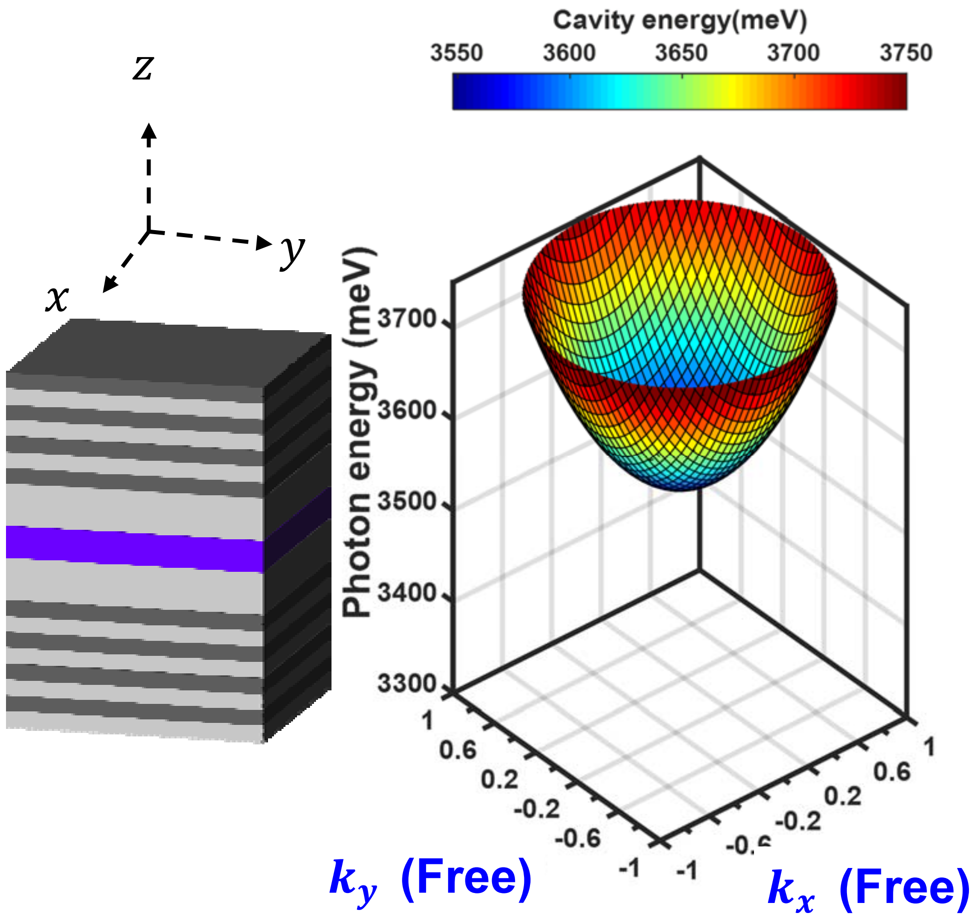
✓ E-k dispersion relation



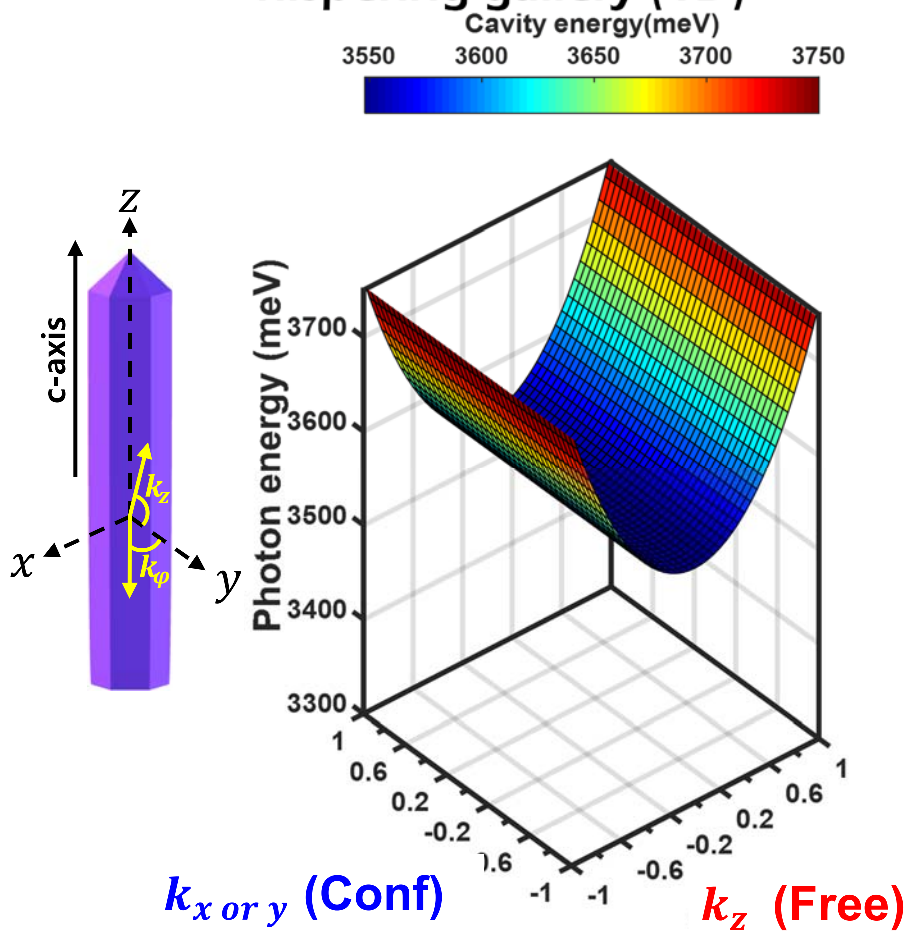
1. Introduction: 1 dimensional degree of freedom



✓ Planer cavity (2D)



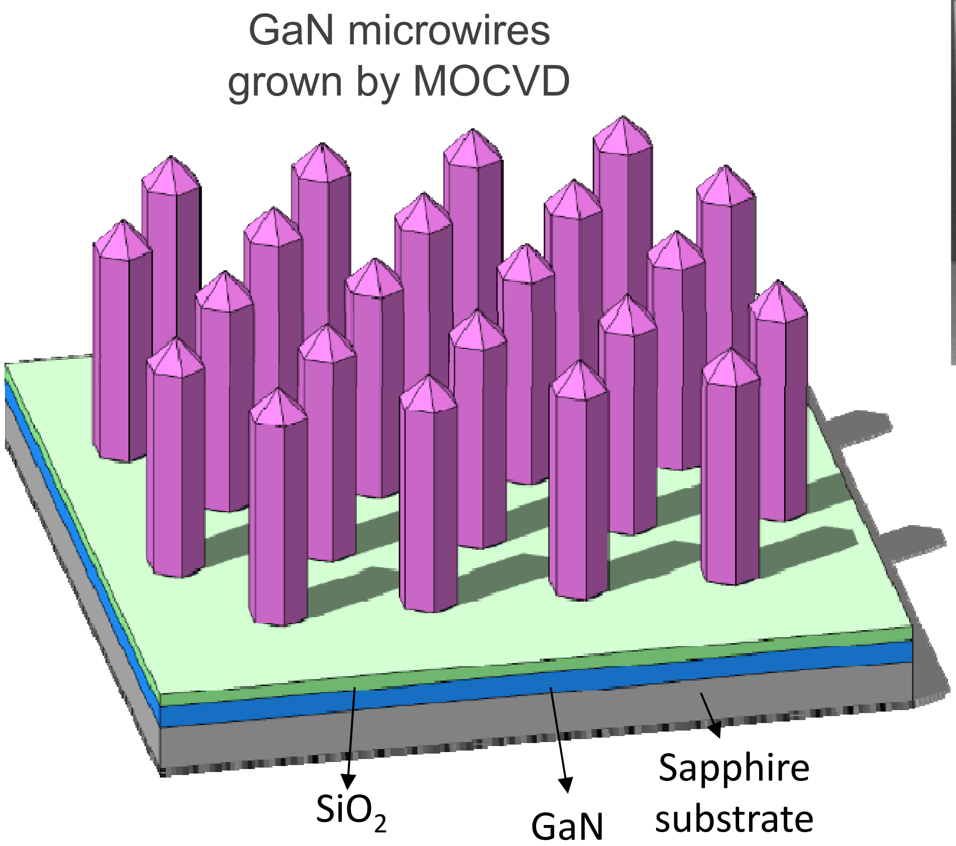
✓ Whispering gallery (1D)



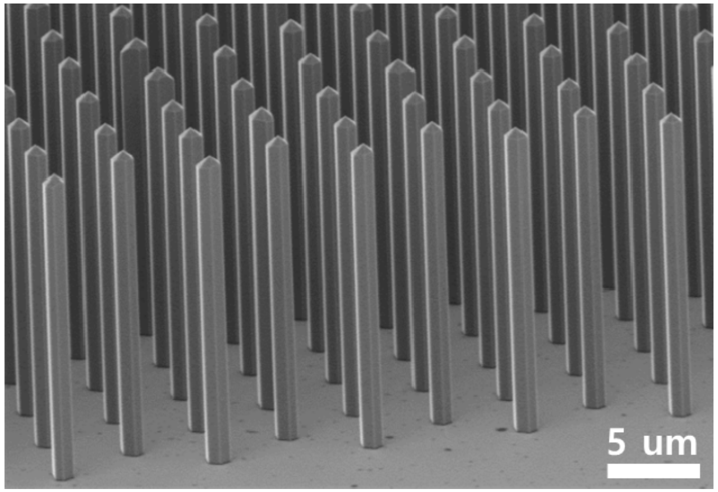
k_z (Confined) : Horizontal dispersion
$k_{x,y}$ (Free) : Parabolic dispersion

k_z (Free) : Parabolic dispersion
$k_{x,y}$ (Confined) : Horizontal dispersion

1. Introduction: Microwire grown by MOCVD

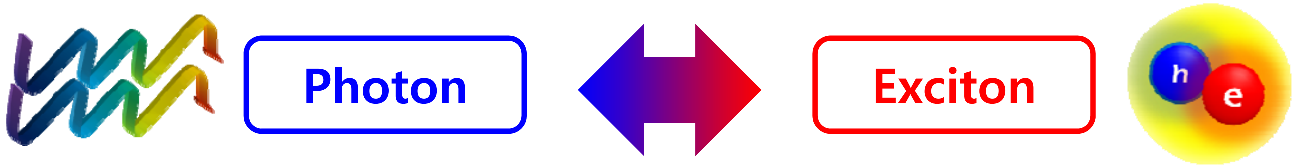


Ensemble SEM image



1. **No Bragg mirror**
2. **No built-in field (no QCSE)**
3. **Larger spatial overlap**

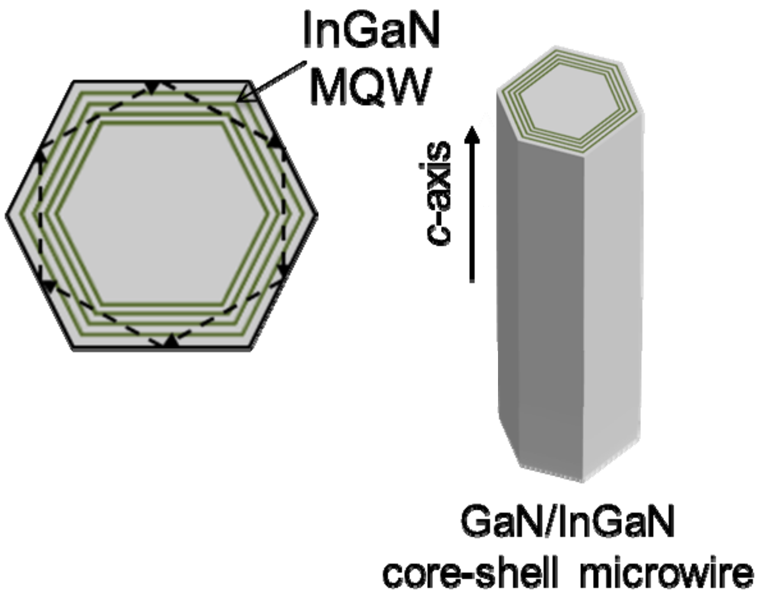
Contents

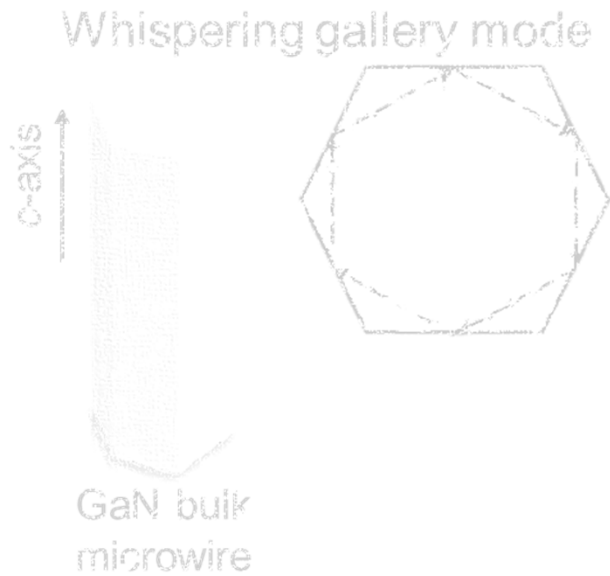


1. Introduction

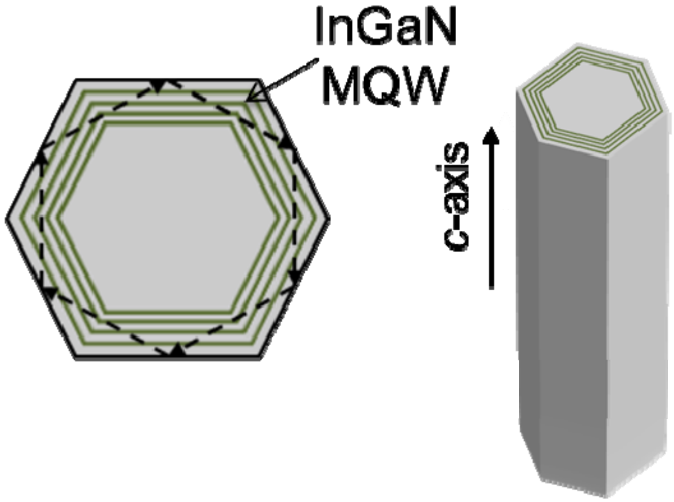
2. Giant Rabi-splitting of GaN/InGaN core-shell microwire

3. Ballistic propagation of polariton condensate for bulk GaN microwire

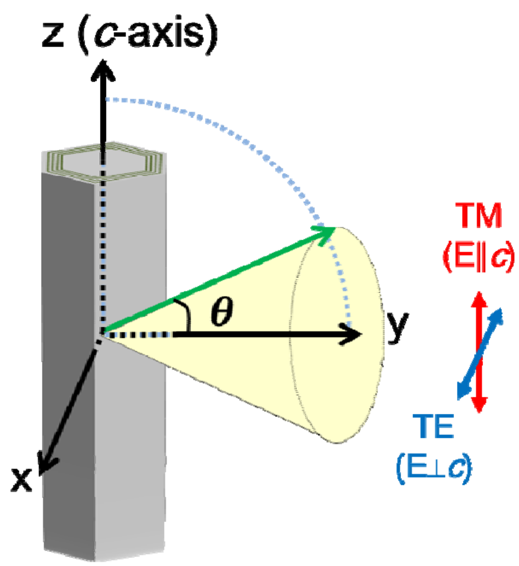




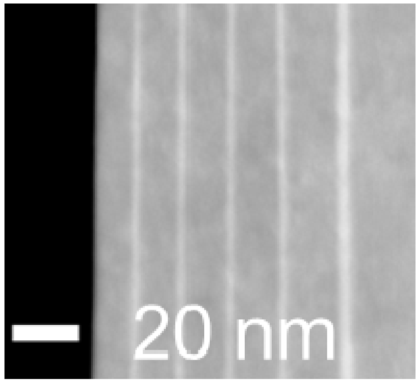
2. Giant Rabi splitting: sample information



GaN/InGaN
core-shell microwire

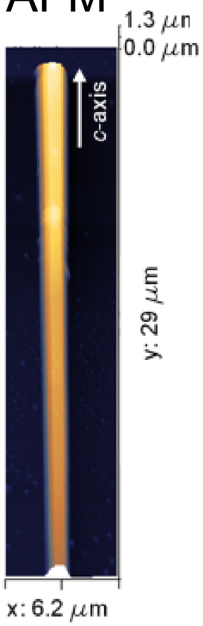


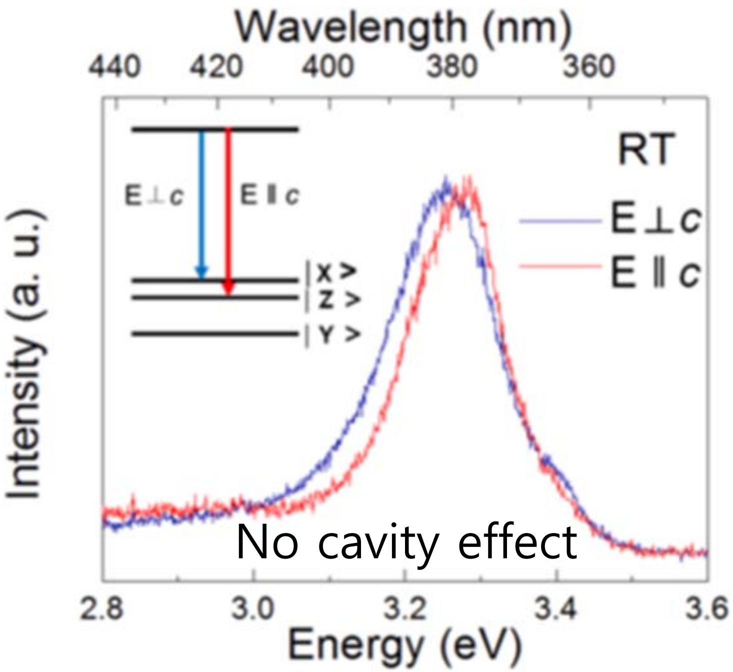
TEM image



Five period InGaN/GaN multi-QWs

AFM





No cavity effect

2. Giant Rabi splitting: Spatial overlap

General equations

$$\hbar\Omega = 2\hbar\sqrt{2\widetilde{\omega}_{LT}\omega_0 \cdot \frac{\int_{active} \varepsilon(r)|E(r)|^2 dr^3}{\int_{cavity} \varepsilon(r)|E(r)|^2 dr^3}}$$

Parameters determining coupling strength

$$\Gamma = \frac{\int_{active} \varepsilon(r)|E(r)|^2 dr^3}{\int_{cavity} \varepsilon(r)|E(r)|^2 dr^3} \quad \text{and } \widetilde{\omega}_{LT}$$

$\widetilde{\omega}_{LT}$: Longitudinal-transverse splitting of QWs

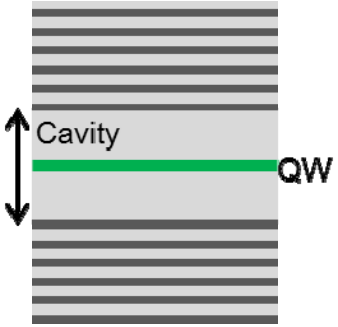
$$\hbar\omega_{LT} = \frac{2\pi}{\varepsilon_\infty}\frac{\hbar e^2}{m_0\omega_0}\frac{f}{V}$$

Longitudinal wave : (Dipole+E-field) + (Lattice)

Transverse wave : (Lattice)

ω_0: Resonance of both exciton and photon

1. QWs in planar cavity



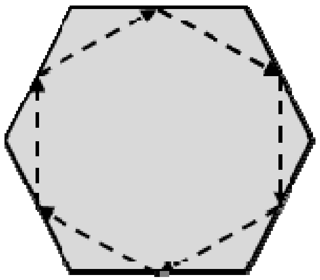
Rabi splitting

$$\hbar\Omega = 2\hbar g = 2\hbar\sqrt{\widetilde{\omega}_{LT}\omega_0 \cdot \frac{L_{active}}{L_{eff}}}$$

L_{active} : Total QW thickness

L_{eff} : Effective cavity length

2. Whispering gallery mode for bulk wire



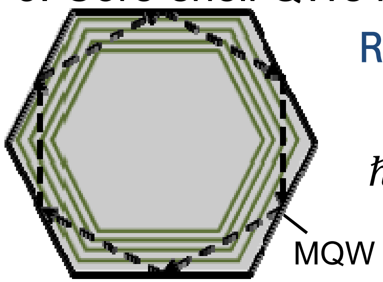
Rabi splitting

$$\hbar\Omega = 2\hbar g = 2\hbar\sqrt{\widetilde{\omega}_{LT}\omega_0 \cdot \frac{S_{active}}{S_{eff}}}$$

S_{active} : Total GaN area

S_{eff} : Effective cavity area

3. Core-shell QWs in microwire



Rabi splitting

$$\hbar\Omega = 2\hbar g = 2\hbar\sqrt{\widetilde{\omega}_{LT}\omega_0 \cdot \frac{S_{active}}{S_{eff}}}$$

S_{active} : Total QW area

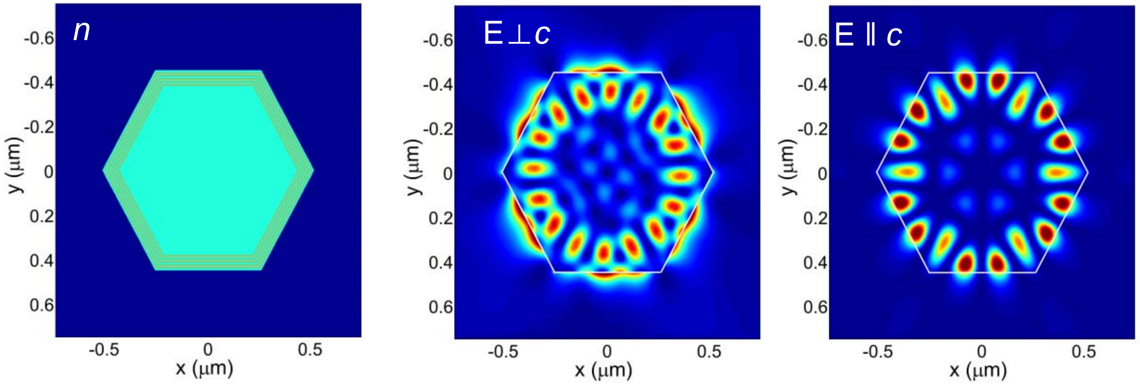
S_{eff} : Effective cavity area

2. Giant Rabi splitting: FDTD simulation

- Spatial overlap (FDTD modeling)

Parameters determining coupling strength

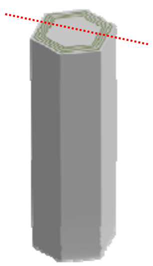
$$\Gamma = \frac{\int_{active} \varepsilon(r)|E(r)|^2 dr^3}{\int_{cavity} \varepsilon(r)|E(r)|^2 dr^3} \quad \text{and } \tilde{\omega}_{LT}$$

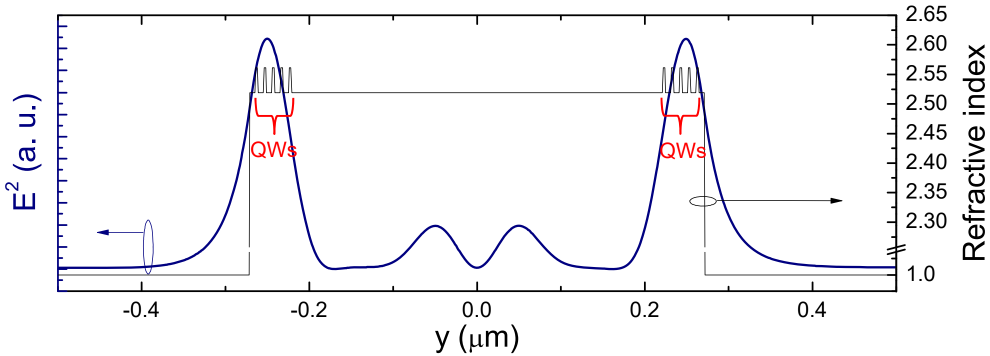


Q (E⊥*c*, TE)= 120

Q (E ∥ *c*, TM)= 280

Micro wire





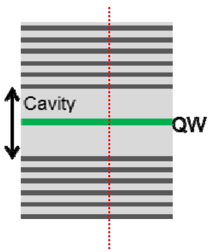
Spatial overlap

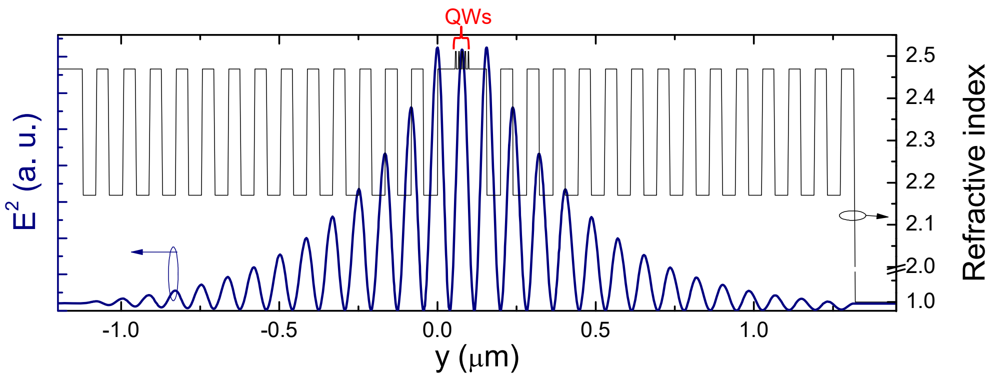
$$\Gamma = \frac{\int_{active} \varepsilon(r)|E(r)|^2 dr^3}{\int_{cavity} \varepsilon(r)|E(r)|^2 dr^3}$$

Γ_{WGM}^{QW} (E⊥*c*, TE)= 9 %

Γ_{WGM}^{QW} (E ∥ *c*, TM)= 16 %

Planar cavity





Γ_{FP} (E ∥ *c*, TE)= 4 %

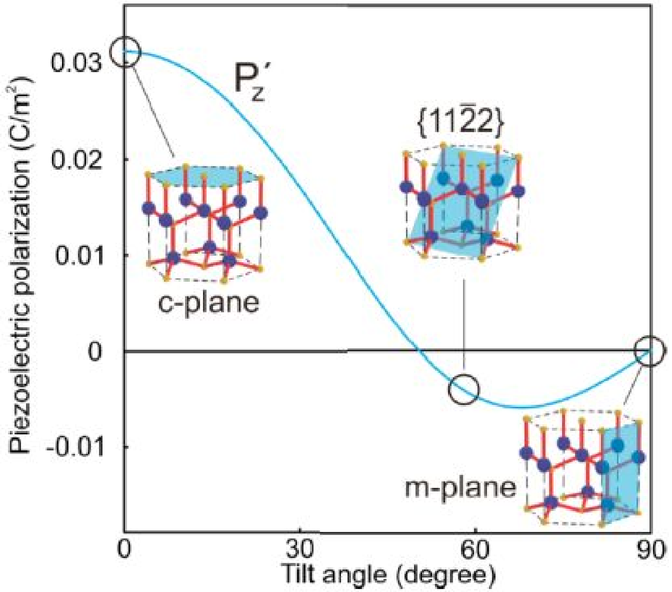
➢ 2~4 times higher spatial overlap than FP

2. Giant Rabi splitting: Non-polar quantum well

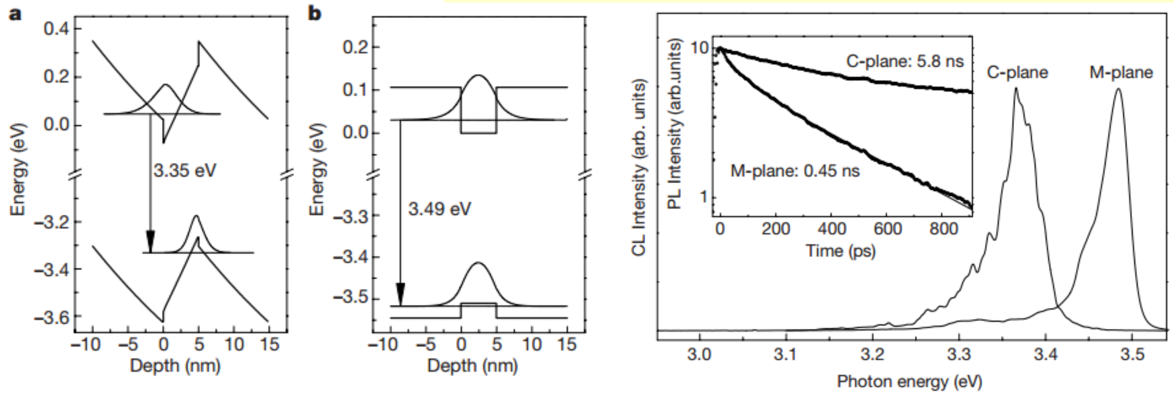
- Non-polar quantum well

Parameters determining coupling strength

$$\Gamma = \frac{\int_{active}^{-} \varepsilon(r)|E(r)|^2 dr^3}{\int_{cavity}^{-} \varepsilon(r)|E(r)|^2 dr^3} \quad \text{and } \tilde{\omega}_{LT}$$



phys. stat. sol. (RRL) 1, A45 (2007)



Nature 406, 865 (2000)

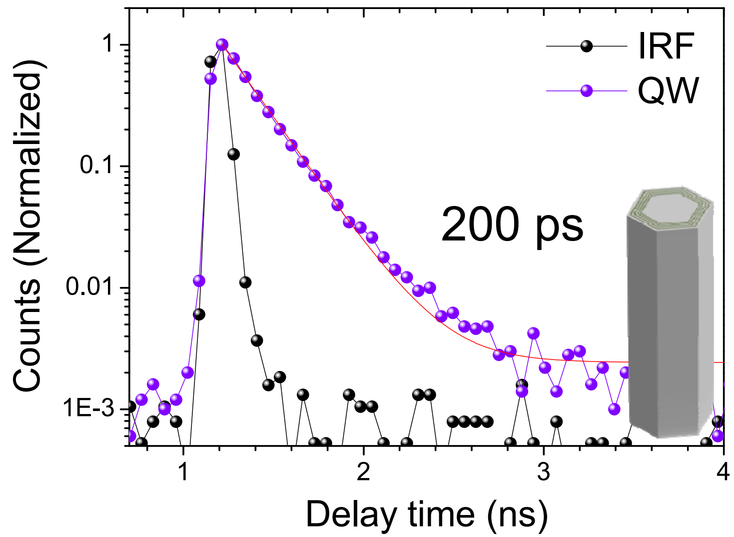
Non-polar nitride quantum well (a-, m- plane)

- ~10 times higher radiative decay rate

Intrinsic radiative decay rate is related to oscillator strength per unit area ($\omega_{LT} \times L_{qw}$) L_{qw}: Thickness of QW

$$\Gamma_{rad} \propto \frac{f}{S} \approx \omega_{LT} \times L_{qw}$$

- One order higher LT-splitting (ω_{LT}) than planer



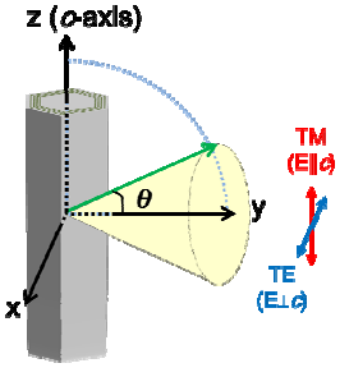
2. Giant Rabi splitting: Experimental Observation of Exciton Polariton

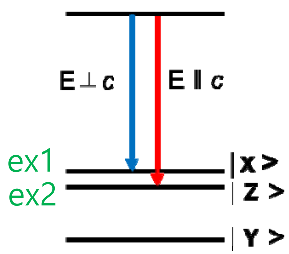
Dispersion of whispering gallery modes

$$\mathrm{E}_{ph}(\theta) = E_0\left(1 - \frac{\sin^2\theta}{\varepsilon(E)}\right)^{-\frac{1}{2}}$$

$$E_0 = \frac{hc}{6nR}\left[N + \frac{6}{\pi}\arctan\left(\beta\sqrt{3n^2-4}\right)\right]$$

R: *radius of nanowire*
N : *mode number*
β: $\frac{1}{n}$ for TM
$\quad n$ for TE

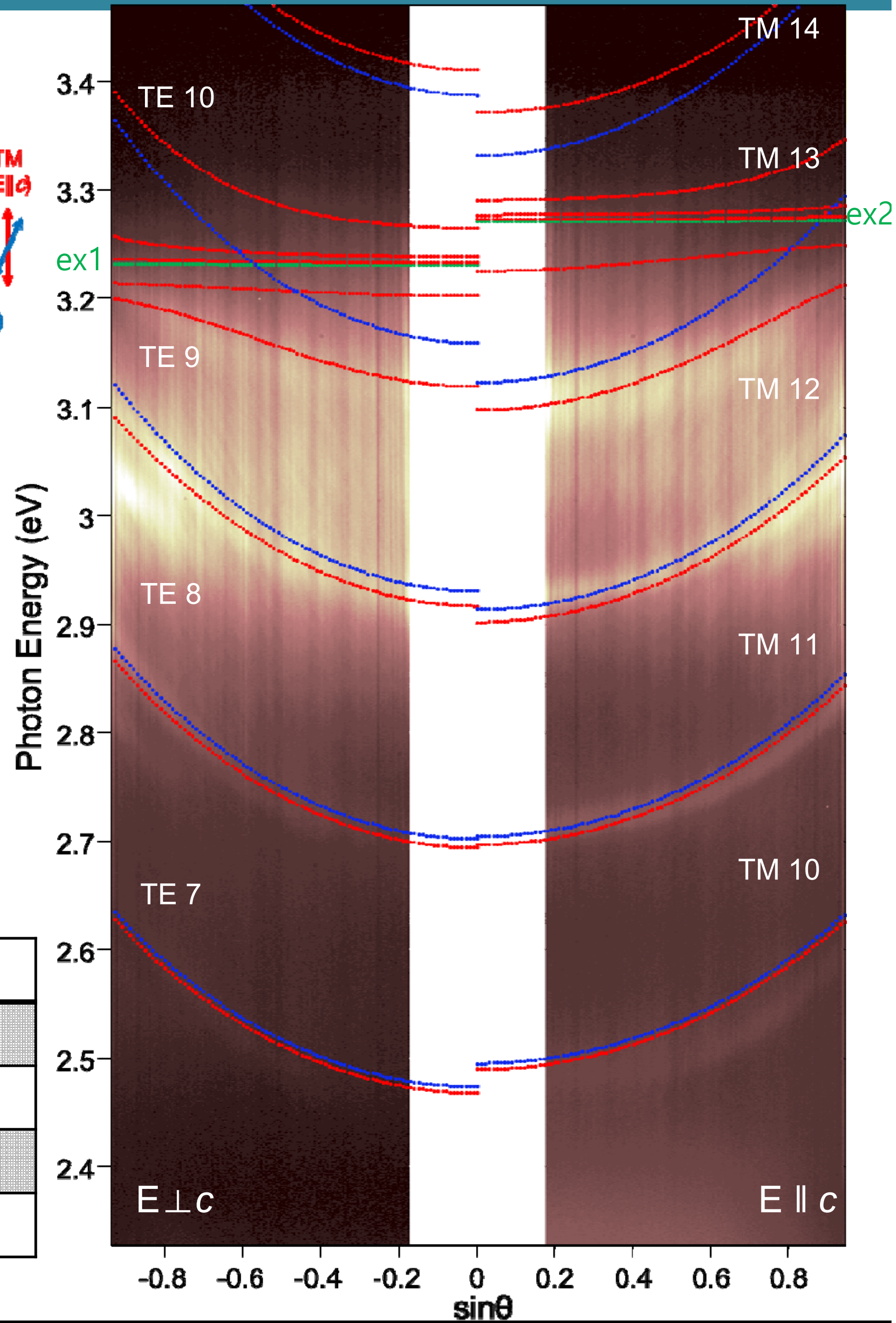




The coupled oscillator Hamiltonian

$$\begin{pmatrix} E_{ph}(\theta) & \hbar\Omega_1/2 & \hbar\Omega_2/2 \\ \hbar\Omega_1/2 & E_{ex1}(\theta) & 0 \\ \hbar\Omega_2/2 & 0 & E_{ex2}(\theta) \end{pmatrix}\begin{pmatrix} \alpha \\ \beta \\ \chi \end{pmatrix} = E_{pol}(\theta)\begin{pmatrix} \alpha \\ \beta \\ \chi \end{pmatrix}$$

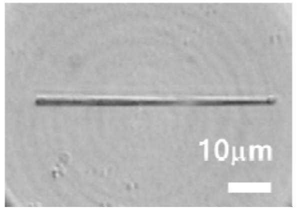
	E ⊥ c (TE)	E ∥ c (TM)
Exciton energy	E_{ex1}=3.429 eV	E_{ex2}=3.265 eV
Effective refractive index	n_o=2.7	n_e=2.95
Vacuum Rabi splitting	**=130 meV**	**=130 meV**
Cavity radius	335 nm	



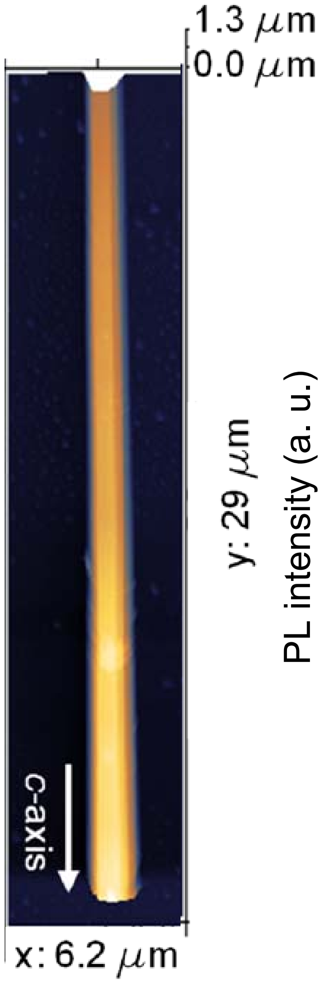
2. Giant Rabi splitting: Experimental Observation of Exciton Polariton

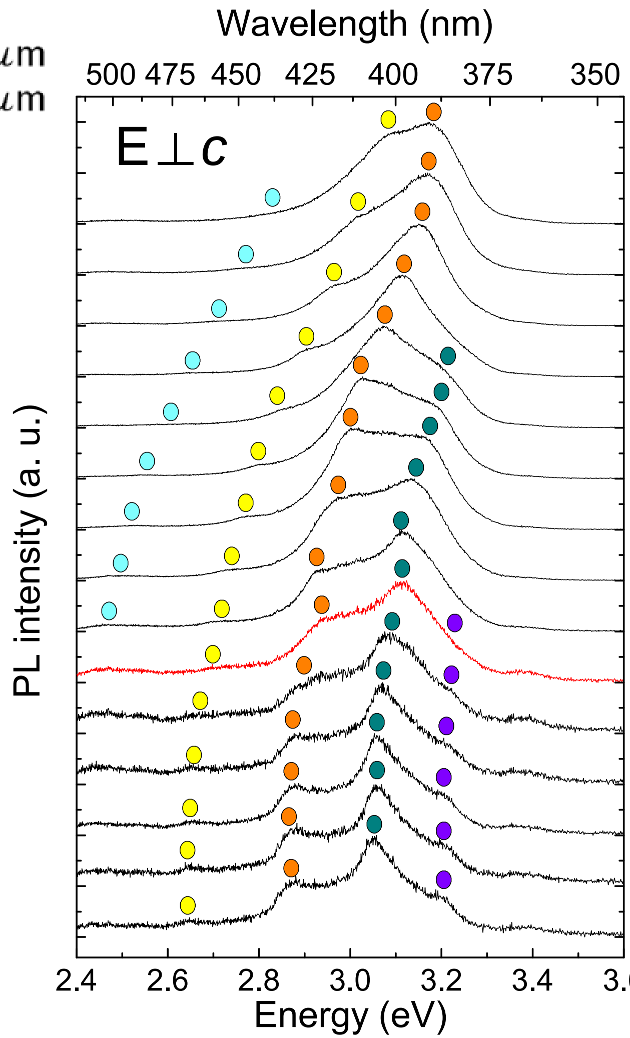
- Position dependent micro-PL

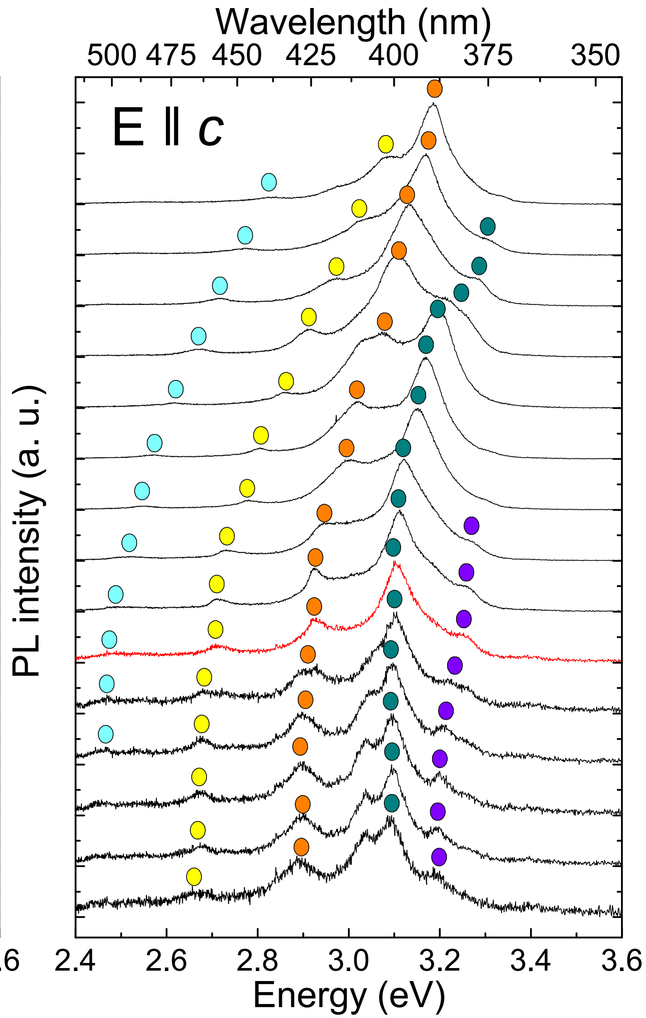
1μm step movement
Laser spot size ~1μm²



CCD image
Perpendicular to the slit of monochromator



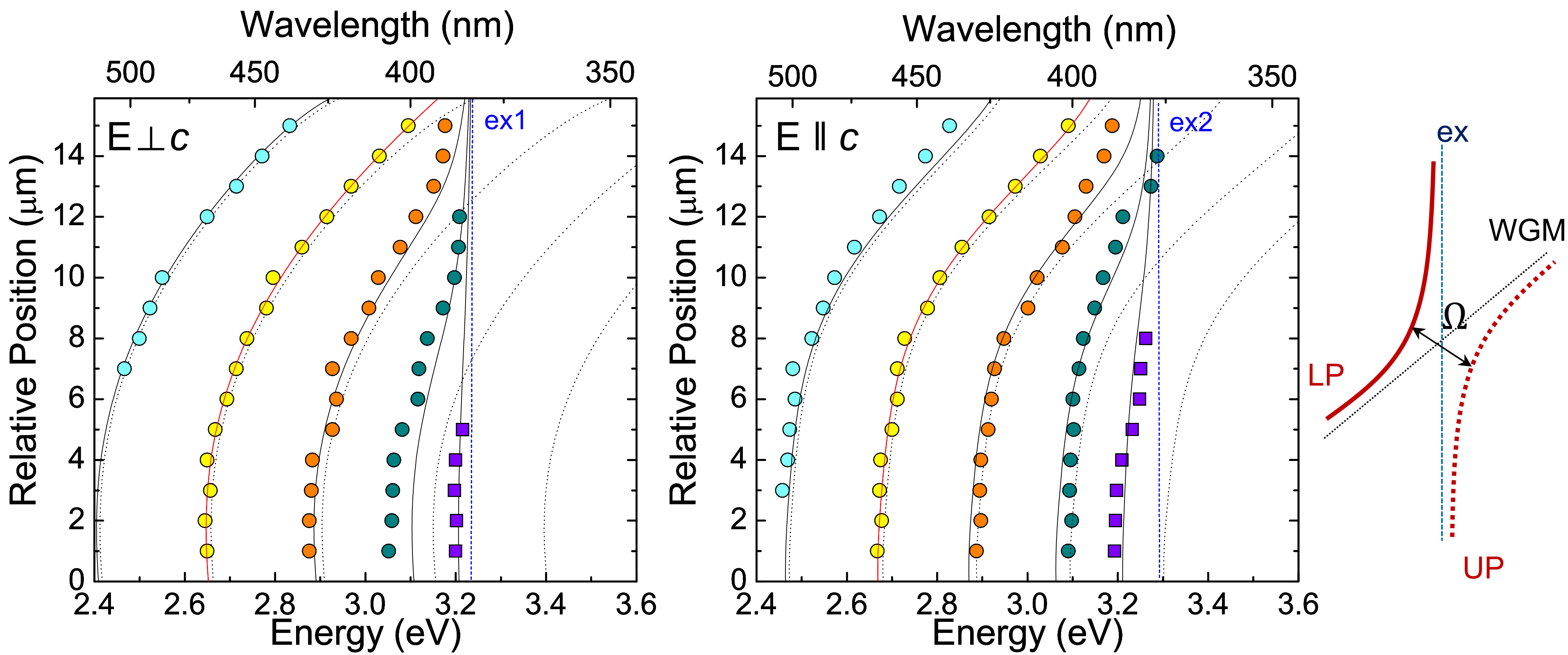




Tapered geometry of microwire
: continuously shift of WGM modes

2. Giant Rabi splitting: Experimental Observation of Exciton Polariton

- Position dependent micro-PL



Clear anti-crossing behavior!

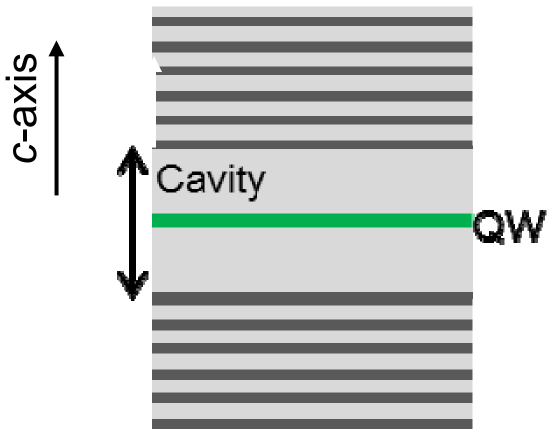
Tapered geometry of microwire
: continuously shift of WGM modes

$$E_0 = \frac{hc}{6nR}\left[N + \frac{6}{\pi}\arctan\left(\beta\sqrt{3n^2-4}\right)\right]$$

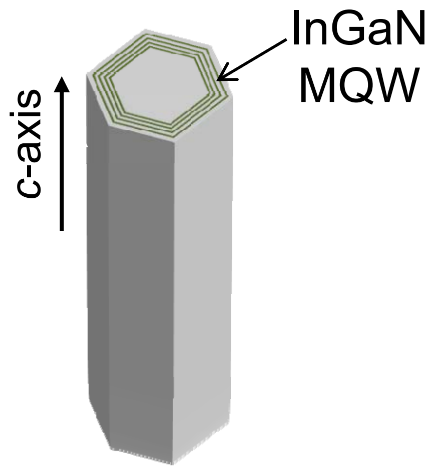
R : radius of nanowire
N : mode number
β : $\frac{1}{n}$ for TM, n for TE

	E ⊥ c (TE)	E ∥ c (TM)
Exciton energy	E_{ex1}=3.225 eV	E_{ex2}=3.265 eV
Effective refractive index	n_e=2.70	n_e=2.95
Vacuum Rabi splitting	=130 meV	=130 meV
Cavity radius	335 nm	

2. Giant Rabi splitting: Results



VS.



- Nitride MQWs in planar microcavity
  $\hbar\Omega$ =9.1~50 meV
  [NL 13,2376 (2014), APL 81, 071107 (2006), PRB 77, 085310 (2008)]

- GaN/InGaN core-shell microwire
  $\hbar\Omega$ = 130 meV

$$\hbar\Omega \approx \hbar\sqrt{2\underline{\tilde{\omega}_{LT}}\omega_0 \underline{\frac{\int_{active}\varepsilon(r)|E(r)|^2dr^3}{\int_{cavity}\varepsilon(r)|E(r)|^2dr^3}}}$$

High quality non-polar multi-QWs
- 10 times higher ω_{LT} than planer

Core/shell Whispering gallery modes
- 2~4 times higher $\boldsymbol{\Gamma}$ than planer

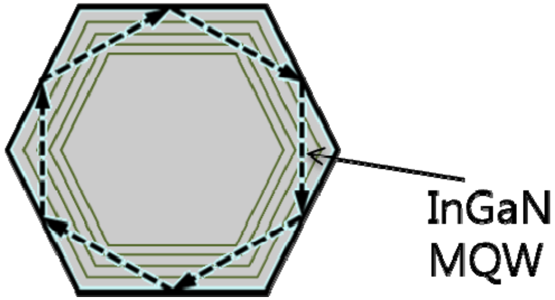
✓ **4~6 times higher Rabi-splitting than planer**
✓ **Giant Rabi splitting ~ 130 meV**

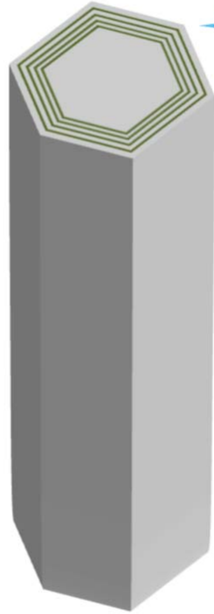
S. H. Gong, Y. H. Cho *et al*, ***Nano Letters*** 15, 4517 (2015)

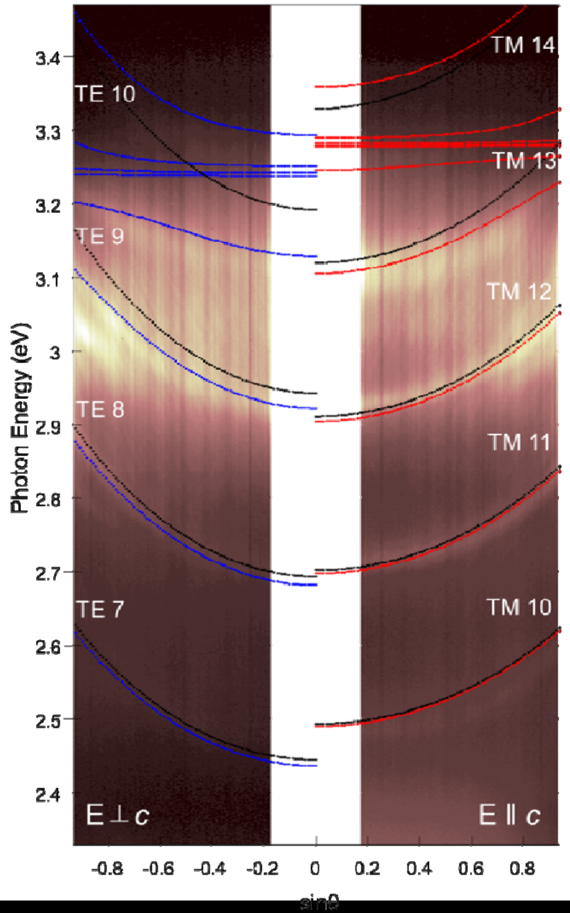
3. Summary

Main challenge on Nitride based cavity polariton system

- Large lattice mismatch of Bragg mirror
- High defect density
- Quantum confined Stark effect
  (large built-in field)





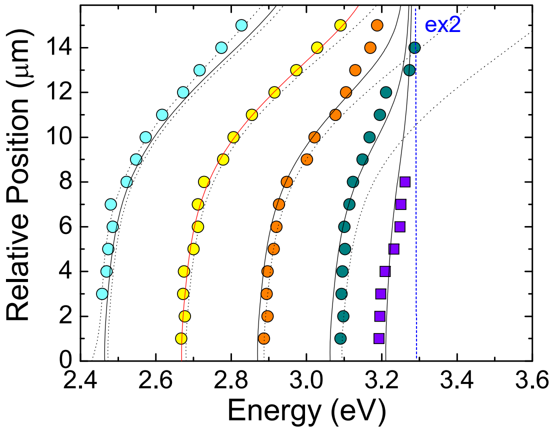


✓ Whispering gallery modes

➢ High spatial overlap (Γ)

✓ High quality non-polar multi-QWs

➢ No built-in field , high LT-splitting (ω_{LT})



✓ Giant Rabi-splitting is confirmed by angle resolved and position dependent micro-PL

✓ Further improvement is expected with high-period MQWs at well-defined spatial overlap.

S. H. Gong, Y. H. Cho *et al*, ***Nano Letters*** 15, 4517 (2015)

Quantum Nanobio Photonics

KAIST

Professor
Yong-Hoon Cho

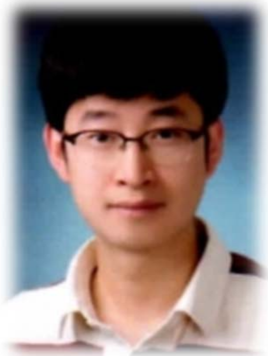
Thank you

Doctor
Su Hyun Gong

InGaN/GaN core-shell

Hyun Gyu Song

Bulk GaN microwire



Min-Sik Kwon

GaAs polariton condensate

Daegwang Choi

GaAs polariton condensate