中国科学院大学
University of Chinese Academy of Sciences
中国科学院北京纳米能源与系统研究所
Beijing Institute of Nanoenergy and Nanosystems,Chinese Academy of Sciences

漫谈从第三代半导体氮化镓材料器件到接触界面光谱学

Dr. Ding Li
Associate Professor
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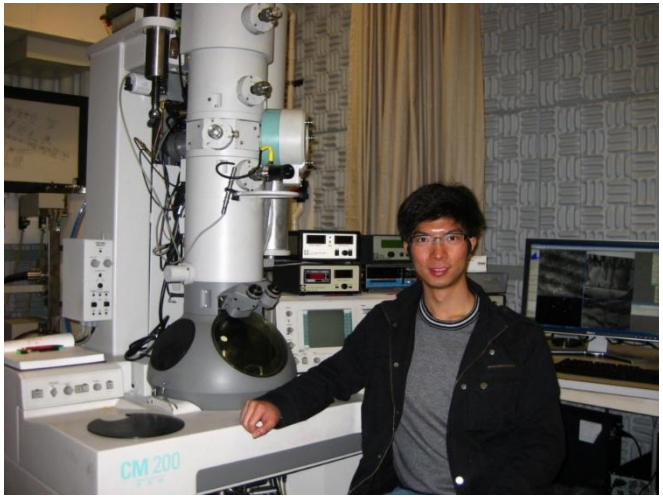
June 7th, 2026

Content

- **Introduction for Dr. Ding Li**
- **The third-generation semiconductor and the Piezo-Phototronics**
- **Inter-atomic Electron-transition Induced Photon Emission in Contact-electrification (CEIIS)**
- **Welcome to BINN, CAS**

Education and Working Experiences



- **2006-2012 Peking University**
  - ✓ **Ph. D (Condensed Matter Physics)**
- **2010 Visiting Scholar, Arizona State University**
- **2002-2006 Tianjin University**
  - ✓ **Bachelor of Science (Applied Physics)**
  - ✓ **Bachelor of Art (English literature)**

Education and Working Experiences

- 2022 – Now UCAS/BINN, CAS
  - ✓ Associate Professor
  - ✓ PhD Supervisor
- 2017 – 2022 BINN, CAS
  - ✓ Associate Professor
- 2014 – 2017 Ferdinand-Braun-Institut Leibniz-Institut für Höchstfrequenztechnik
  - ✓ Postdoc
- 2012-2014 Peking University
  - ✓ Postdoc
- 2006-2012 Peking University
  - ✓ Ph. D (Condensed Matter Physics)
- 2010 Visiting Scholar, Arizona State University
- 2002-2006 Tianjin University
  - ✓ Bachelor of Science (Applied Physics)
  - ✓ Bachelor of Art (English literature)

Volunteer in spare time

My Home Town– Ya’an(雅安), Sichuan

Home town of Gaint Panda

Panda baby

Adult

Panda in Kindergarden

My Home Town– Ya’an (雅安), Sichuan

Home town of Panda

Home town of Green tee

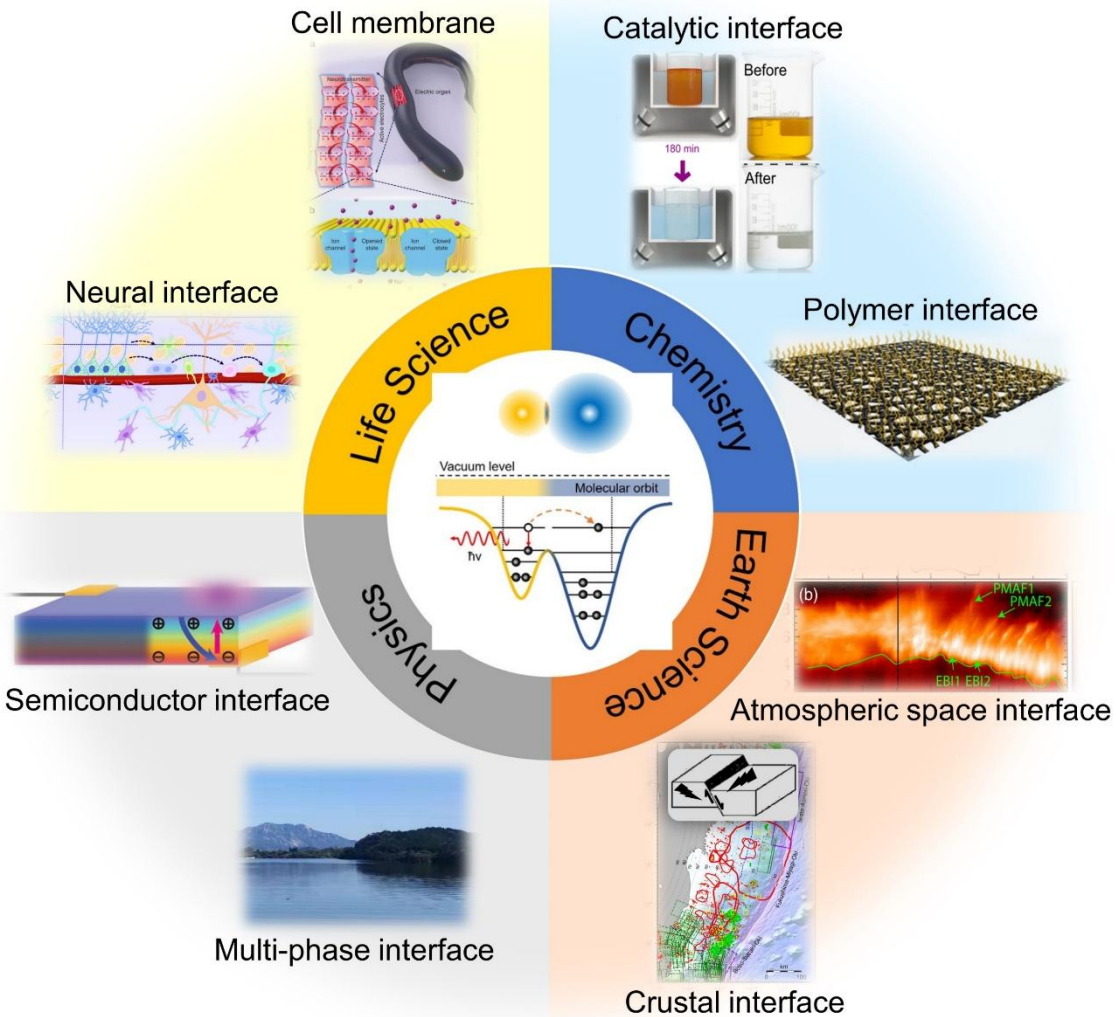
Famous for “三雅” (san ya)

雅女(Ya’Nv): beautiful girls

雅雨(Ya’Yv): The most rain in mainland China

雅鱼(Ya’Yv): A special kind of fish in river with water from ice mountains

My Research Area I: CEIIS



My Research Area II: the 3rd Generation Semiconductor and the Piezo-Phototronics

- Focus on GaN Laser Diode (LD). And obtained a series of original achievements on design, growth and mechanism.
- More than 5 W GaN LD output with the top of world performance.

More than **20 years** MOCVD experience

Growth

p-SL for high hole concentration
APE, 0610026, 2013
JJAP, 07100171, 2012
APL, 0611106, 2010

Electrical behavior
APL, 123501, 2013
Optical behavior
Opt. Express, 2536, 2014

Lasing mechanism
Submitted to Nat. Comm

Laser Diode

MQWs for higher IQE
JAP, 0731067, 2011
JAP, 0131021, 2013

Mechanism ⟷ **Design**

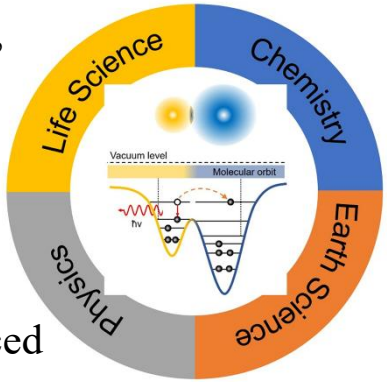
Electron blocking layer for better efficiency
APL, 0311053, 2012

回国后主要工作一览

✓五篇代表性论文发表情况：

- **D. Li**, C. Xu, Y. J. Liao, W. Z. Cai, Y. Q. Zhu, Z. L. Wang. Interface inter-atomic electron-transition induced photon emission in contact-electrification, *Sci Adv*, 2021, 7(39): eabj349.
- Y. Hou, X. Dong, **D. Li**, D. Shi, W. Tang, and Z. L. Wang. Self-Powered Underwater Force Sensor Based on a T-Shaped Triboelectric Nanogenerator for Simultaneous Detection of Normal and Tangential Forces, *Adv. Funct. Mater.*, 2023, 33, 2305719（通讯作者）
- Q. Guo, **D. Li**, Q. L. Hua, K. Y. Ji, W. H. Sun, W. G. Hu, Z. L. Wang. Enhanced heat dissipation in gallium Nitride-Based Light-Emitting diodes by piezo-phototronic effect, *Nano Lett.*, 2021, 21(9): 4062-4070.（共同一作）
- T. Liu, **D. Li**, H. Hu, X. Huang, Z. Zhao, W. Sha, C. Jiang, C. Du, M. Liu, X. Pu, B. Ma, W. Hu, Z. L. Wang. Piezo-phototronic effect in InGaN/GaN semi-floating micro-disk LED arrays, *Nano Energy*, 2020, 67: 104218（共同一作）
- H. Y. Kou, H. M. Wang, R. W. Cheng, Y. J. Liao, X. Shi, J. J. Luo, **D. Li**, Z. L. Wang. Smart pillow based on flexible and breathable triboelectric nanogenerator arrays for head movement monitoring during sleep, *ACS Appl Mater Inter*, 2022, 14(20): 23998-24007.（共同通讯作者）

接触界面光谱学



压电光电子学与第三代半导体

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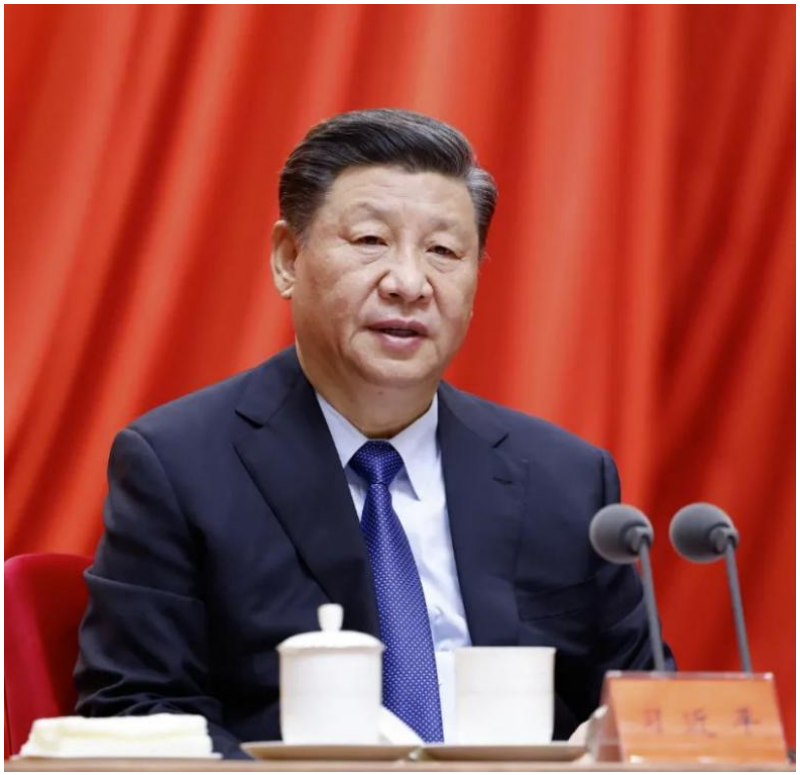
发展第三代半导体意义重大



◆ 2021年，习总书记指出“要从国家急迫需要和长远需求出发，在石油天然气、基础原材料、高端芯片等方面关键核心技术上全力攻坚，加快突破关键核心技术。”

中华人民共和国中央人民政府
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03 集成电路

集成电路设计工具、重点装备和高纯靶材等关键材料研发，集成电路先进工艺和绝缘栅双极型晶体管（IGBT）、微机电系统（MEMS）等特色工艺突破，先进存储技术升级，碳化硅、氮化镓等宽禁带半导体发展。

◆ 《中华人民共和国国民经济和社会发展第十四个五年规划和2035年远景目标纲要》明确将“SiC、GaN等宽禁带半导体发展”列入科技前沿领域中的攻关重点。

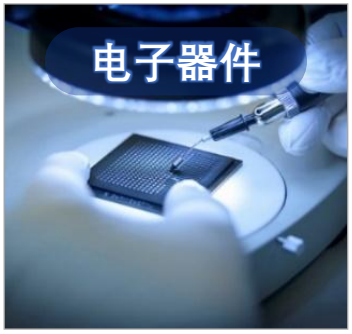
发展第三代半导体意义重大

- 2020年4月28日，美国商务部将GaN的设备、衬底和晶圆（3B001/C005/C006）列入出口管制；
- 2022年8月9日，美国总统拜登签署《芯片和科学法案》，加入“中国护栏”条款，进一步扭曲全球半导体供应链。（“ The act requires recipients of federal financial assistance to agree not to expand semiconductor manufacturing in the People’s Republic of China ”）　*美国商务部

ECCN	产品大类	大类描述	具体ECCN举例
3B001	电子	用于制造半导体器件或材料的设备，及其特殊设计的组件和配件	3B001.a.2 用于半导体制备的金属有机化学气相沉积反应器
3C002	电子	抗蚀剂材料和涂有抗蚀剂的基材	3C002.a设计用于半导体光刻的抗阻材料
3C005	电子	高电阻材料	3C005 碳化硅、氮化镓、氮化铝或氮化铝镓等半导体底片材料
3C006	电子	3C001未指定的材料，由3C005指定的基板和至少一层碳化硅、氮化镓、氮化铝或氮化铝镓的外延层组成	3C006 具有至少一层碳化硅，氮化镓，氮化铝或氮化铝镓的外延层的基板

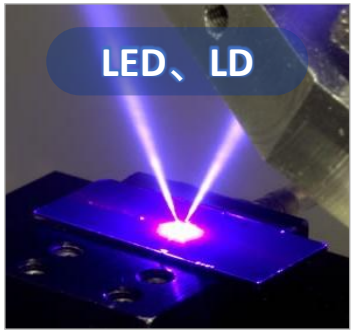
美、欧、日、韩等其他半导体科技强国将第三代半导体材料列为国家战略计划

超高功率雷达
与电子对抗



阈值电压高于
Si基器件10倍

能源存储过程
耗能减少66%



2030年市场
约2500亿美元

高效率

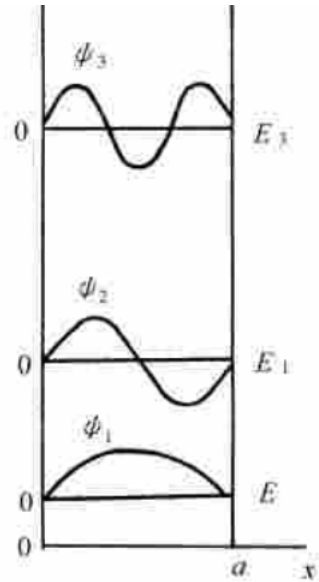
低能耗

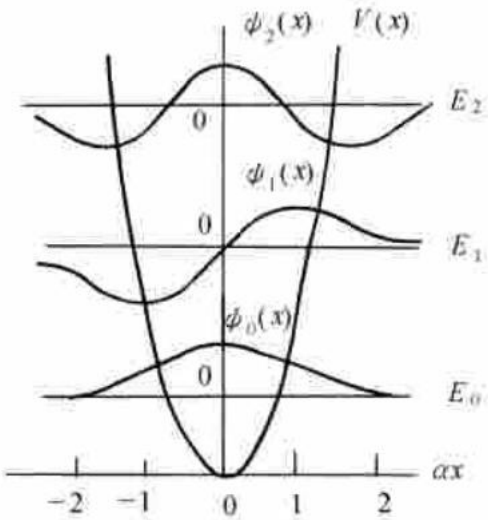
低成本

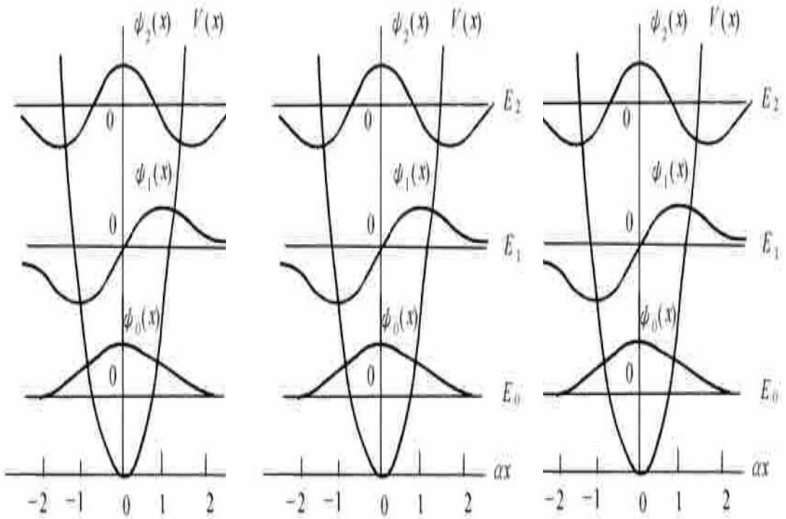
稳定可靠

(数据来源：美国能源部报告)

从一维无限深势阱到半导体能带



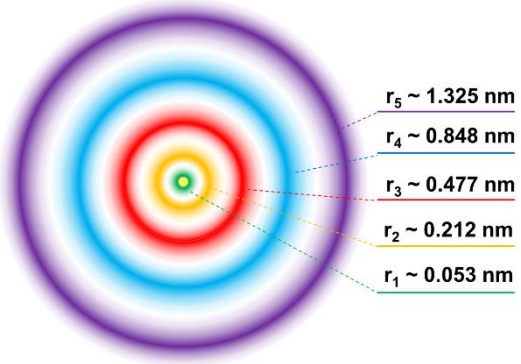


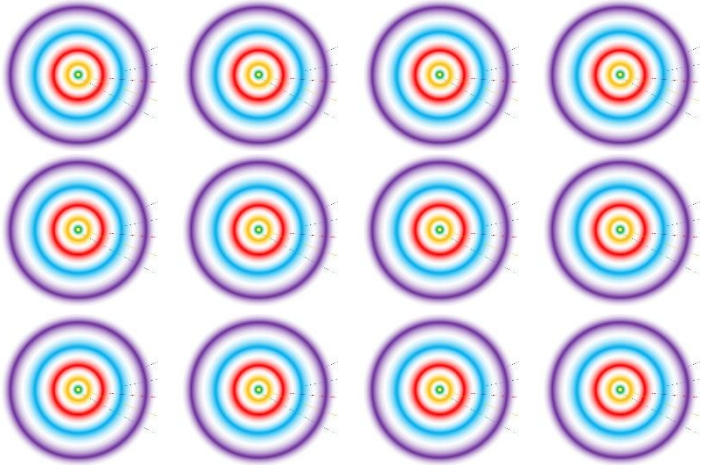


From 曾谨言《量子力学》卷I （第三版 ）2000年

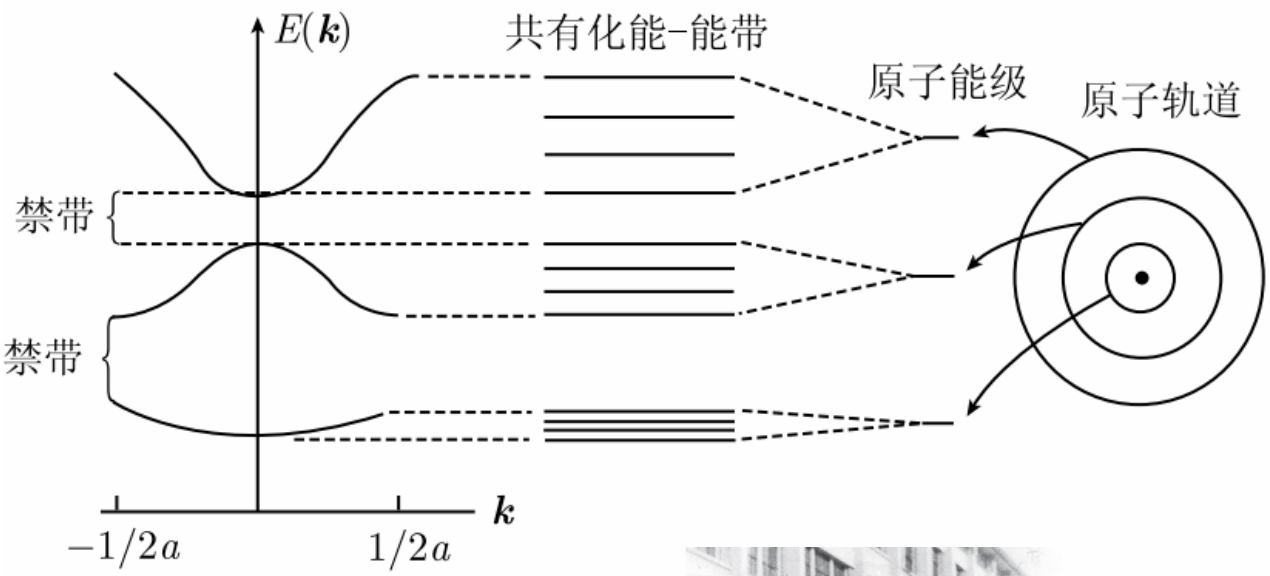
一维无限深势阱

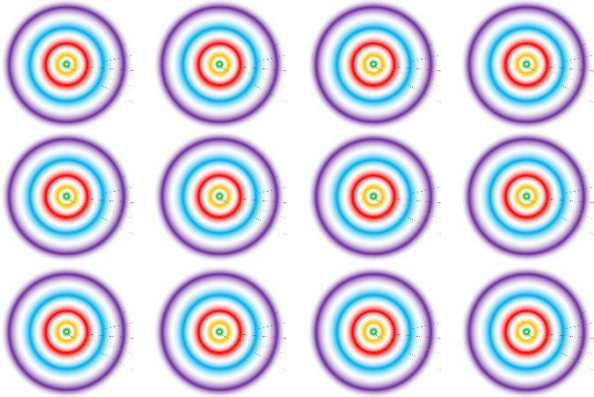
一维有限深势阱





从一维无限深势阱到半导体能带

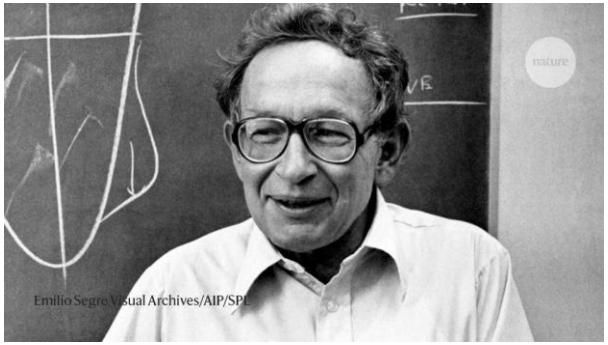




More is Different

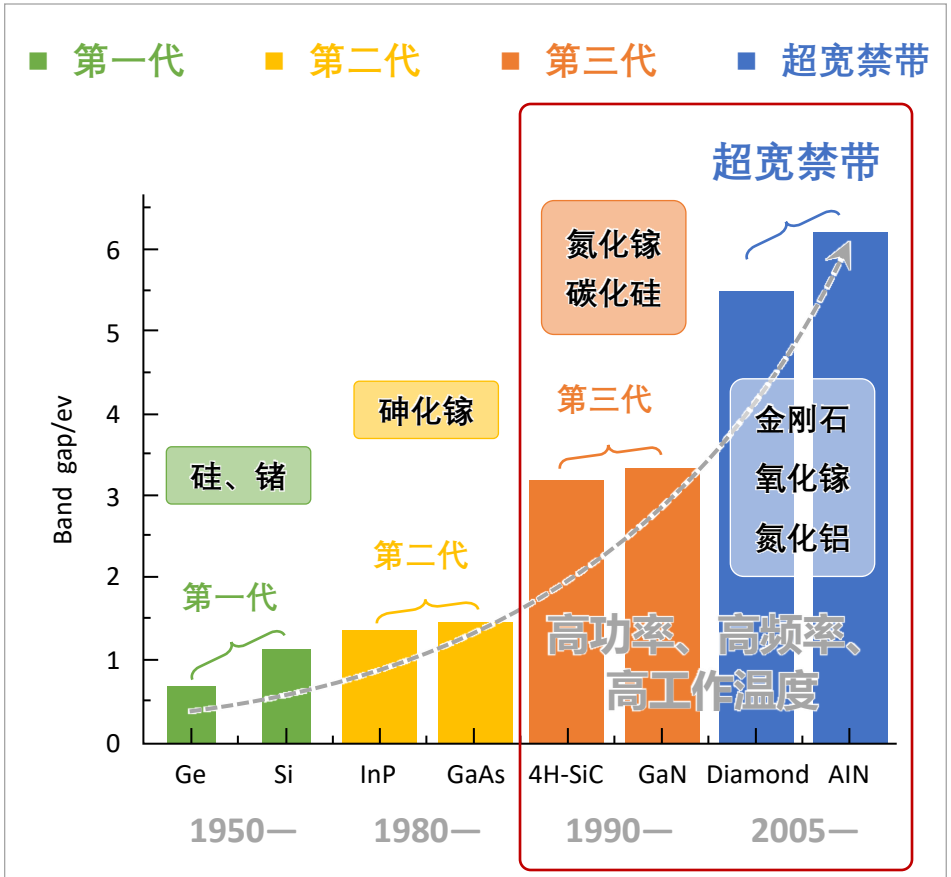
黄昆 谢希德《半导体物理学》2012年

黄昆 先生

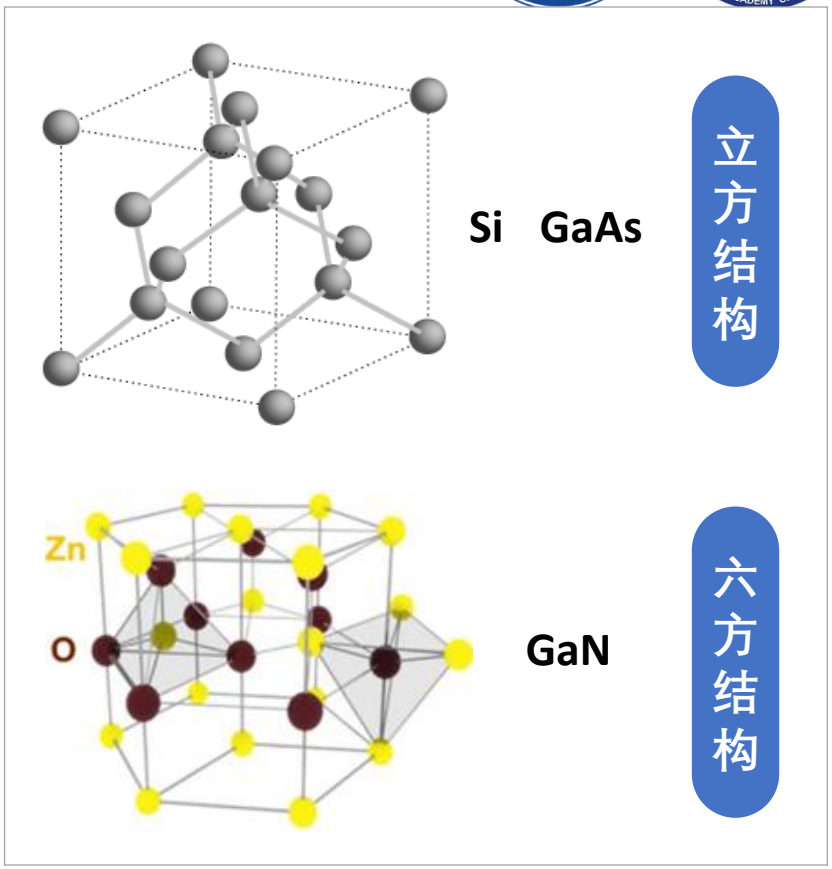


P W Anderson

半导体材料结构特征



禁带宽度



第三代半导体的典型特征

按照禁带宽度，半导体发展可划分为三代

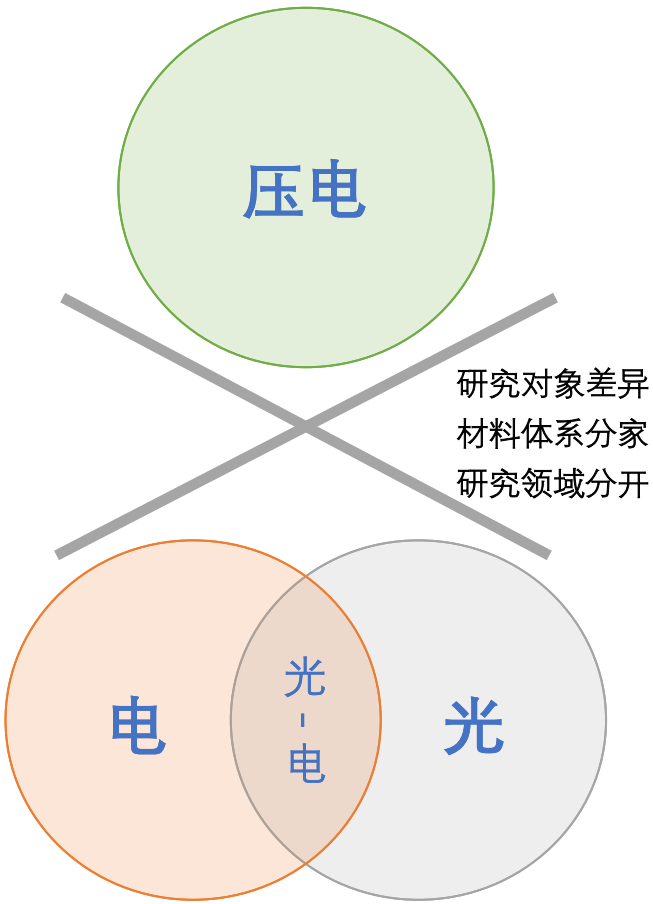
六方纤锌矿结构，非中心晶体结构带来的压电效应

第三代半导体材料中的压电效应

传统压电材料研究

传统半导体物理研究

钛酸钡、锆钛酸铅— 无半导体性

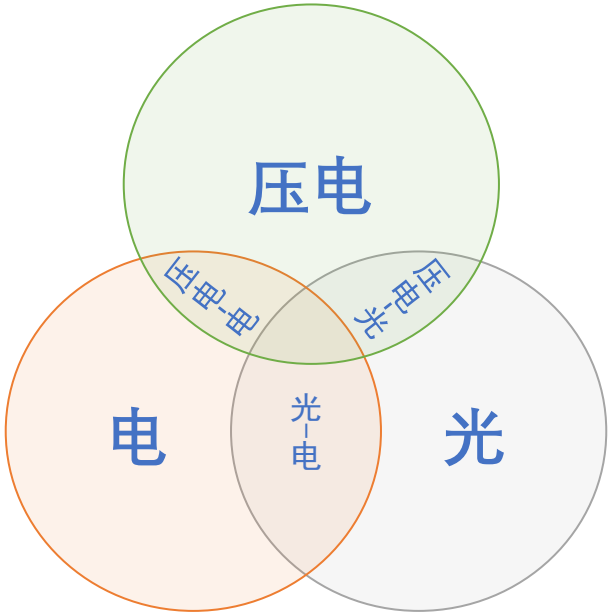


硅、锗、镓砷 — 无压电性

第三代半导体

压电 ✚ 半导体

氮化镓氧化锌

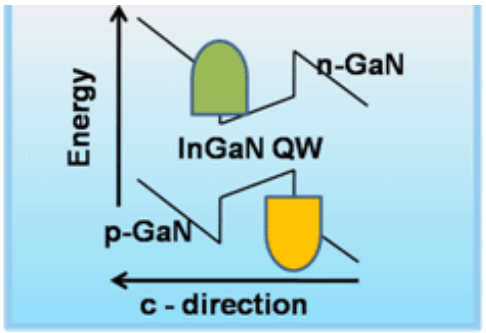


第三代半导体由于其独特的压电效应，应变场引起的压电场为半导体材料的光、电等研究打开了一扇新的大门！

第三代半导体材料中的压电效应

压电极化场是调控第三代半导体器件性能的决定因素

材料晶格失配引入的压电极化场

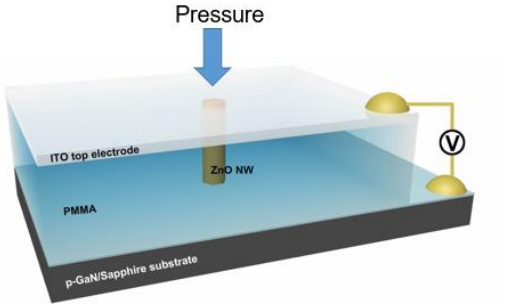


失配应力 ~Gpa，量子结构 ~nm

内极化场强 ~1000 kV/cm

VS.

外应力引入的压电极化场

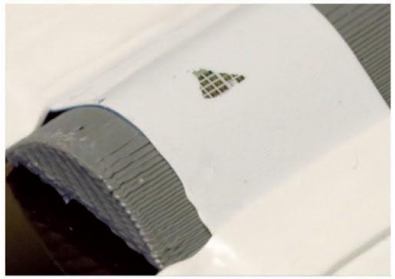


外加应力 ~GPa （0.5%应变）

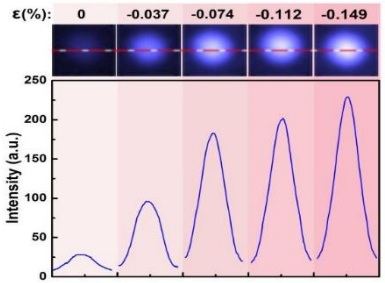
外极化场强 >2000 kV/cm

功率晶体管：
内外极化场相加

LED：
内外极化场相消



0.1%应变提升晶体管功率20%



0.15%应变，光强增强6.5倍

Shuji Nakamura, Nature Photonics 3, 180 (2009), Nature Photonics, 2013, 7, 752 ,

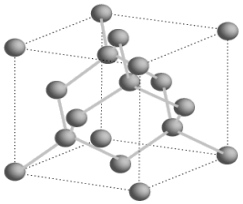
压电-电-光耦合新效应、材料与器件研究

揭示新机理 → **突破信息材料与器件技术瓶颈**

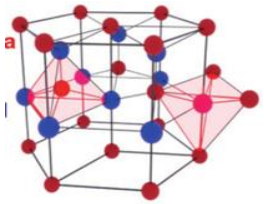
代表性半导体材料

- 第一代：Ge、Si
- 第二代：GaAs
- 第三代：Sic、ZnO、GaN

立方结构（中心对称）



六方结构（非中心对称）



压电-电-光新效应

国家安全

大功率晶体管与雷达

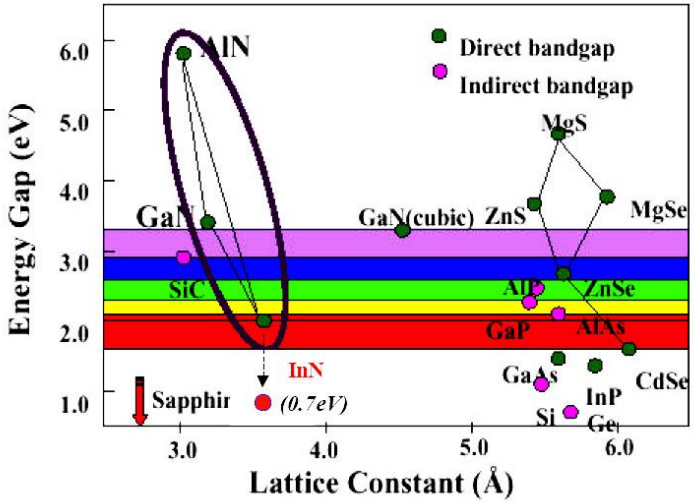
信息电子

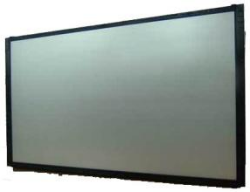
高出光LED与照明显示

新材料、新器件、新技术

科学前沿　　**重大需求**

GaN基材料及其应用背景





照明 显示

微波发射 功率器件

	Si	GaAs	4H-SiC	GaN
禁带宽度(eV)	1.1	1.4	3.0	**3.4**
电子迁移率 ($cm^2/V\cdot s$)	1500	8500	350	**1500**
饱和电子速度 ($\times 10^7$ cm/s)	0.9	2	2	**2.7**
击穿场强($\times 10^6$ V/cm)	0.4	4	4	**5**
热导率 (W/cm·K)	1.5	0.45	4.9	**1.3**

第一代半导体 第二代半导体 第三代半导体

GaN基LED及其应用

手机背光

交通指示灯

奥运会

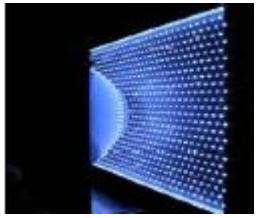
景观照明

世博会

LED

Incandescent Lamp GLS	Compact Fluorescent Lamp CFL	LED Lamp
Classic A	DULUX Superstar Classic A	Parathom A55 with Golden Dragon LEDs
40 W	8 W	8 W
Lifetime: 1.000 h	Lifetime: 10.000 h	Lifetime: 25.000 h
25 x	2,5 x	1 x

电视背光



GaN基HEMT及其应用

大的导带不连续性
AlN/GaN～1.75eV

强的极化效
~MV/cm

大的能带弯曲，深的三角形量子阱

↓

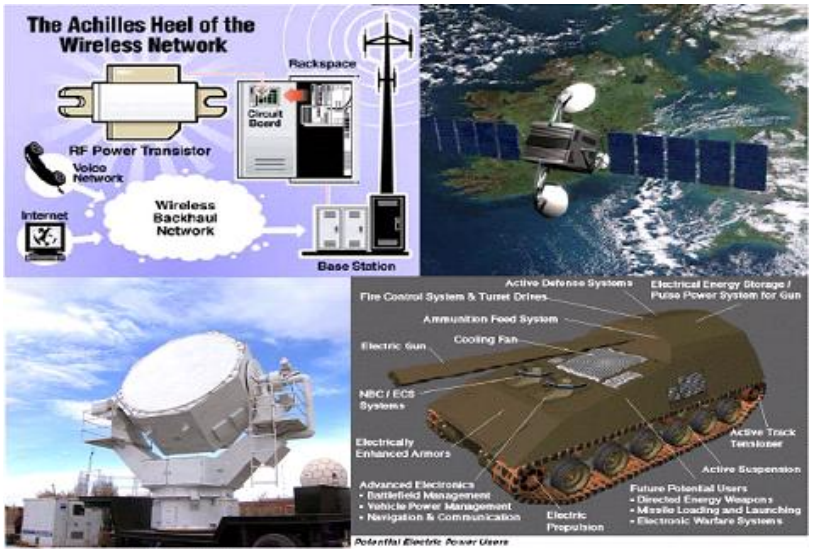
高的二维电子气
（2DEG）浓度 (10^{13} cm^{-2}量级)

↓

高2DEG迁移率
(1500~2200 cm^2/Vs)

↓

GaN based HEMTs



1. 广泛应用于雷达和无线通讯等领域；
2. 并在高温、强辐射等苛刻环境下的正常工作。

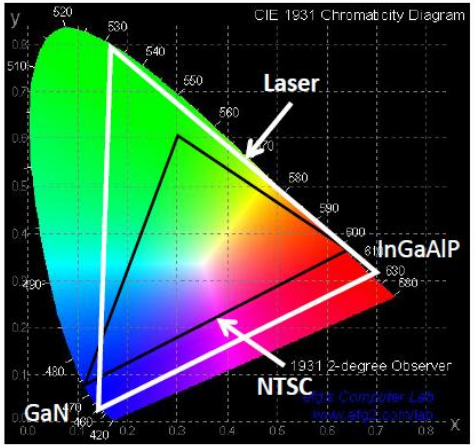
GaN基激光器及其应用

生化应用

紫外水净化

GaN激光器

便携式激光投影



高色彩饱和度

激光显示

高密度存储

高清制式

激光武器

美军阿富汗战争中的激光武器

GaN基激光器——蓝光与绿光的源泉

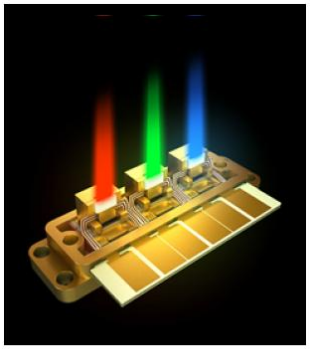


image source: http://www.engadget.com/2007/06/25/mitsubishis-laser-tv-coming-to-ces/

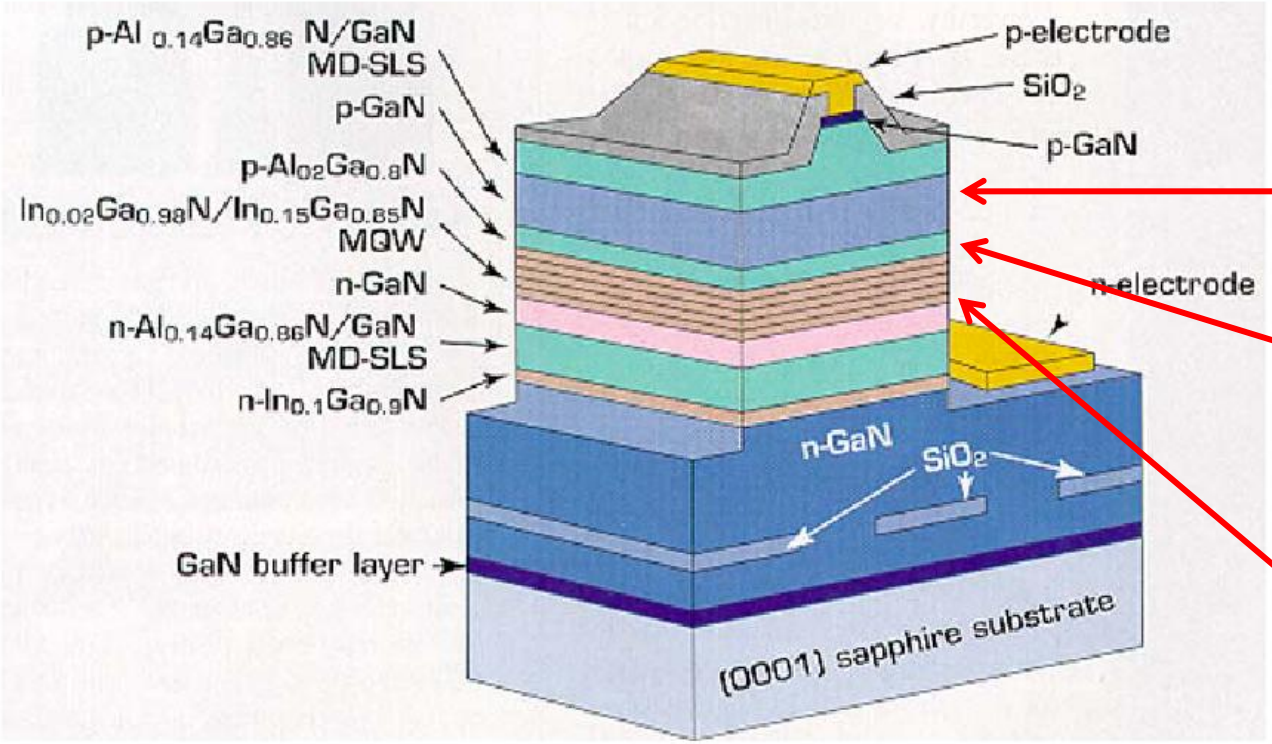
激光电视

GaN激光器外延面临的问题

诺贝尔奖获得者中村修二教授公布的典型激光器结构

Nichia Chemical Nitride Laser Diode

10,000 hr Lifetime SCH-MQW Laser



1. p型AlGaN/GaN 超晶格：显著提升空穴浓度

2. 电子阻挡层：大注入情况下的电子溢出

3. 多量子阱：
发光特性
阈值处光电行为

p-type Superlattice for high hole concentration

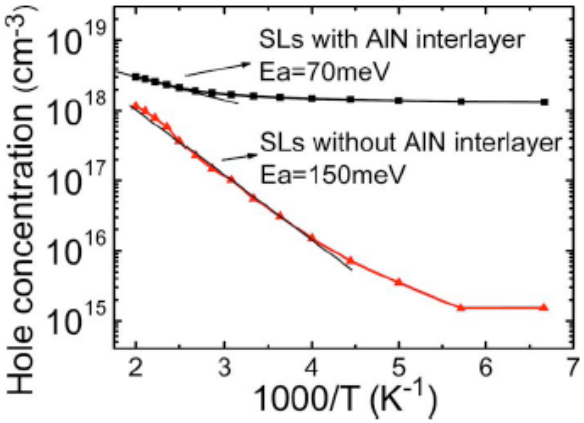
Thomas Swan CCS MOCVD

Growth Rate = 1 um/h
Pressure: 75 Torr

Growth Rate = 1.8 um/h
Pressure: 200 Torr

Al: TMAl Ga: TMGa
Mg:Cp_2Mg N: NH_3

Hole improvement by piezo-field modification



Lei Wang *et al*, Appl. Phys. Lett., **96**, 061110 (2010)

	1#	2#	3#	4#* Undoped
Description	Al=0.14	Al=0.14 no AlN	Al=0.3	Al=0.3
Carrier concentration $\times 10^{18}$ /cm^3	0.93 p-type	0.05 p-type	1.26 p-type	-1.0
Mobility cm^2/Vs	2.97	7.53	1.25	125

The activation energy was alerted, leading enhancement of hole concentration

Huge increase of Hole concentration

Hole concentration did not decrease with Al content

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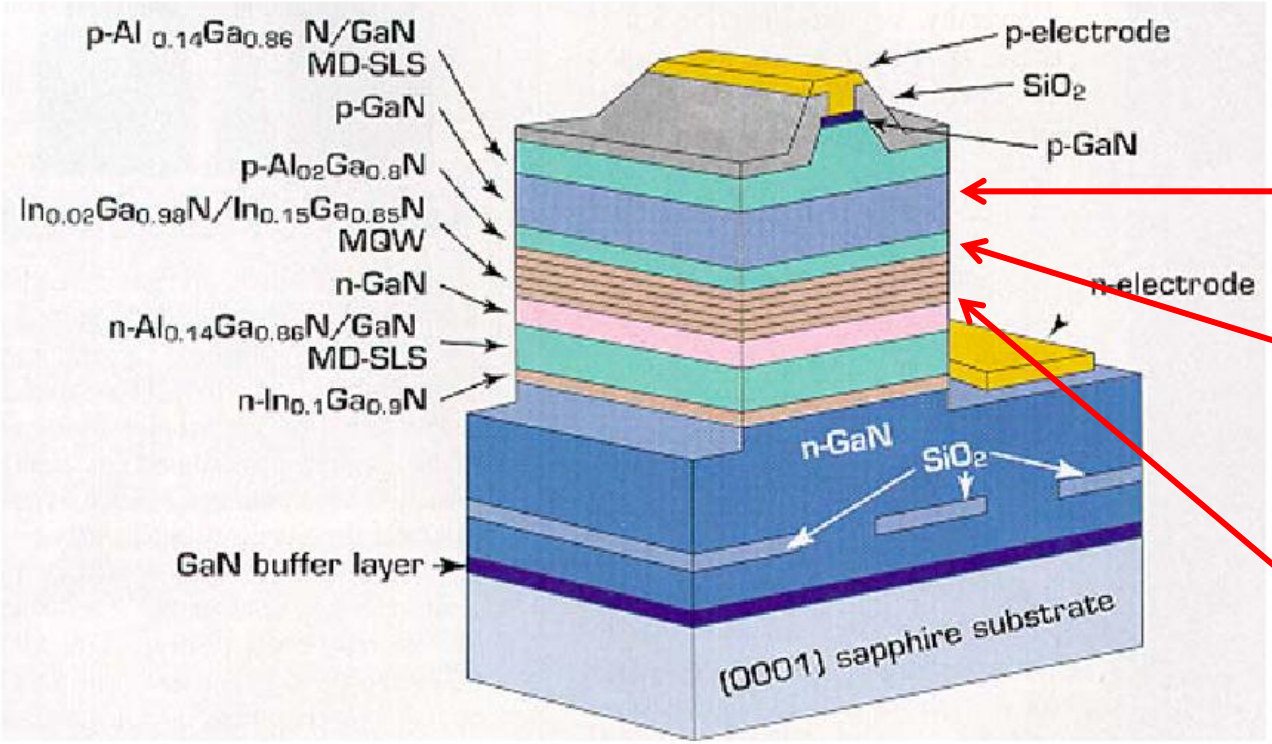

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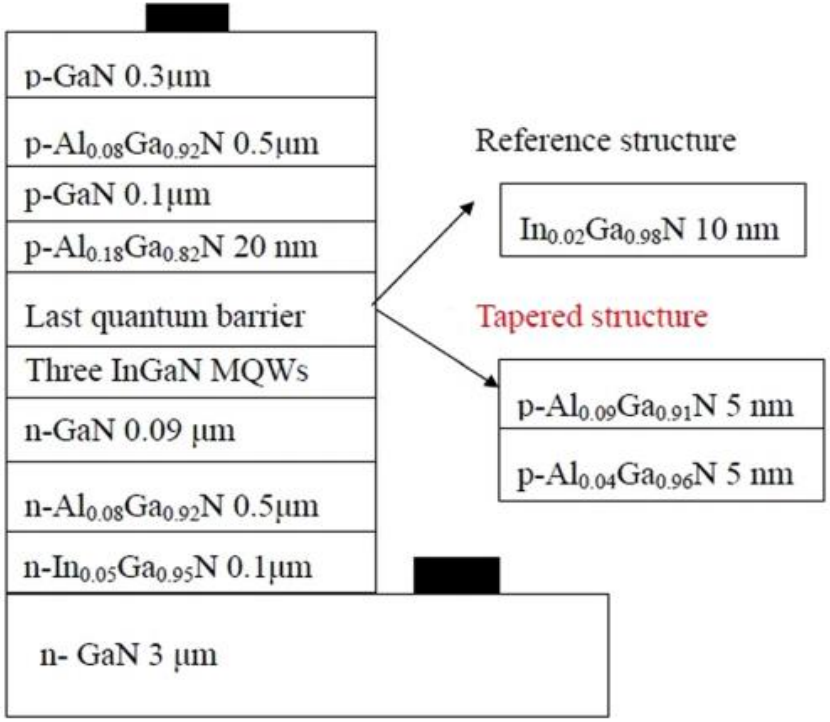
AlGaN taped EBL



Traditional EBL

10 nm p-type Mg-doped $Al_{0.18}Ga_{0.82}N$

New design

5 nm p-type Mg-doped $Al_{0.04}Ga_{0.96}N$

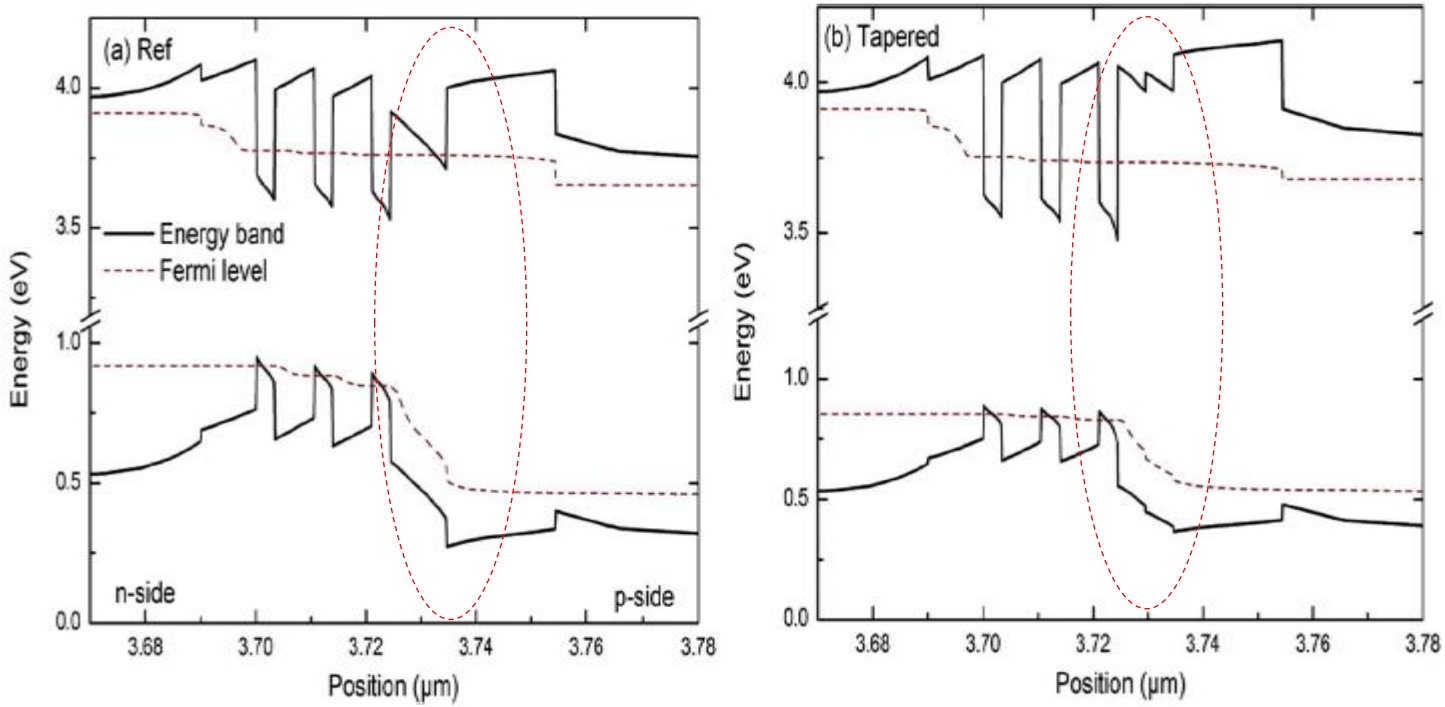
+5 nm p-type Mg-doped $Al_{0.09}Ga_{0.91}N$

- Wei Yang, **Ding Li,** Xiaodong Hu,et al, Appl. Phys. Lett., 100, 031105 (2012)**(Co-first author)**

AlGaN taped EBL

Band structure of tradition LD

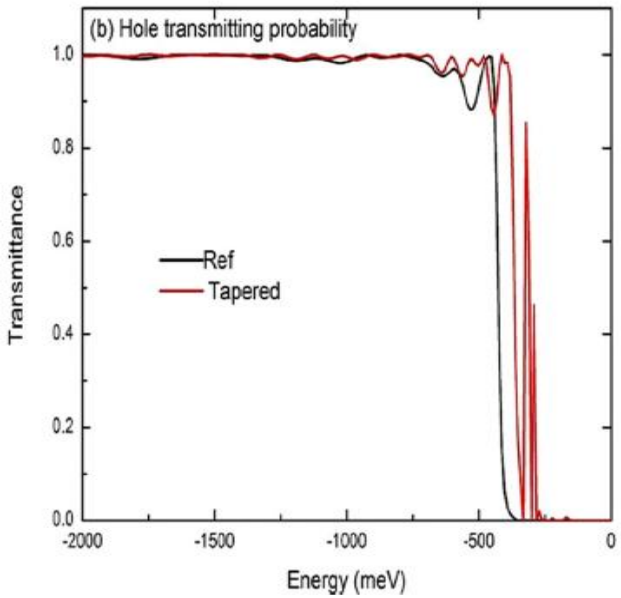
Band structure of taped EBL LD



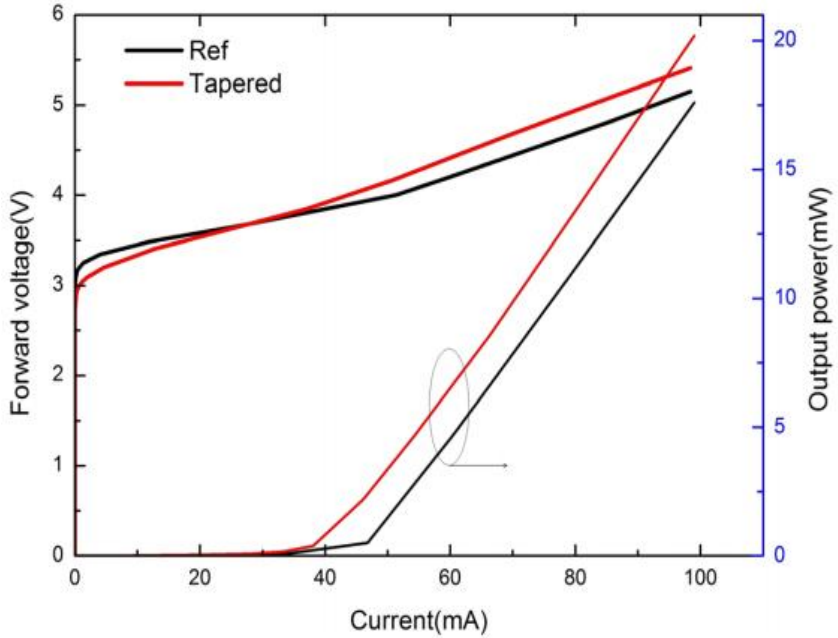
- ✓ Band offset higher above the quasi Fermi level
- ✓ Easy for holes to injection

➢ Wei Yang, **Ding Li,** Xiaodong Hu,et al, Appl. Phys. Lett., 100, 031105 (2012)**(Co-first author)**

AlGaN taped EBL



空穴在电子阻挡层的透过率



LD器件的IV特征曲线以及光输出曲线

- ✓ Less chance for electron to escape
- ✓ Threshold current drop from 2.0kA/cm^2 to1.6kA/cm^2, and 15% increase for output.

➢ Wei Yang, **Ding Li,** Xiaodong Hu,et al, Appl. Phys. Lett., 100, 031105 (2012)**(Co-first author)**

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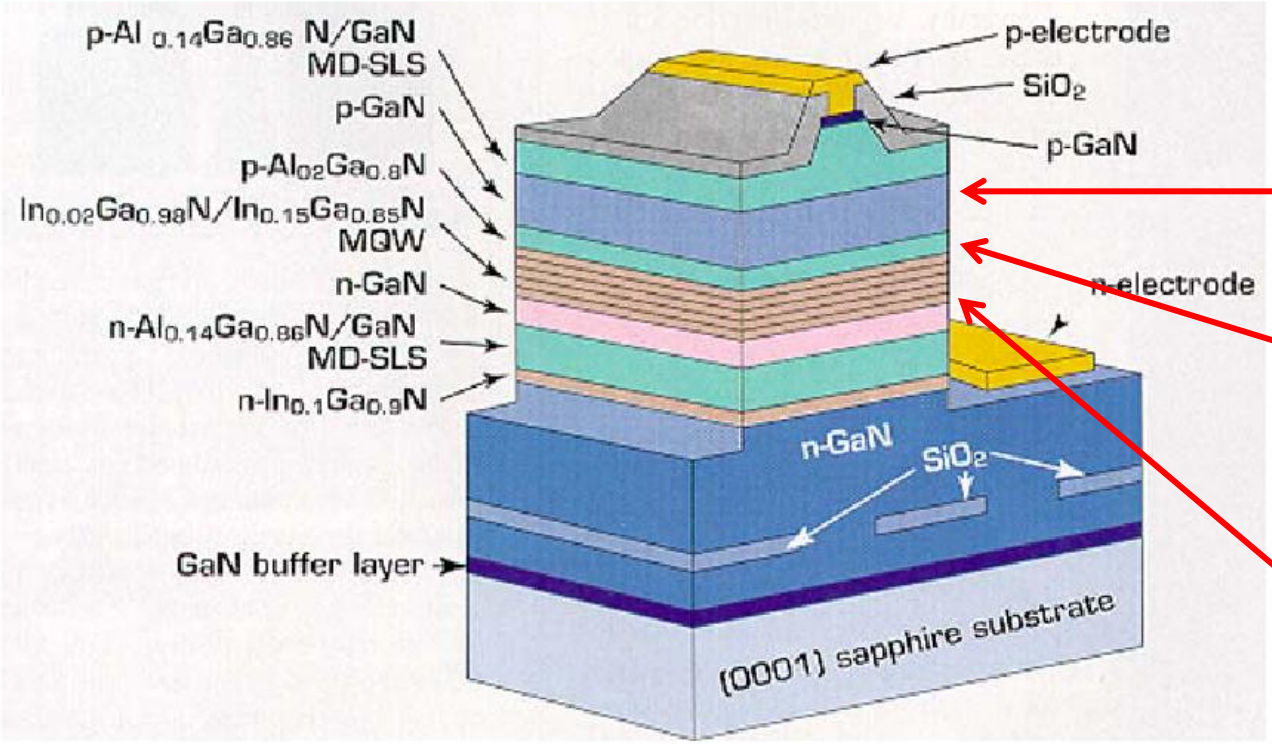

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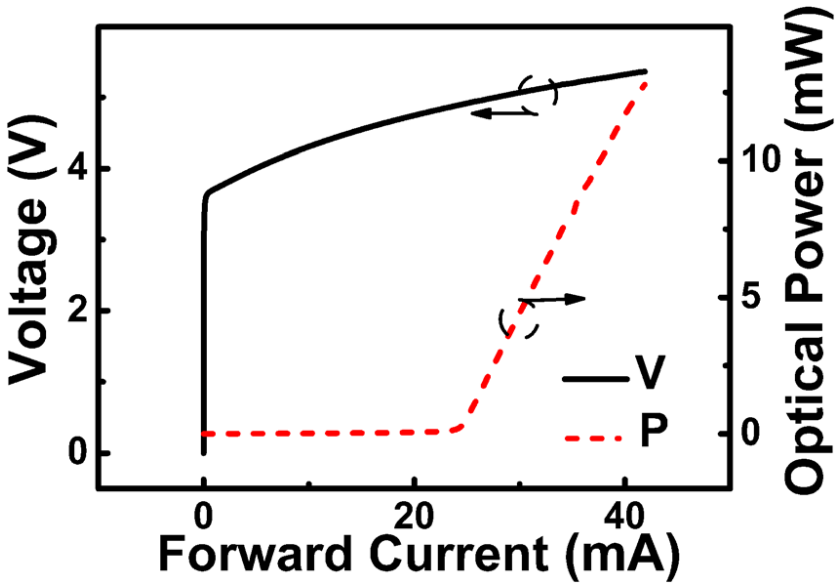
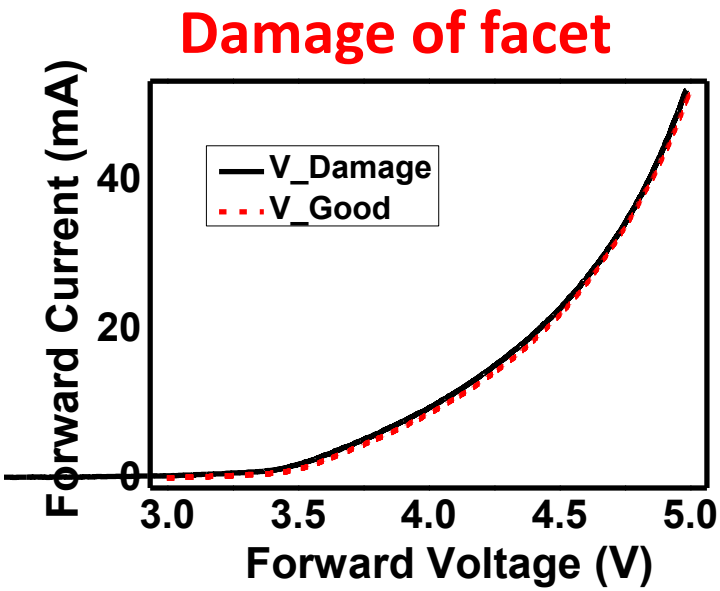
Model for laser Diode

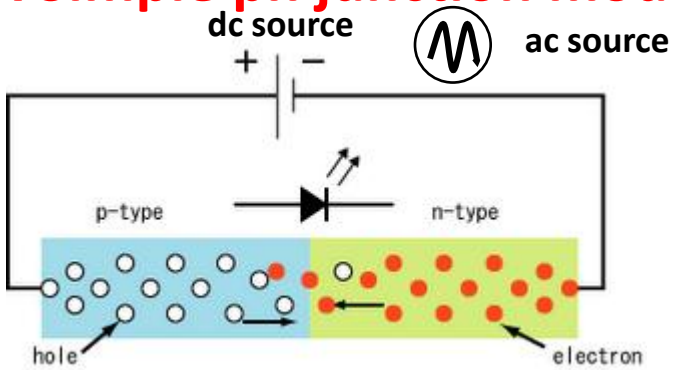




Real space limited

Model for laser Diode

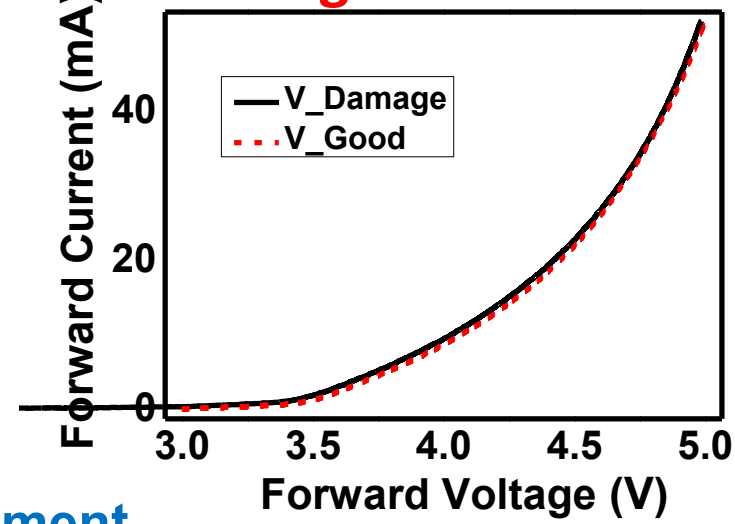
A Simple pn junction model



$$I = I_s\left(e^{\frac{qV_j}{nkT}} - 1\right)$$

- r_s :series resistance
  bulk + contanct resistance
- C: Junction Capacitance
- G: Junction Conductance
- C_p: Apparent Capacitance
- G_p: Apparent Conductance

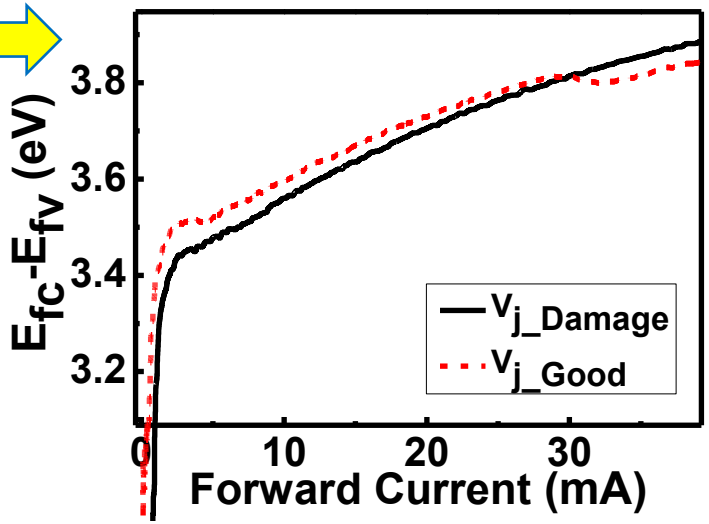
Damage of facet



Real space

limited

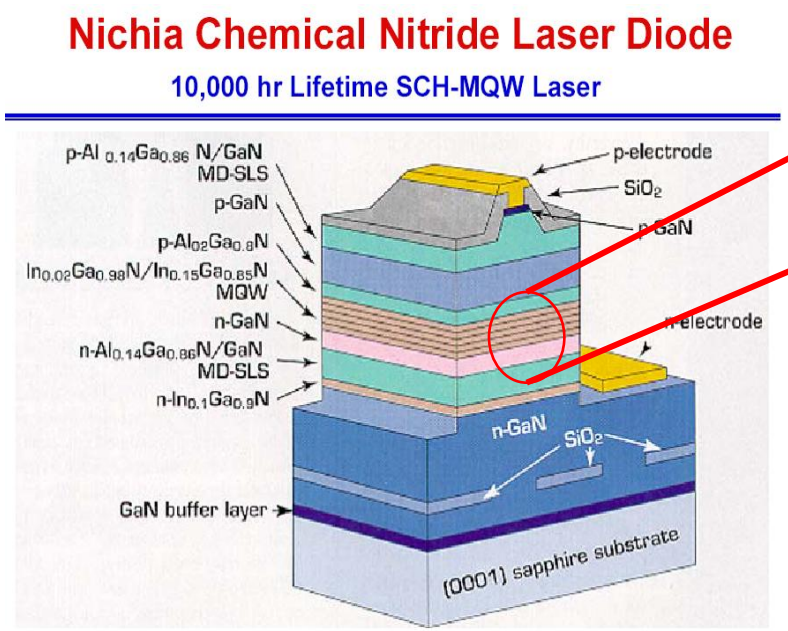
Direct measurement

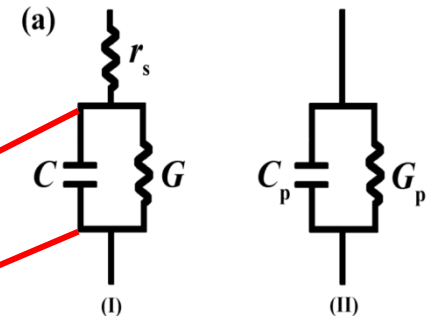


Complex space

Rich informa tions

Model for laser Diode





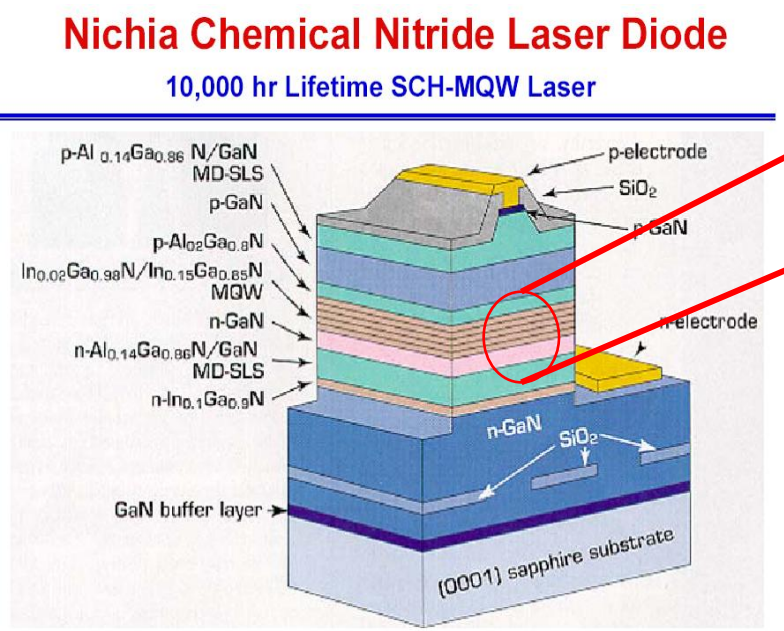
Assuming the depletion region only exists in MQWs

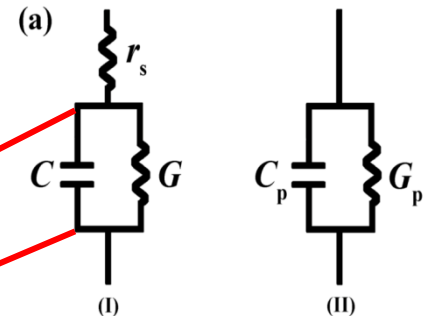
$$G_P = \frac{G(1 + r_s G) + r_s(\omega C)^2}{(1 + r_s G)^2 + (\omega r_s C)^2}$$

$$C_p = \frac{C}{(1 + r_s G)^2 + (\omega r_s C)^2}$$

measurement

Model for laser Diode





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When

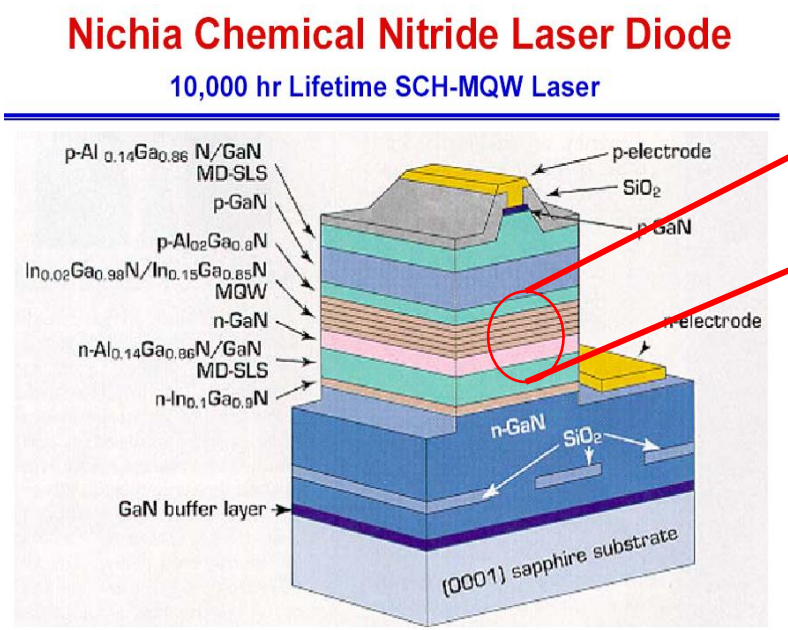
$$G >> \omega C$$

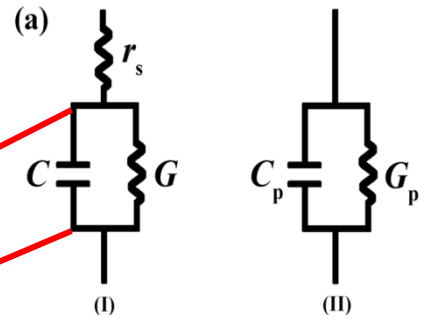
is held

LCR measurement

Approximate condition satisfied

Model for laser Diode





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$$C_p = \frac{C}{(1+r_sG)^2+(\omega r_sC)^2}$$

Assuming the depletion region only exists in MQWs

When

$$G >> \omega C$$

is held

Simplified to

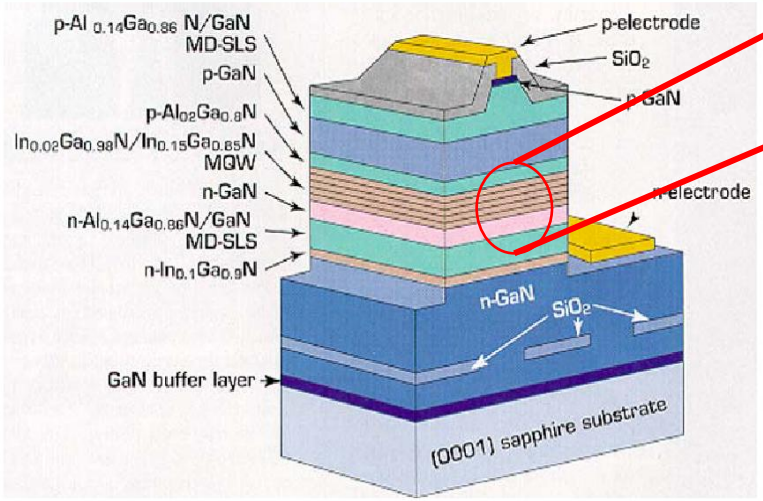
$$G_p = \frac{1}{\frac{1}{G}+r_S}$$

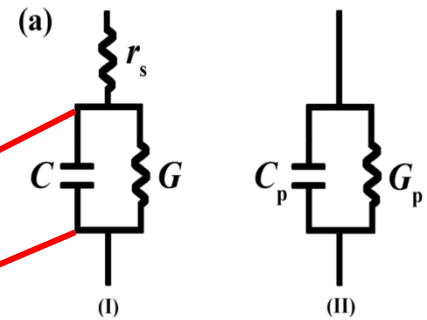
$$C_p = \frac{C}{(1+r_SG)^2}$$

Model for laser Diode

Nichia Chemical Nitride Laser Diode

10,000 hr Lifetime SCH-MQW Laser





$$r_s = \frac{1}{G_p} - \frac{1}{G},$$

$$V_j = V - Ir_s,$$

Assuming the depletion region only exists in MQWs

$$G = \frac{dI}{dV_j} = \frac{q}{nkT}(I + I_s),$$

$$n = \frac{qV_j}{kT\ln[(I+I_s)/I_s]},$$

When

$$V_j >> nkT/q$$

$$G >> \omega C$$

$$G_p = \frac{1}{\frac{1}{G} + r_s}$$

$$C_p = \frac{C}{(1 + r_s G)^2}$$

+ $$I = I_S\left(\exp\left(\frac{V_j}{n(V_j)kT}\right) - 1\right)$$ **is held**

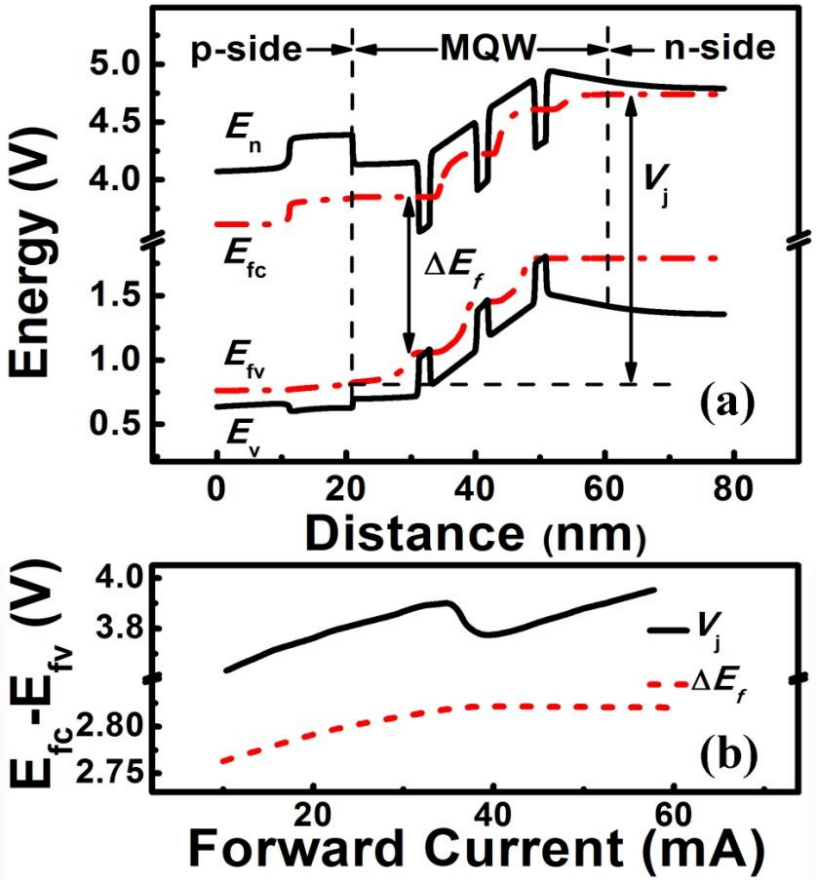
Electrical parameters

Approximate condition satisfied

LCR measurement

Model for laser Diode

Band diagram of a diode

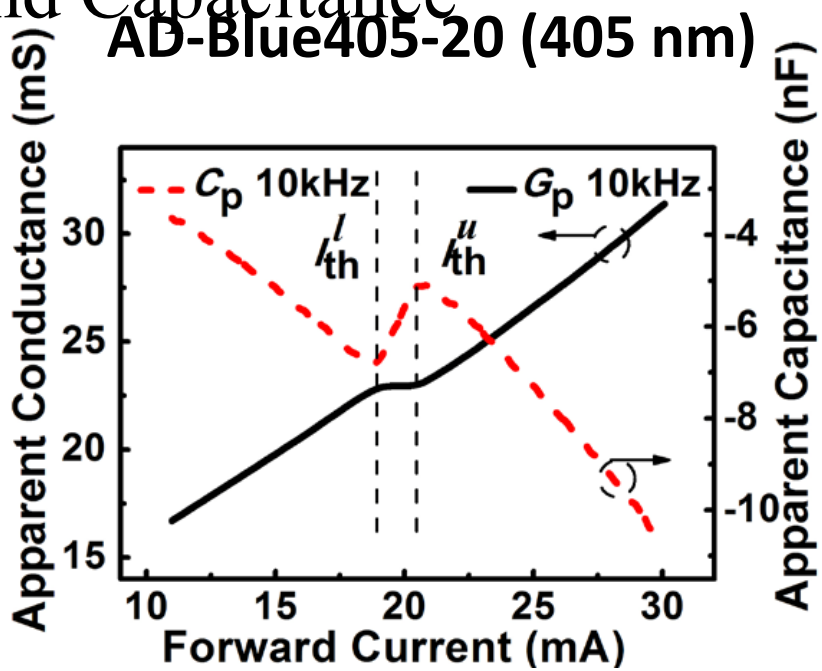


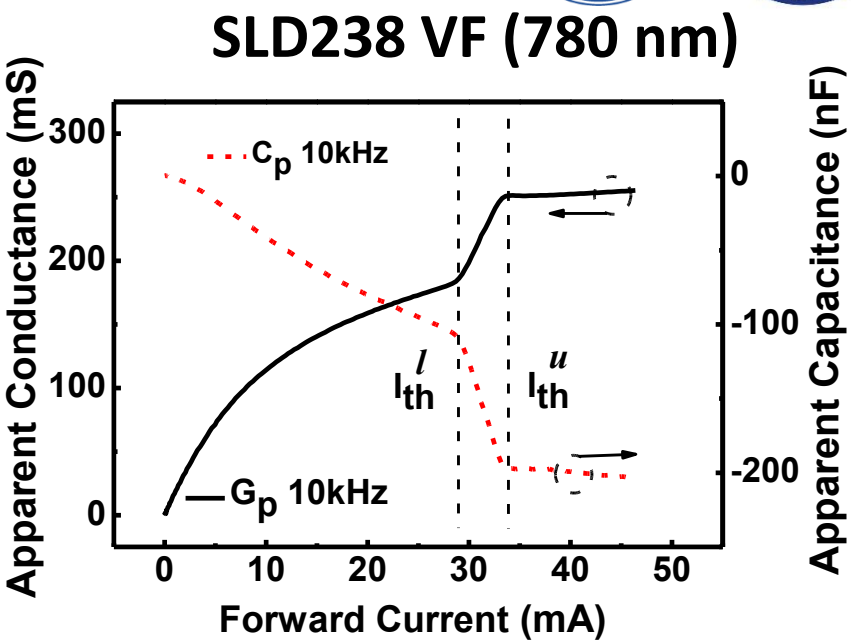
V_j corresponds to the separation of quasi-Fermi level for Holes and electrons

$$E_{fc} - E_{fv} >> h\nu$$

Inversion of populations

Anomalous changes of Apparent Conductance and Capacitance





GaN LDs

GaAs LDs

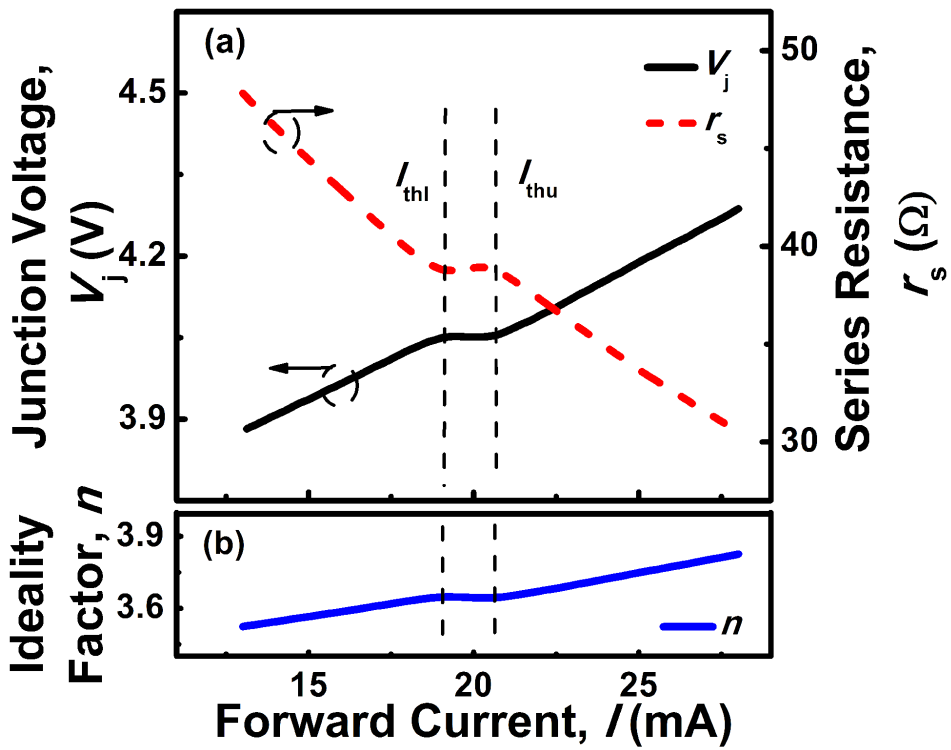
A temporary "saturation" ← G_p → **A jump**

A jump ← C_p → **A drop**

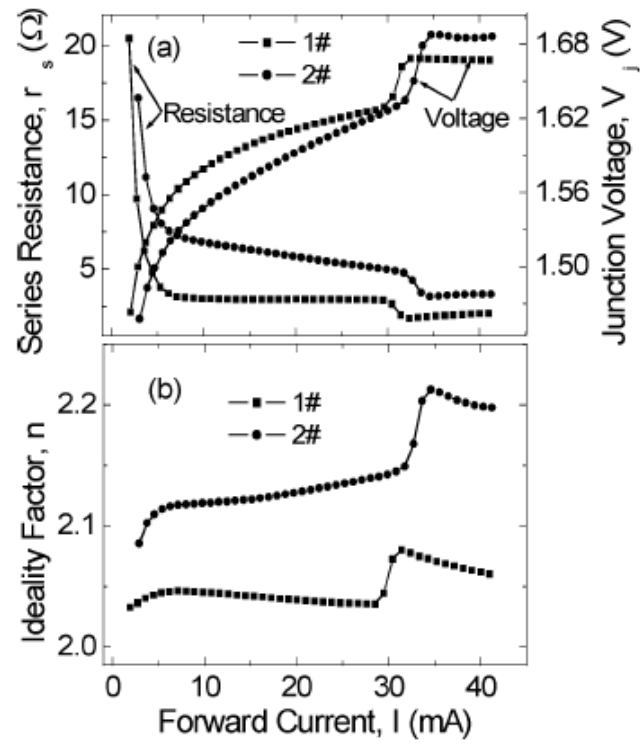
D. Li *et al*, APL, 123501, 2013

Electrical Parameters vs Current

AD-Blue405-20 (405 nm)



SLD238 VF (780 nm)



L. F. Feng *et al*, IEEE *JQE*-43, 2007

Threshold
Temporary
"pinning"
(or drop)

Junction voltage V_j

Series resistance r_s

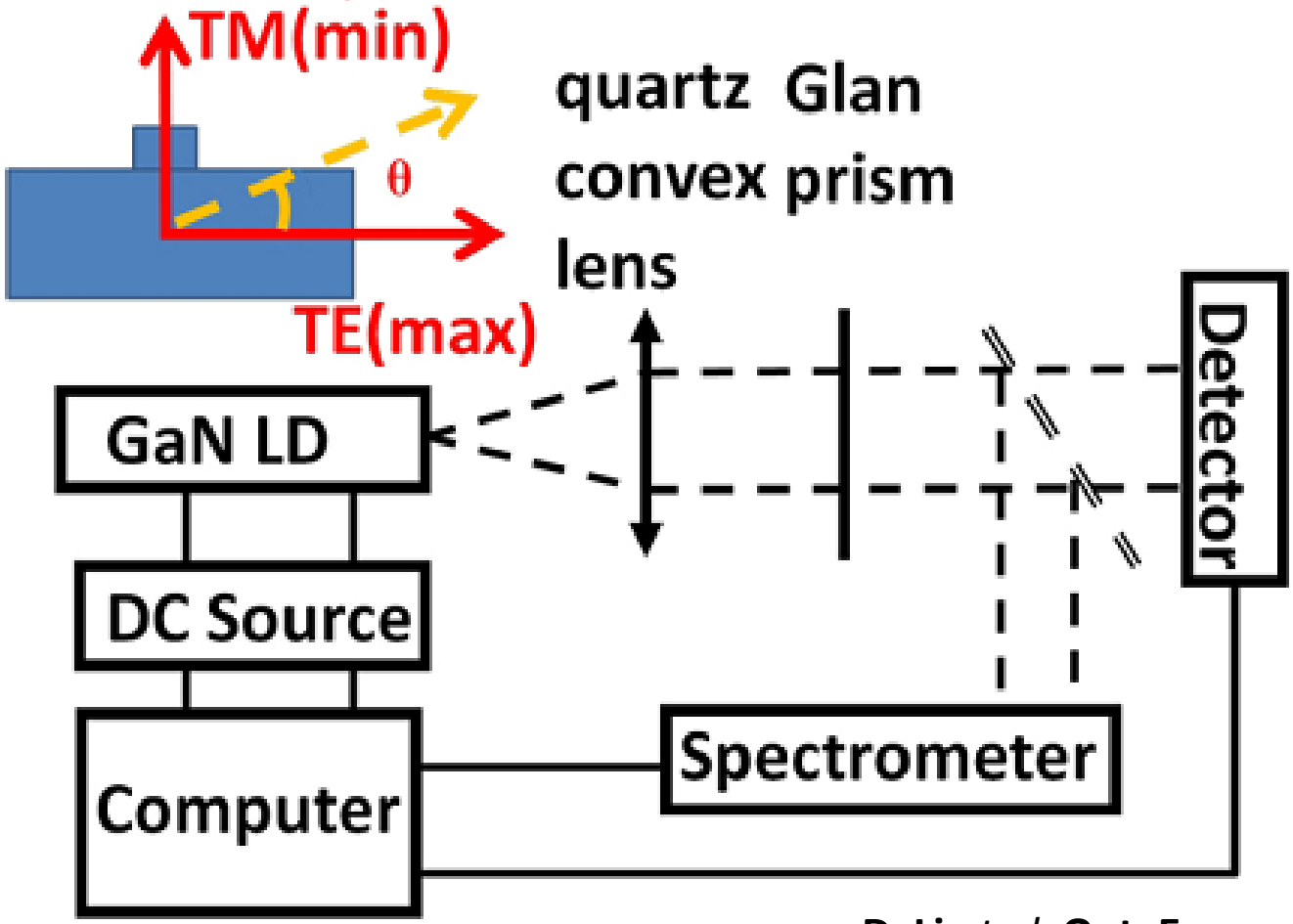
Ideality factor n

Threshold
Sudden
changes

D. Li *et al*, APL, 123501, 2013

Optical properties of GaN-Based LD

Experiment setup



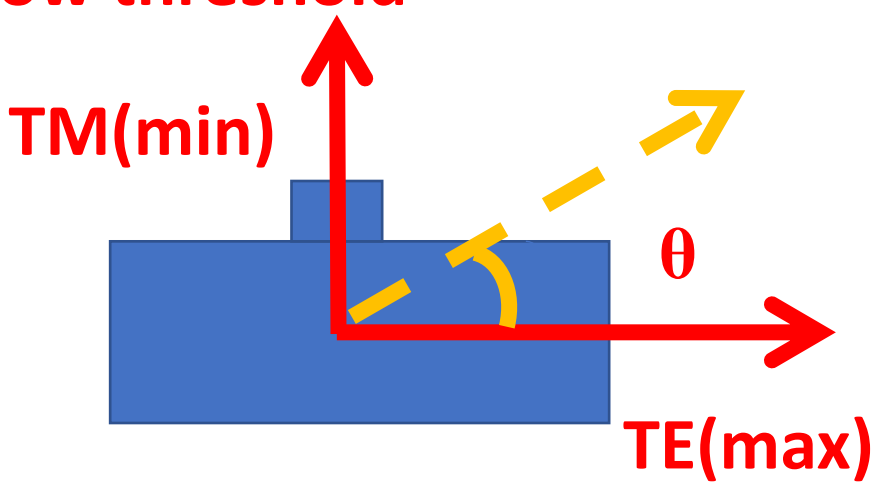
D. Li *et al*, Opt. Express, 2536, 2014

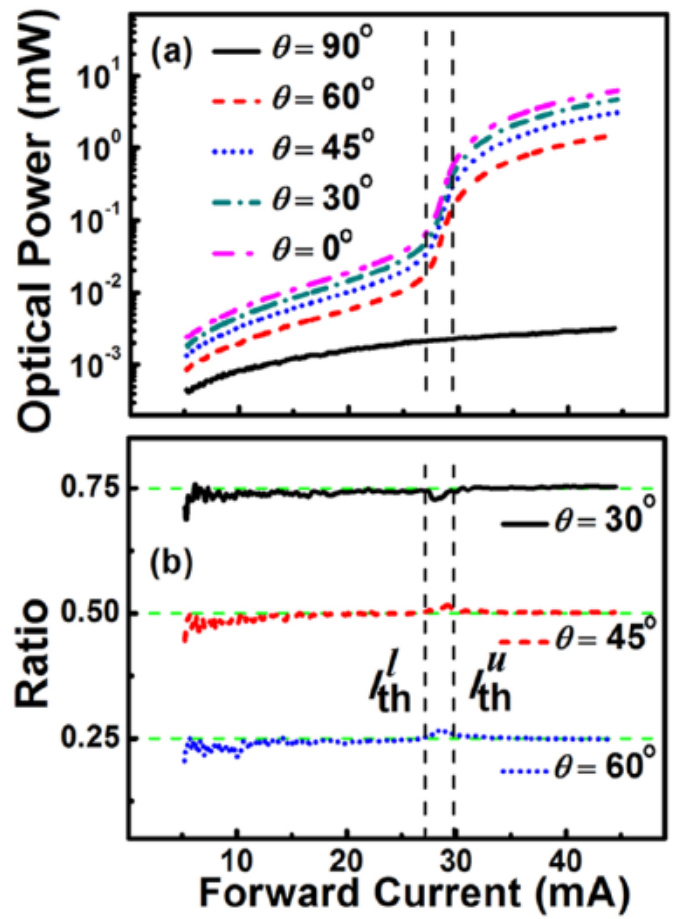
Ratio of Optical Power at different polarization angles

Ratio=(P_θ-P_{min}) /(P_{max}-P_{min})

Ratio=(P_θ-P_{min}) /(P_{max}-P_{min}) =$\cos^2\theta$

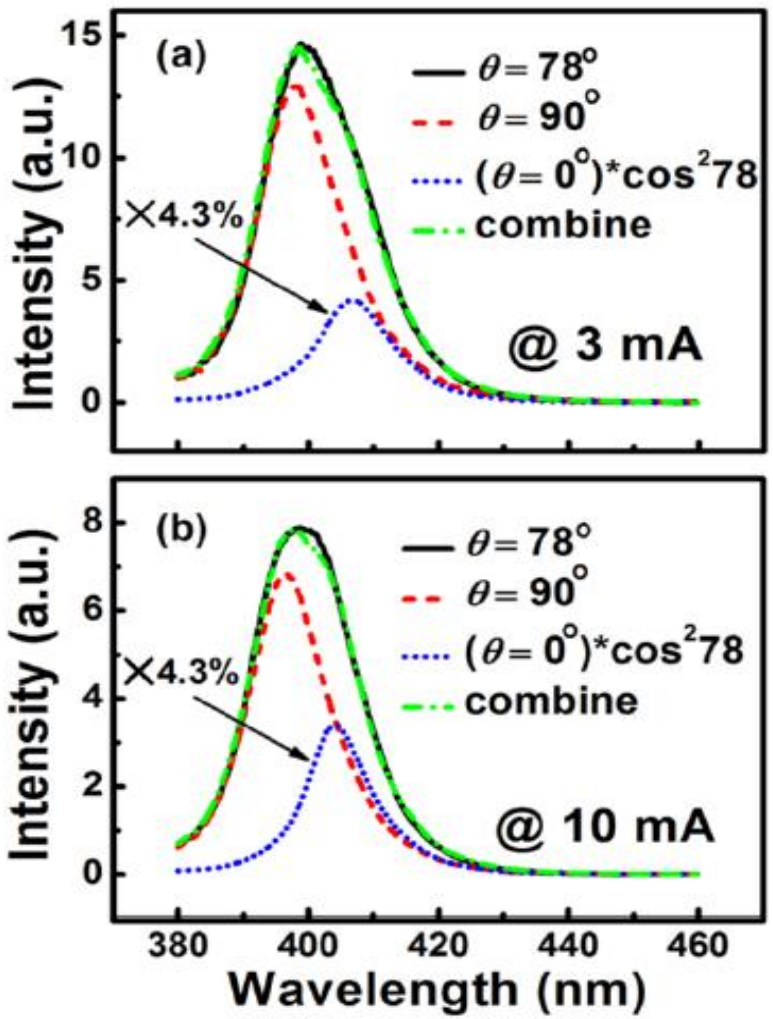
Highly polarized emission blow threshold





D. Li *et al*, Opt. Express, 2536, 2014

Optical Spectra at different polarization angles

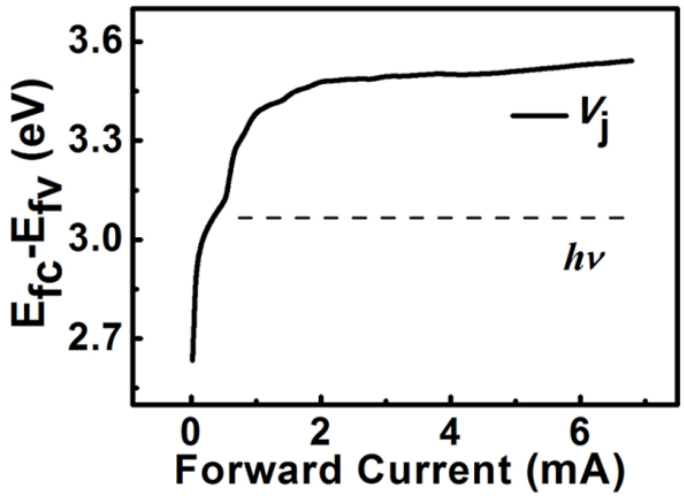


Stimulated emission attenuation $Cos^2 78=0.04$

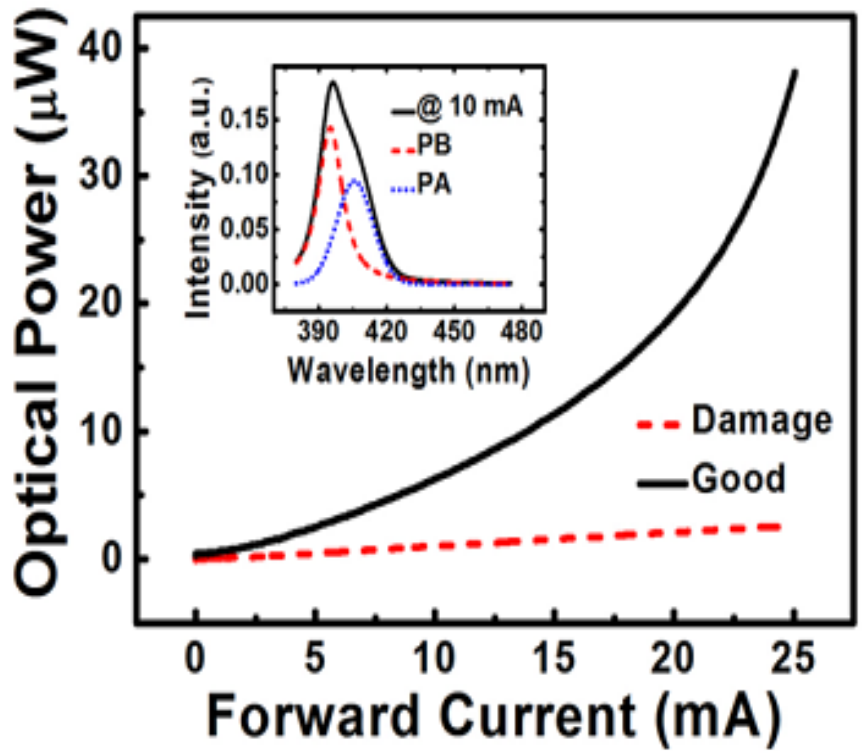
The spectra collected along cavity exhibited two types of polarity. The combination (dot dash) of spectra at θ = 90° (dash) and at θ = 0° (with attenuation of cos278° about 4.3%, dot) is identical to the one recorded at θ = 78° (solid). The one with lower energy is dominate emission when injection below the threshold. (a) at 3mA and (b) at 10 mA

D. Li *et al*, Opt. Express, 2536, 2014

Optical Properties after damage mirrors



the separation of quasi-Fermi levels of electrons and holes across the active region has already reached the population-inversion



Spontaneous+Stimulated

Below the threshold region

The stimulated emission is closely related to resonant cavity and increases super-linearly with current.

D. Li *et al*, Opt. Express, 2536, 2014

Acknowledgements

- Thanks to great supports from Prof. Zhong Lin Wang
- Thanks to co-operation with
- Cunda Wang,[1,2] Wei Yang,[1] Xiufang Yang,[2] Liefeng Feng,[2] Markus Weyers,[3] Bo Shen,[1] Guoyi Zhang,[1] and Xiaodong Hu[1]
- [1]State Key Laboratory for Artificial Microstructure and Mesoscopic Physics, School of Physics, Peking University, Beijing 100871, People's Republic of China

  [2]Tianjin Key Laboratory of Low Dimensional Materials Physics and Preparing Technology, Faculty of Science, Tianjin University, Tianjin 300072, People's Republic of China

  [3]Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik, Gustav-Kirchhoff-Straße 4, Berlin12489, Germany
- National Natural Science Foundation of China (Grant No. 51432005, 5151101243, 51561145021, 61804010, 51605033)
- the International Postdoctoral Exchange Fellowship Program of China under No. 20130042.

Content

- **Introduction for Dr. Ding Li**
- **The third-generation semiconductor and the Piezo-Phototronics**
- **Inter-atomic Electron-transition Induced Photon Emission in Contact-electrification (CEIIS)**
- **Welcome to BINN, CAS**

Contact Electrification (CE) is everywhere

From NASA @https://science.nasa.gov/universe/star-clusters-inside-the-universes-stellar-collections/

星云

光年尺度

From 国科大张京科老师摄影作品

闪电

千米尺度

蜜蜂采蜜

微米尺度

History of CE

Contact-electrification (triboelectrification)

Known for 2600 years and experienced every second, but not fully understood!!!

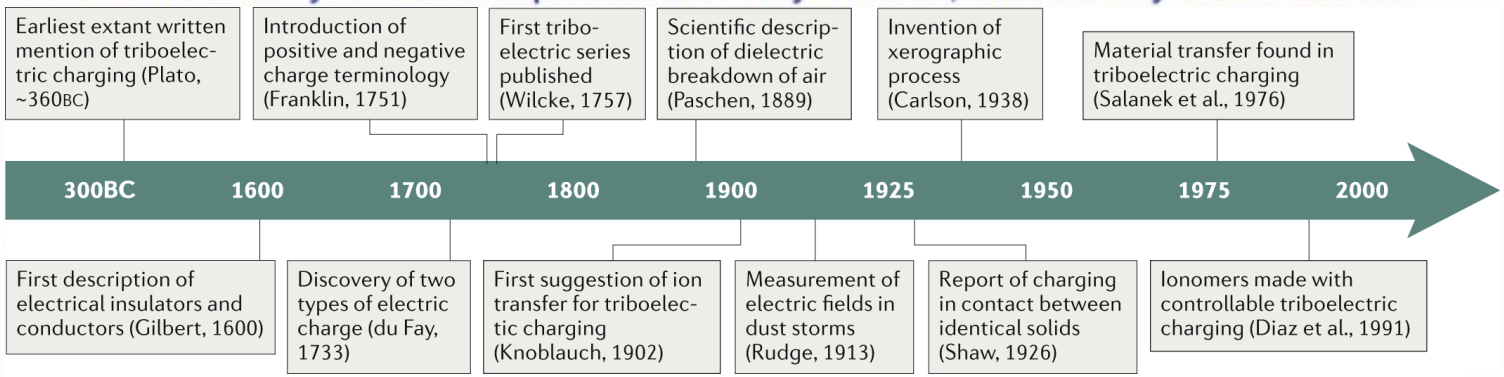


Fig. 1 | **Timeline of major developments in the history of triboelectric charging.** Triboelectric charging has been observed since antiquity, but the root causes of the phenomenon are still not completely understood.

Lacks, Nature Rev. Chemistry, https://doi.org/10.1038/s41570-019-0115-1

Happens

- Solid-solid
- Liquid-solid
- Liquid-liquid
- Gas-liquid
- Gas-solid

Due to:

- Electron transfer
- Ion transfer
- Materials species transfer

A slide from Prof. Z. L. Wang

Difficulties in CE Explorations

❖ Why is the elementary-school phenomenon of triboelectric charging so poorly understood and why do deeper investigations seem to provide less, rather than more, clarity?

- First, macroscopic effects originate from rare events, making their theoretical description and experimental observation challenging.
- Second, charging depends strongly on surface morphology.
- Third, all of the phenomena involved are intrinsically non-equilibrium because neither tribocharging nor discharge appear in an equilibrium state.
- Finally, any contact between surfaces typically involves making and breaking of bonds through mechanisms that are themselves not well understood.

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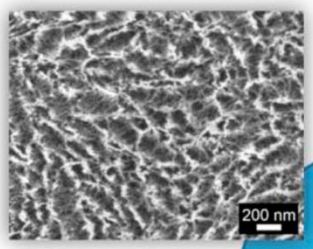
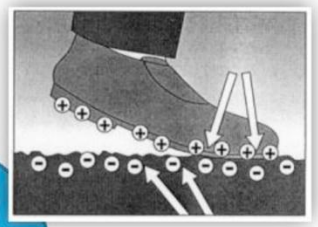
Other Important factors



Surface structure A



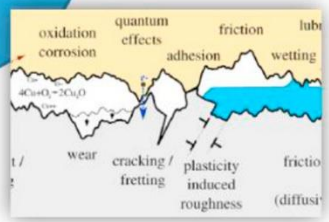
Triboelectric surface charge density σ_T

Maxwell's displacement current

$$I = A\,\sigma_T \frac{dH}{dt} \frac{d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2}{[d_1\varepsilon_0/\varepsilon_1 + d_2\varepsilon_0/\varepsilon_2 + z]^2}$$

Dielectric property ε

Materials robustness

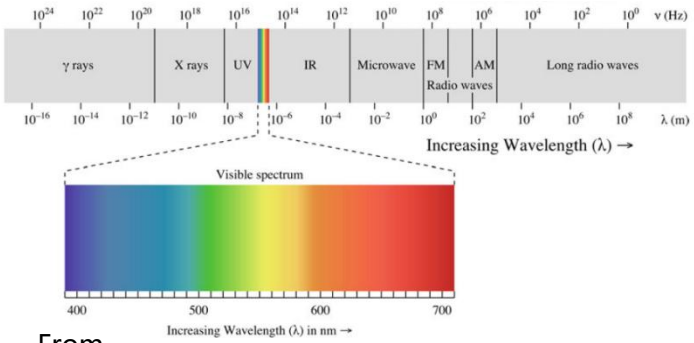


Zhong Lin Wang, Nano Energy, 68(2020)104272

Photon in CE？

闪电

From 国科大张京科老师摄影作品



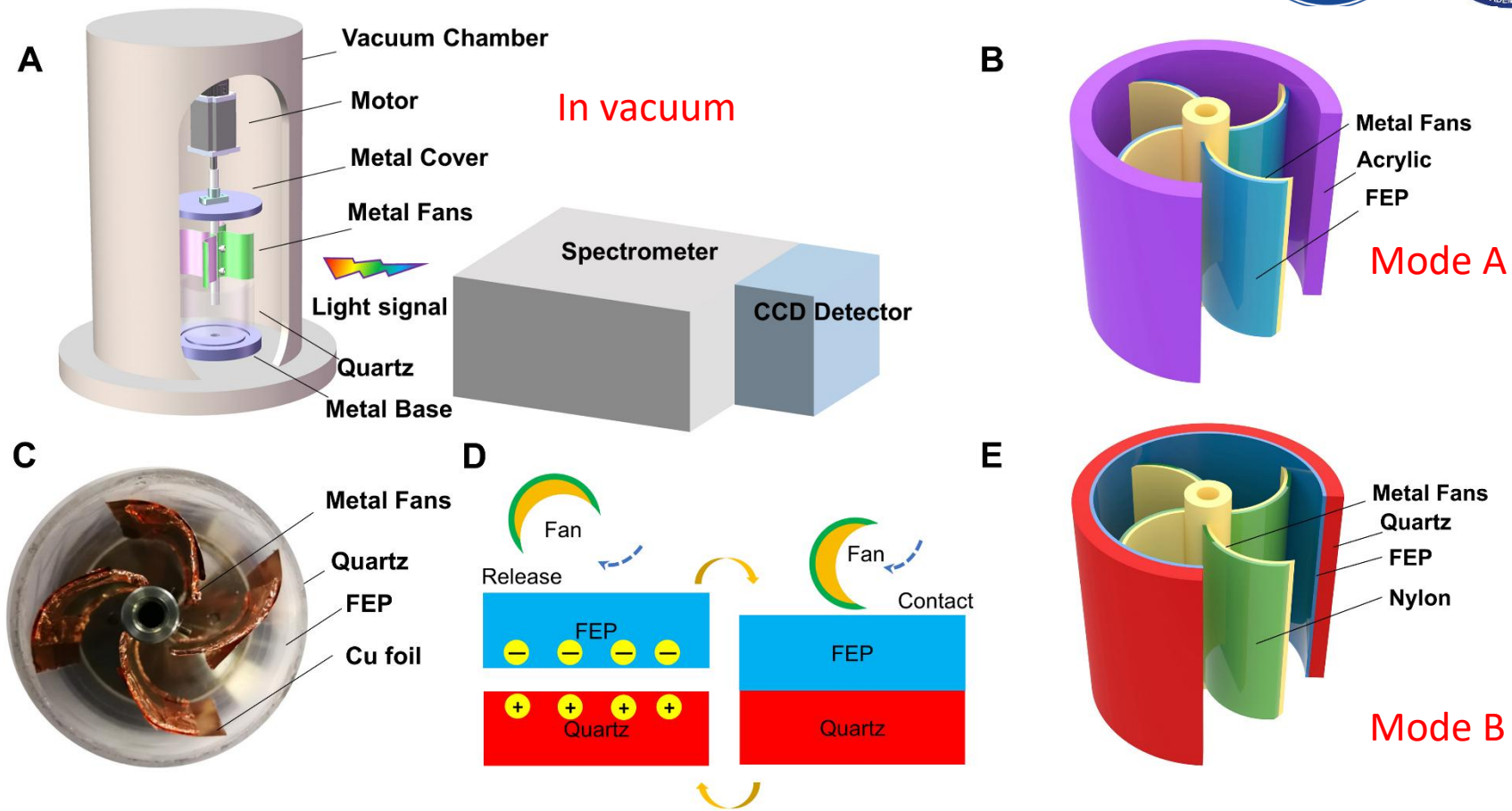
From http://en.wikipedia.org/wiki/Electromagnetic_radiation

蜜蜂采蜜

CE过程中有光么？
能传递什么信息？

光能传递信息

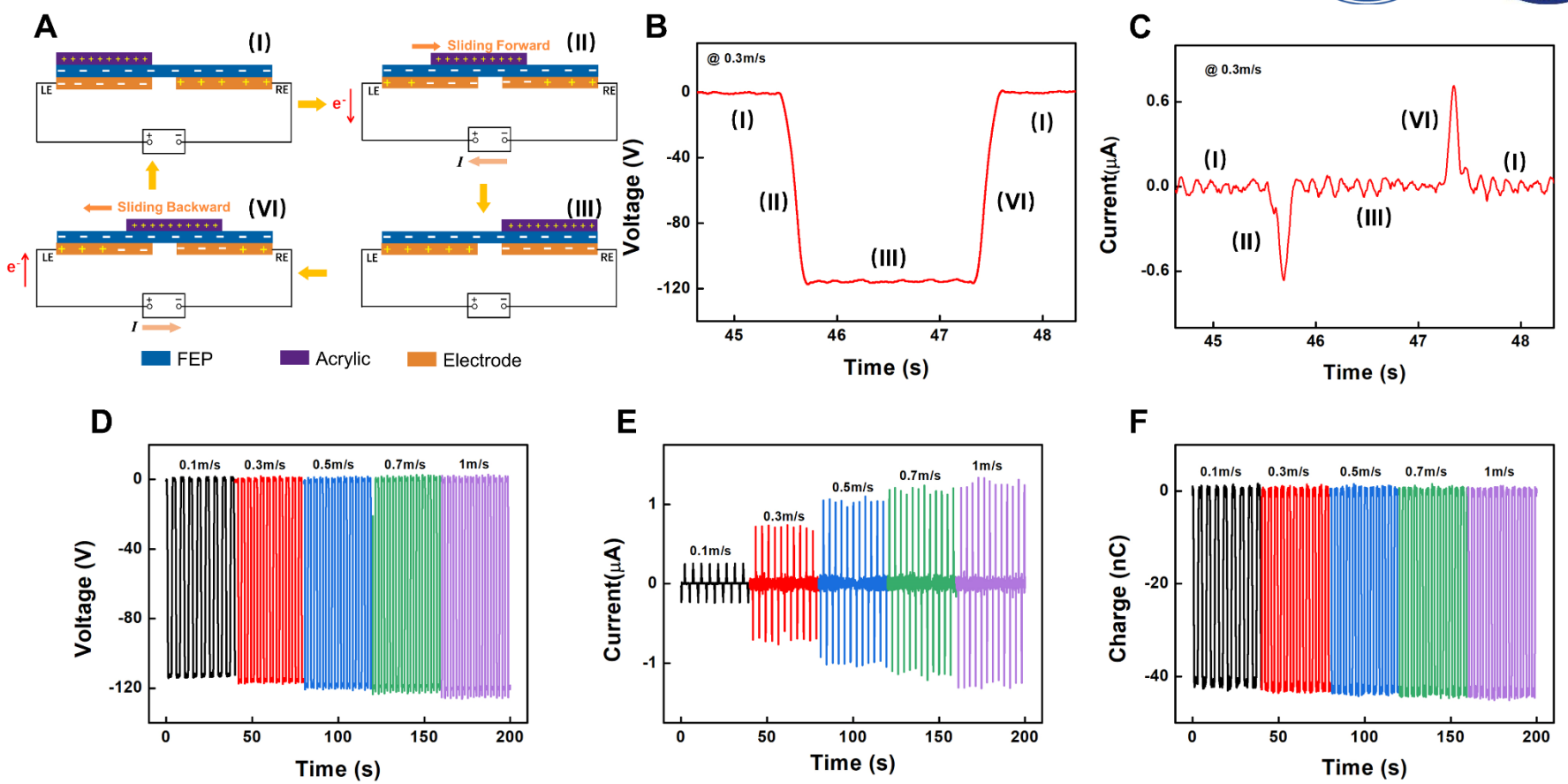
CEIIS-experimental setup



In vacuum: carefully excluded the features contributed by air discharge.
Mode A: FEP on fans and directly contact with quartz or acrylic.
Mode B: FEP attached to quartz or acrylic with nylon, etc. on fans.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-Charge situation

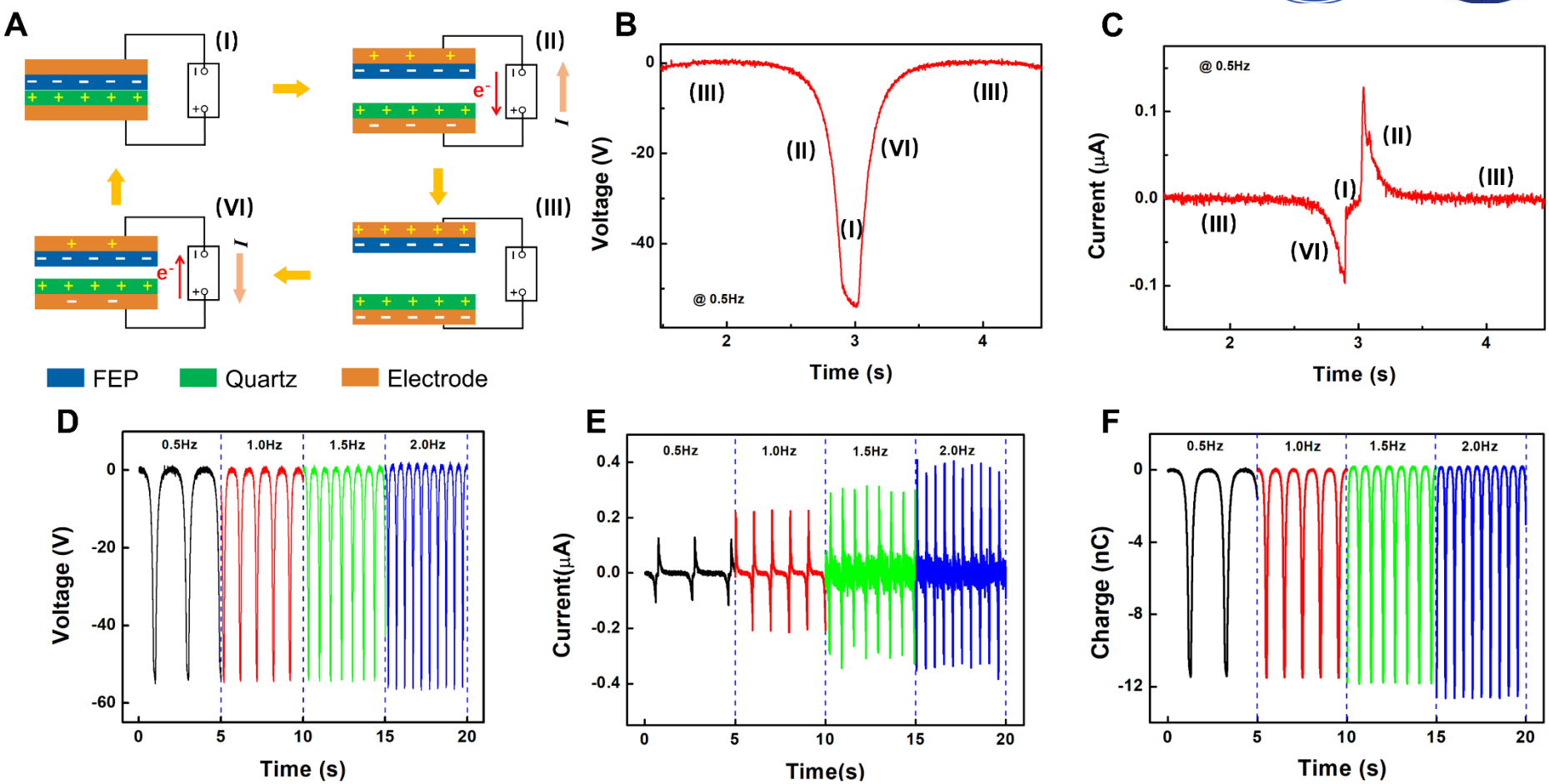


TENG as a probe.

FEP : negatively charged.

Acrylic: positively charged.

CEIIS-Charge situation

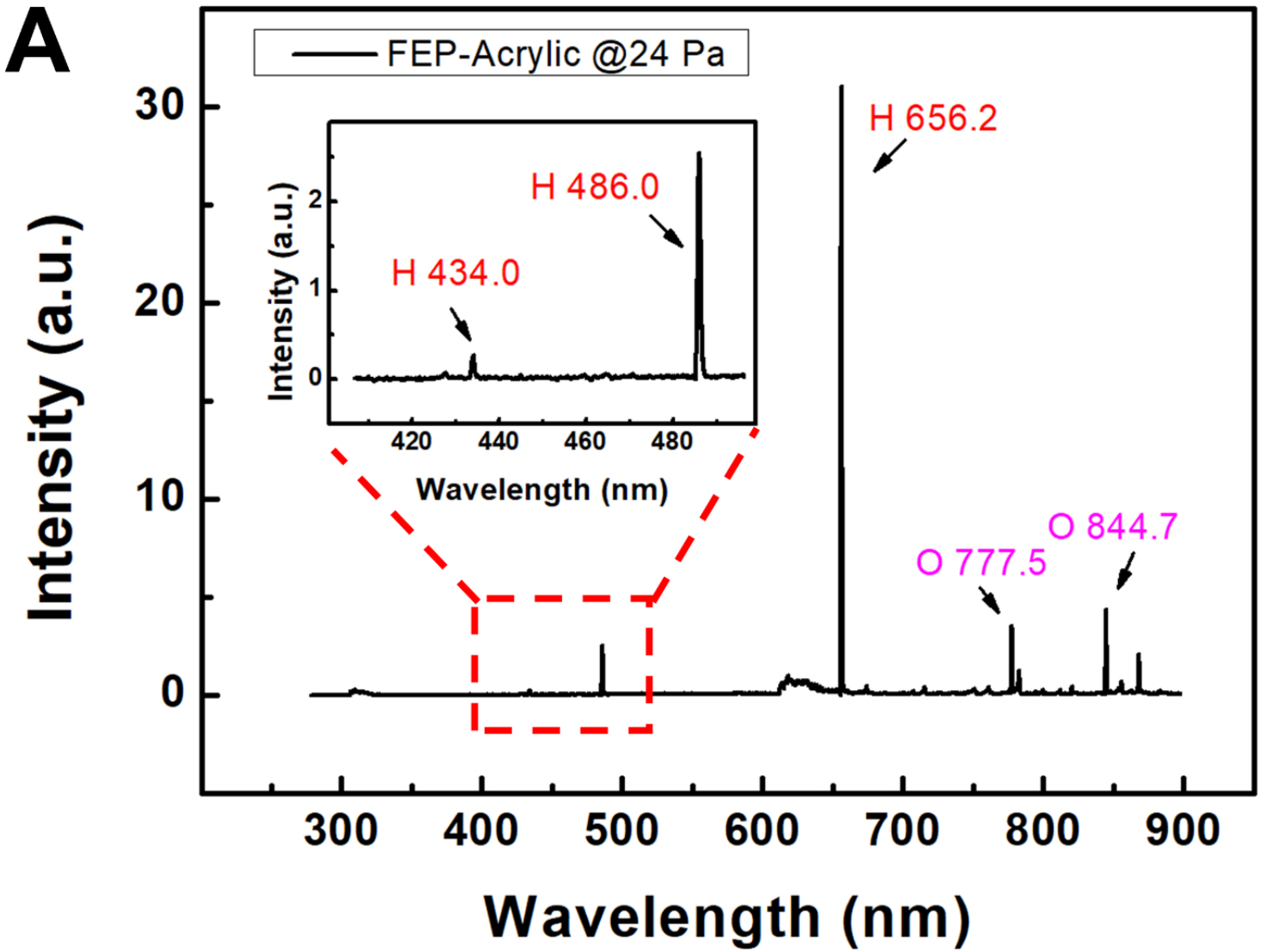


TENG as a probe.

FEP : negatively charged.

Quartz: positively charged.

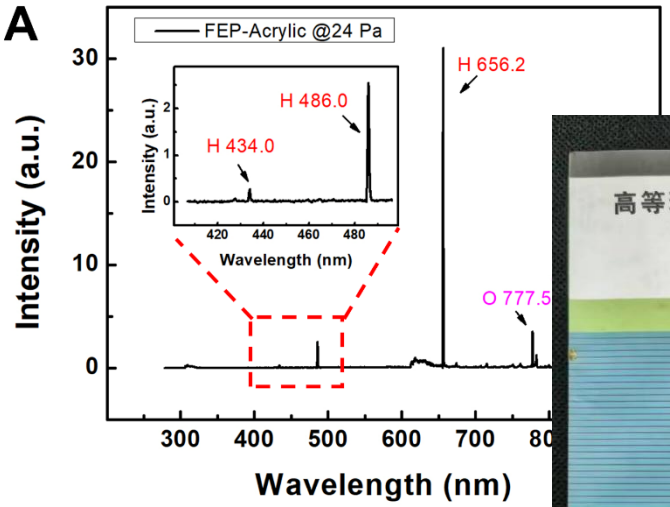
CEIIS-Atomic featured spectra

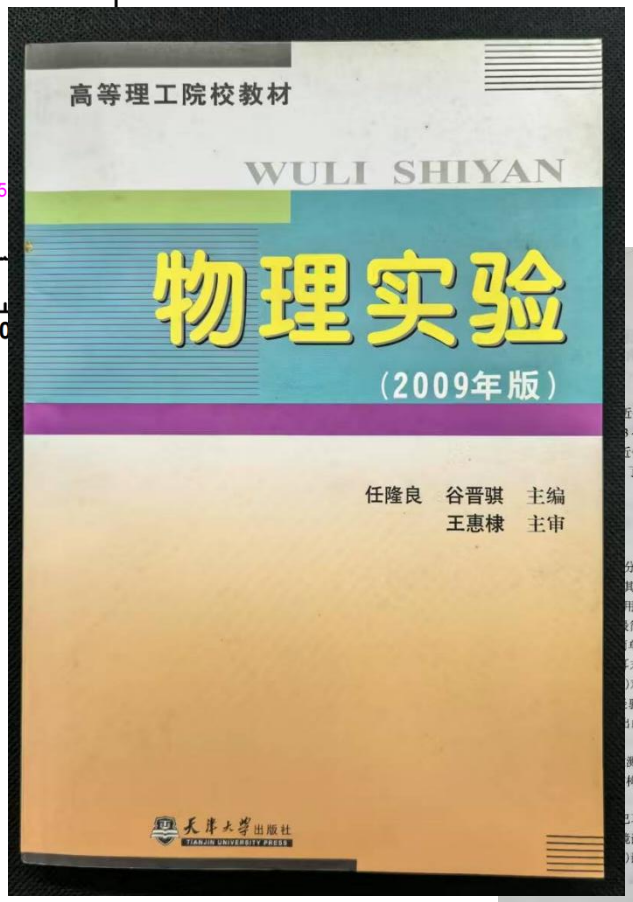


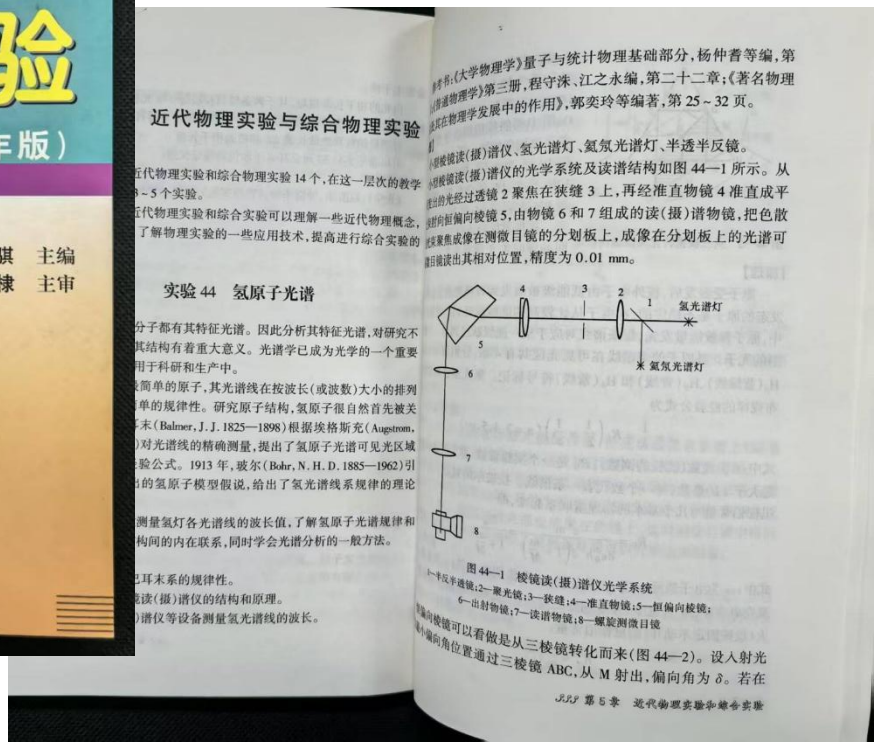
- Sharp Lines
- Discrete Distribution

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-Atomic featured spectra



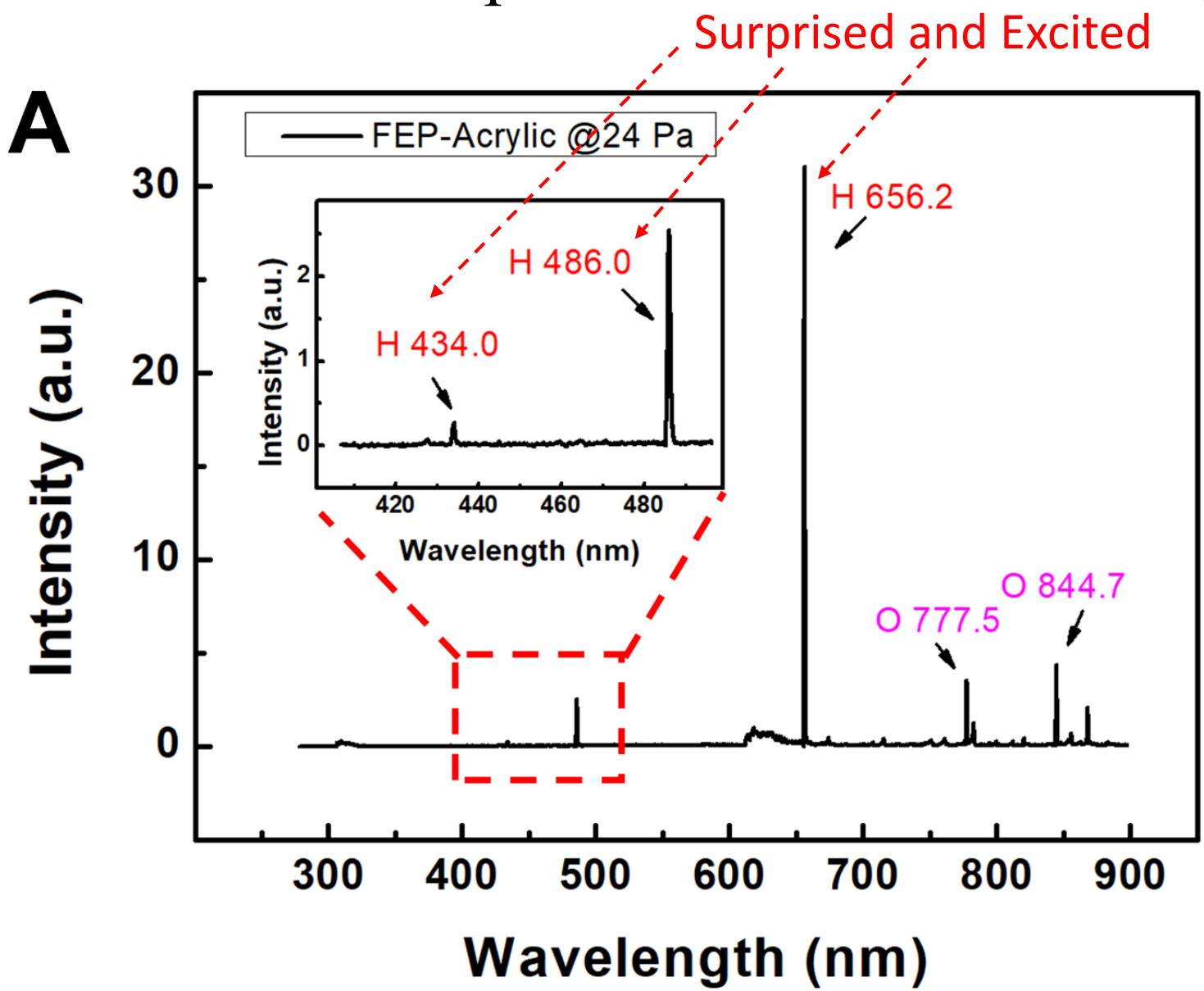




- Sharp Lines
- Discrete Distribution

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-H atom spectra

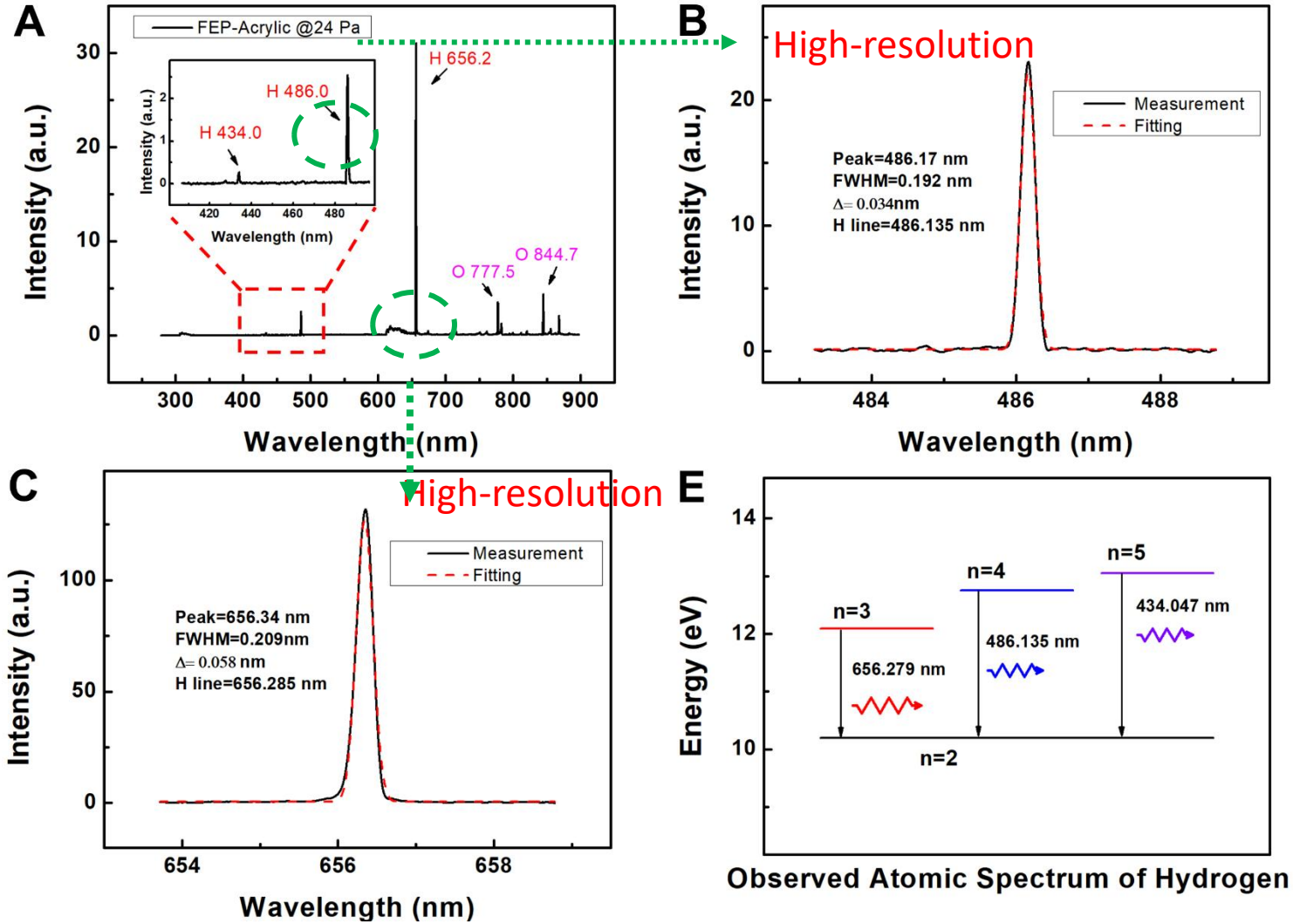


Atomic Spectrum featured

- Sharp Lines
- Discrete Distribution

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-H atom spectra identification



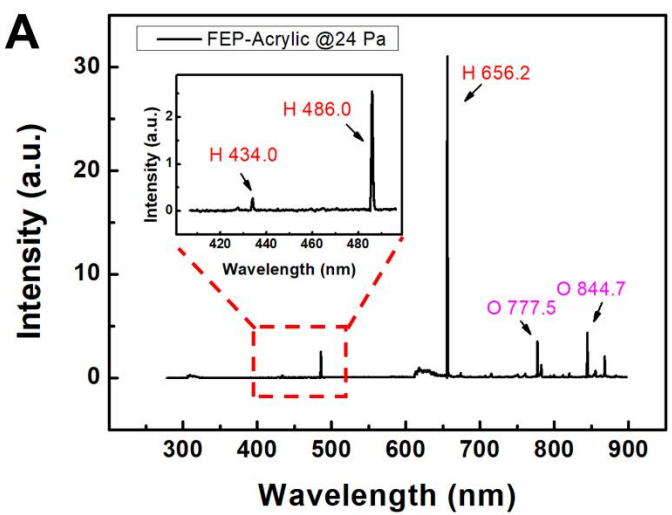
Atomic Spectrum featured

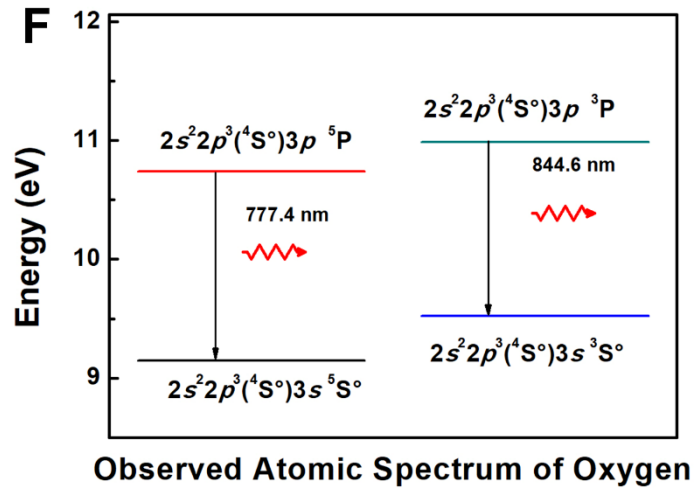
H atom spectra

H atom Energy Level

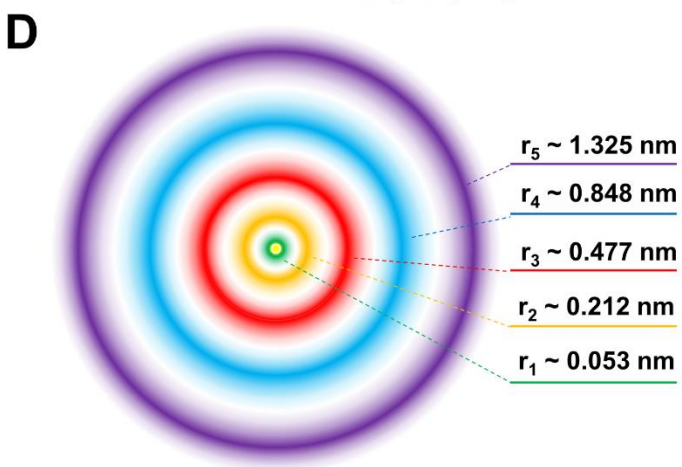
Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

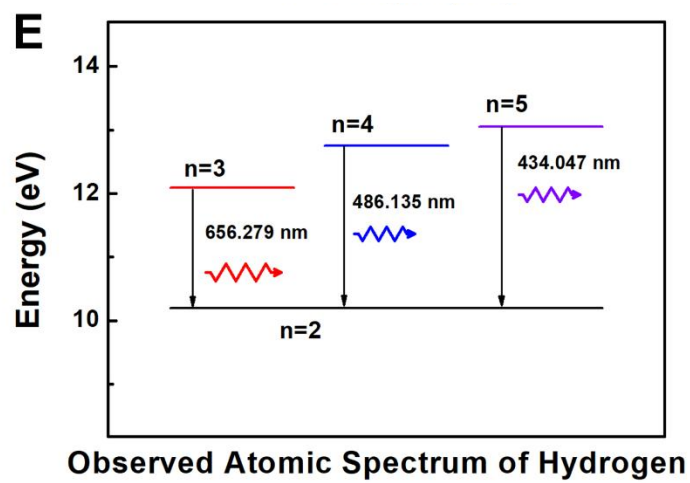
CEIIS-H/O energy levels





O atom Energy Level

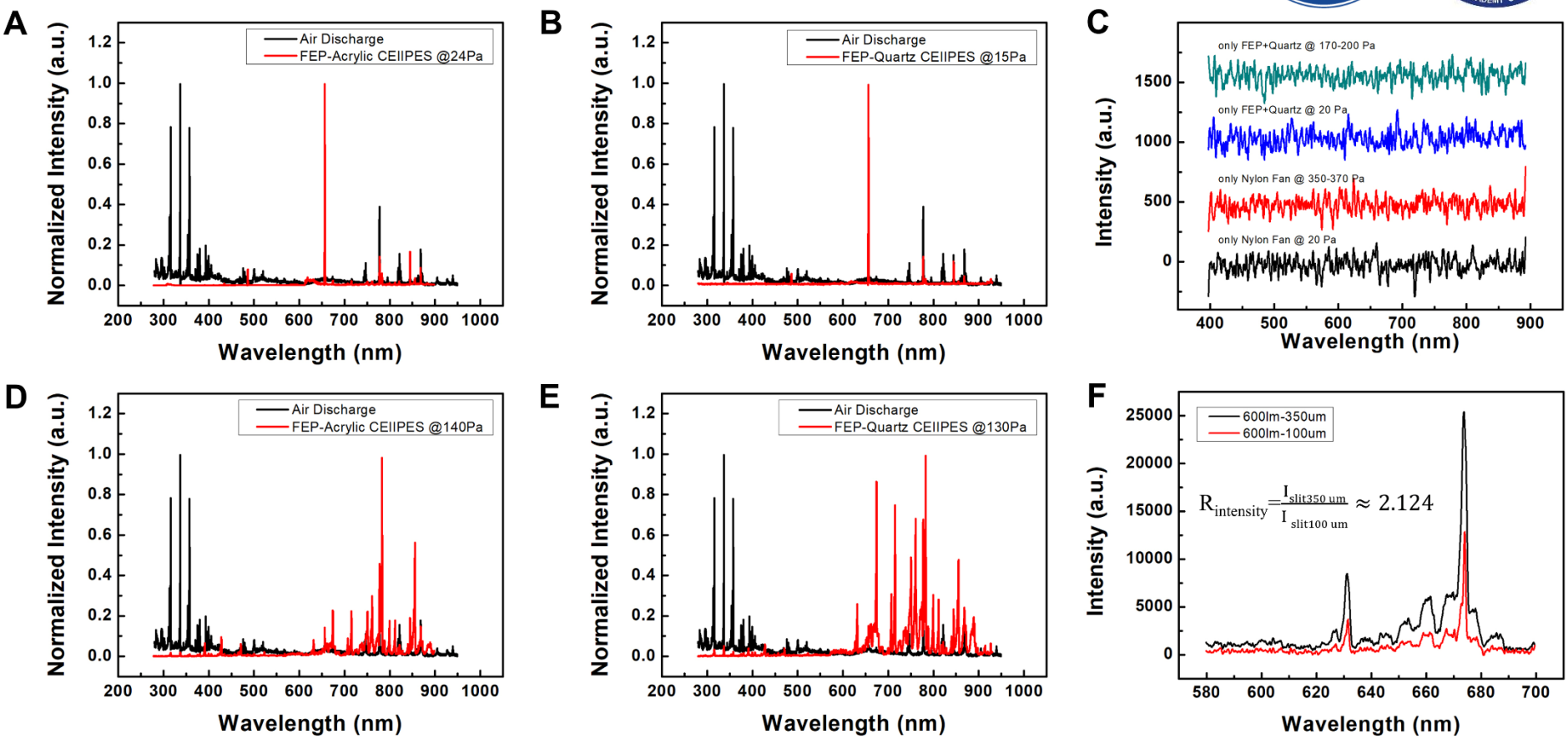




H atom Energy Level

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

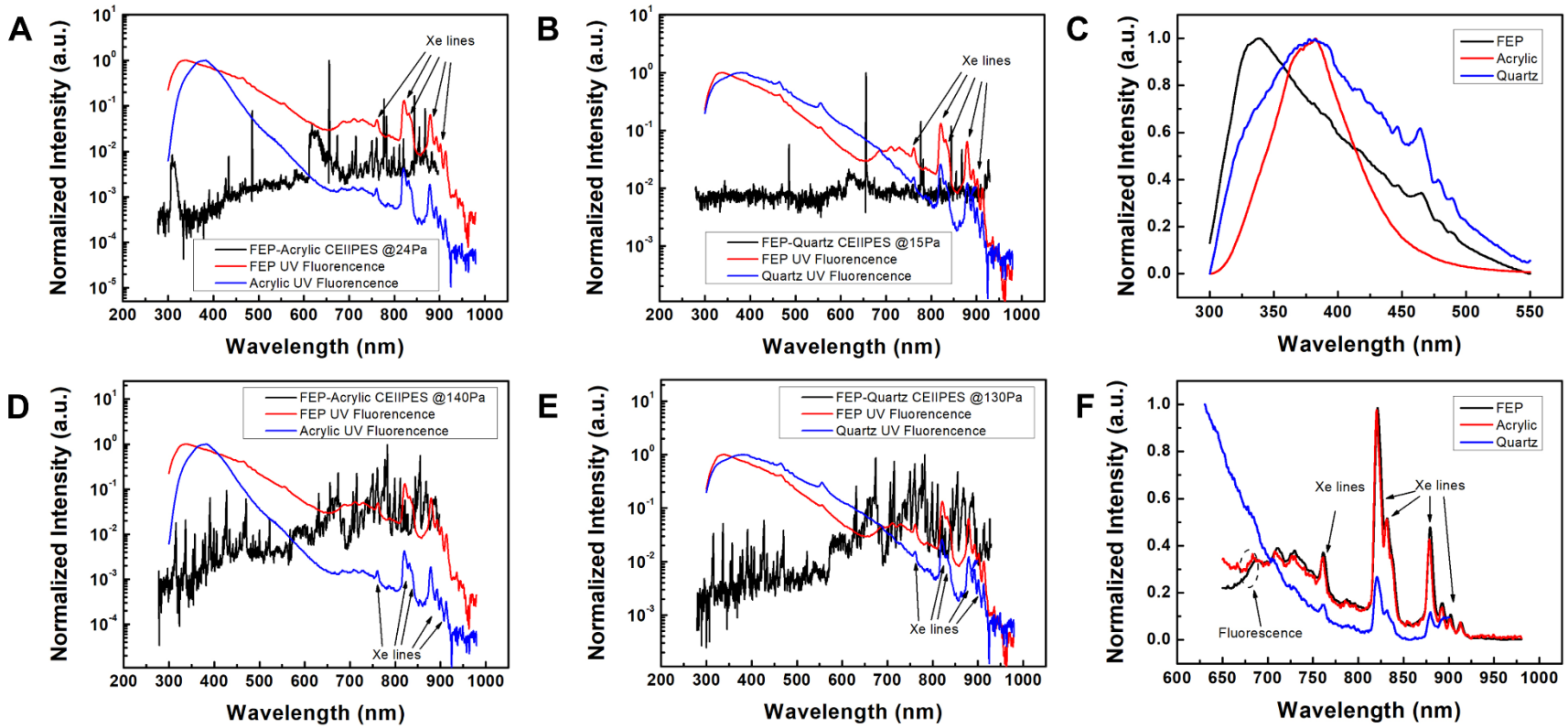
CEIIS-excluded from air discharge



Comparisons between air discharge spectra (black line) and CEIIPES (red line) from FEP-Acrylic group in Model A at 24 Pa (A) and 140 Pa (D), from FEP-Quartz group in Model B at 15 Pa (B) and 130 Pa (E). CEIIPES is different from air discharge spectra. Especially, H atom lines (486 nm and 656 nm) exist in CEIIPES under pressure blow 25 Pa, which do not exist in air discharge spectra.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-excluded from fluorescence

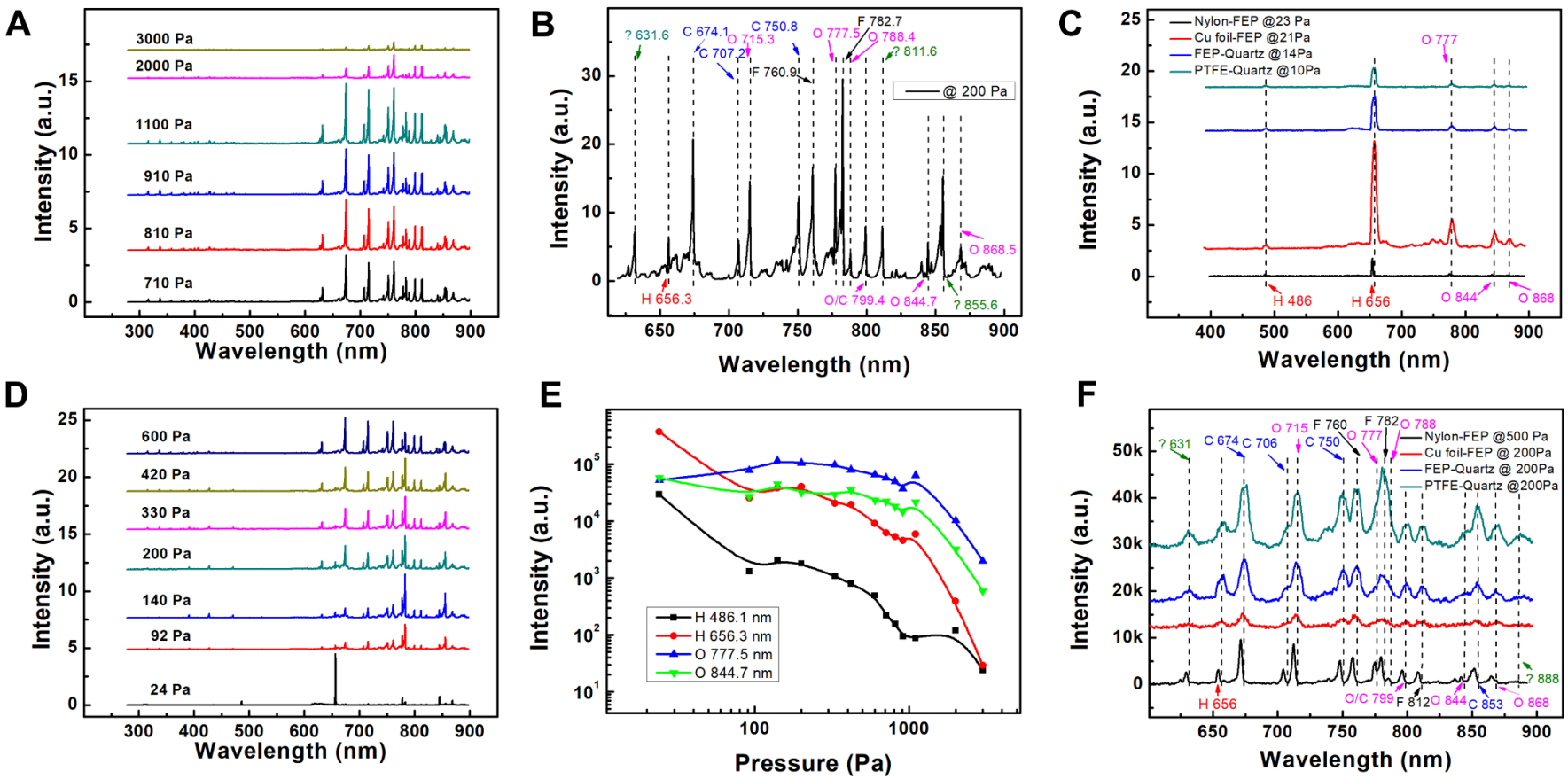


(1) the origins of photon emission: CEIIPES is a photon emission associated with electron transfer between two atoms, while fluorescence spectra are associated with electron transition between molecular levels with many vibrational sublevels.

(2) the spectra features: CEIIPES is discrete atomic featured sharp lines with FWHM less than 1 nm, while fluorescence spectra are normally continuous board bands with FWHM up to tens of nanometers

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-different pressures/contact materials



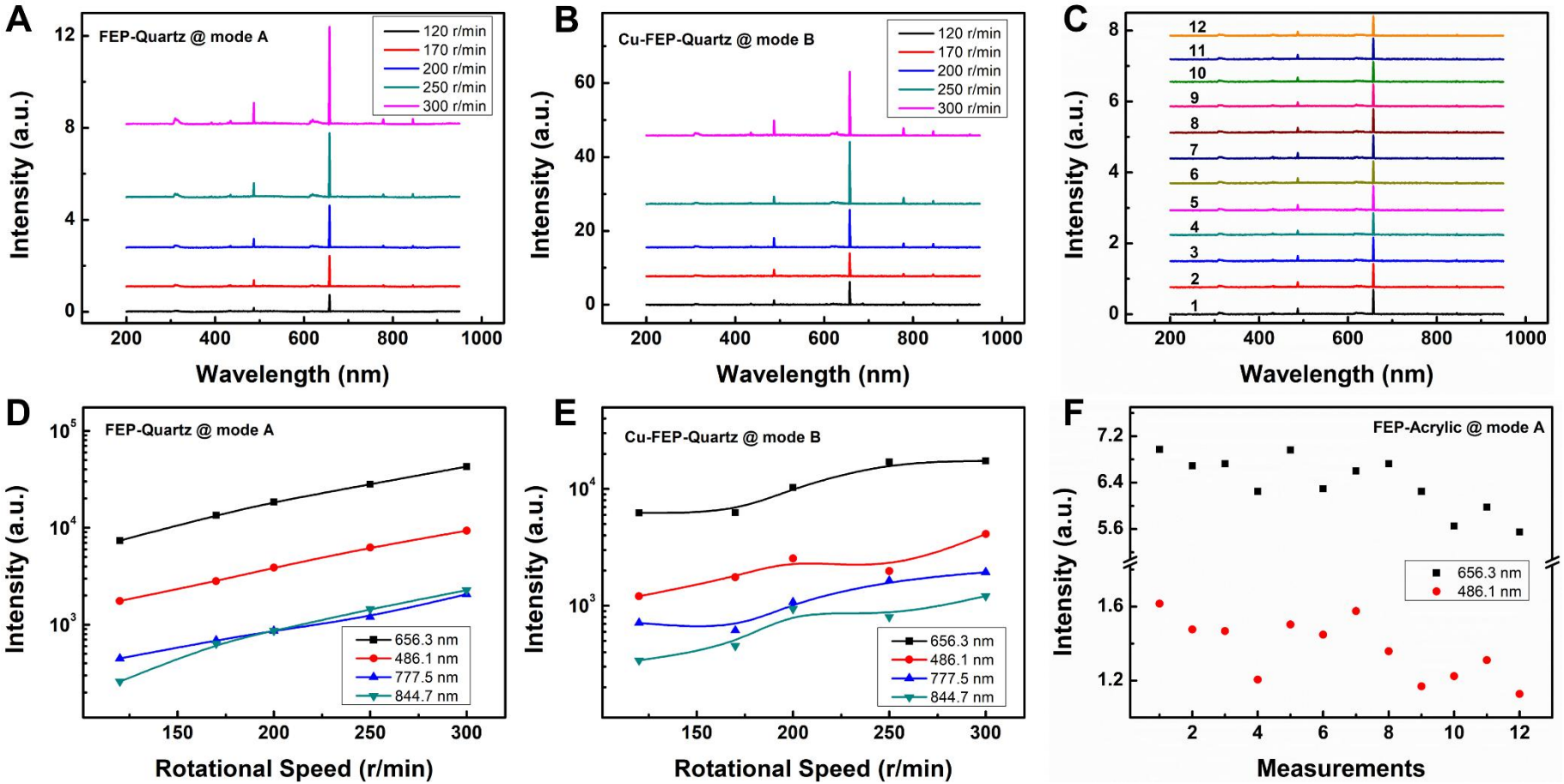
CEIIPES at different pressures for different contact materials groups.

(A and D) CEIIPES of the FEP-acrylic group at different atmosphere pressures

(C and F) CEIIPES of different groups at different atmosphere pressures with identifications of atomic lines.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-reproduceable



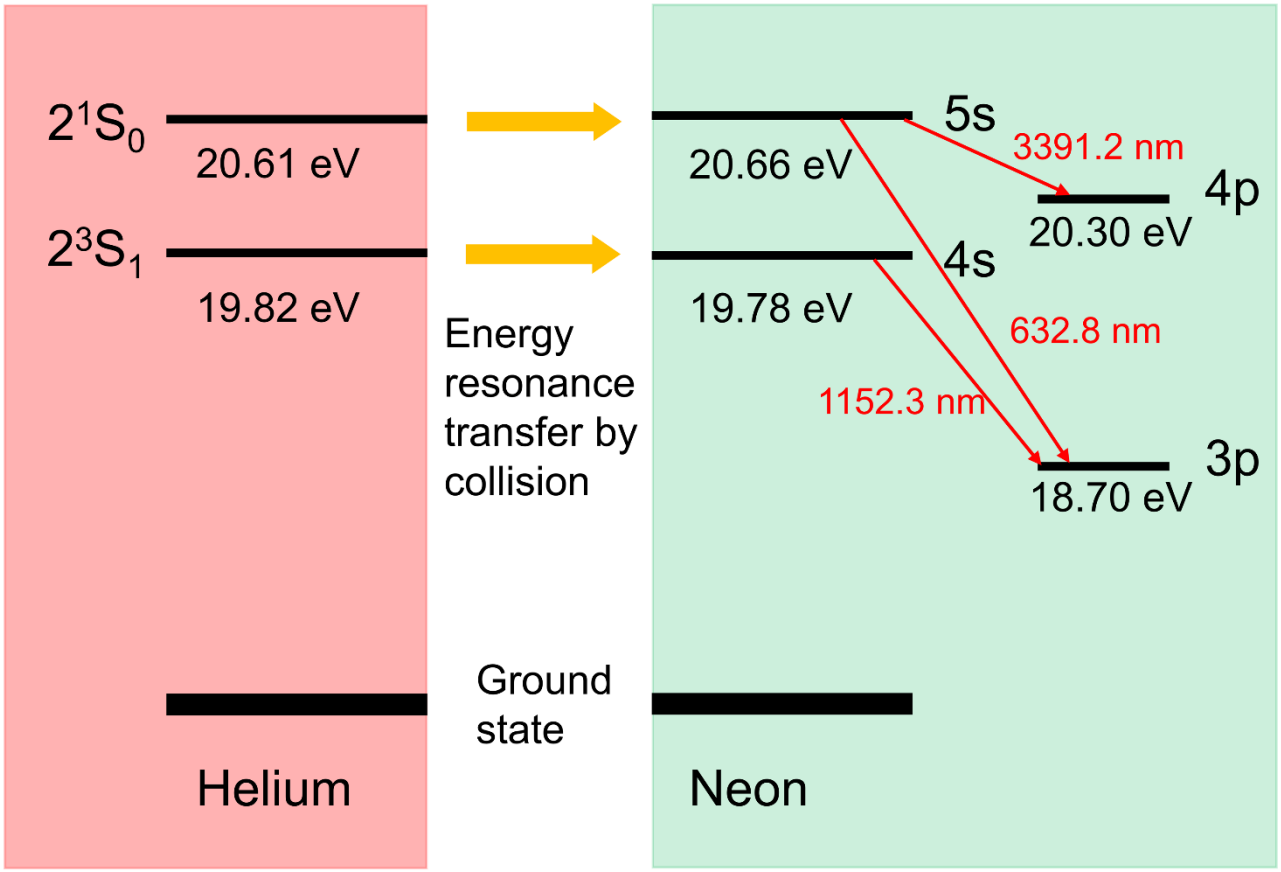
CEIIS-list of identified peaks

Supplementary Note III A Table List of Strong Atomic Lines We Identified at 200 Pa (Fig. 3B)

Table S1. The strong atomic lines we identified at 200 Pa in Fig. 3B

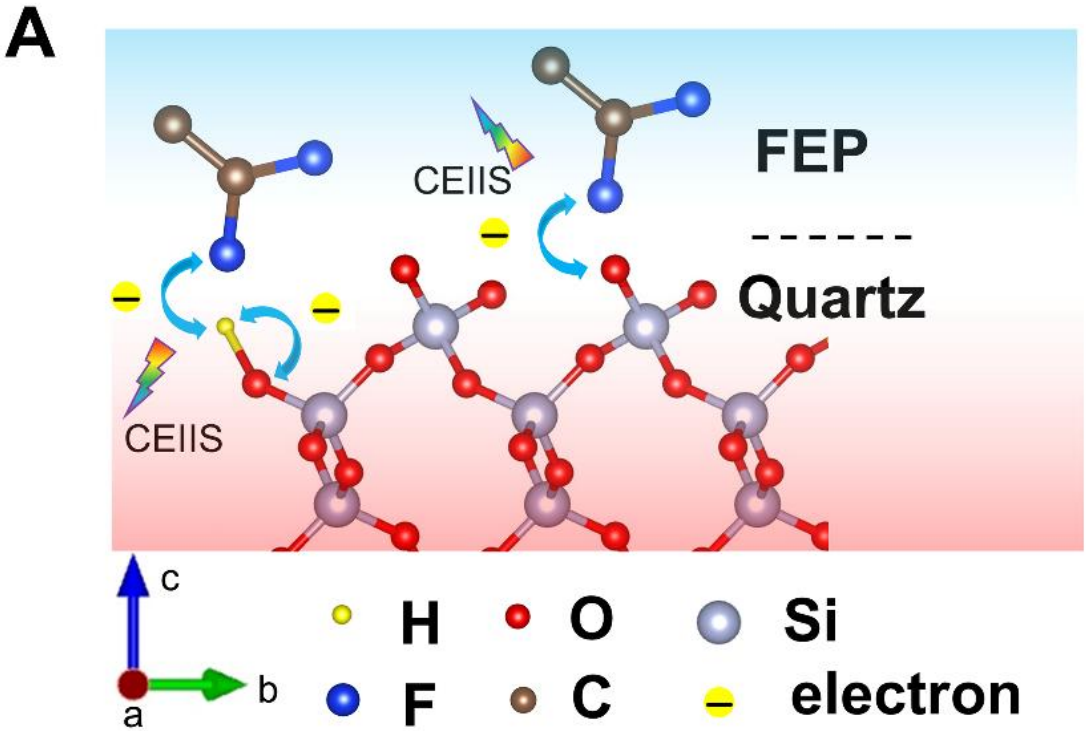
Elements	λ (nm) observed	λ (nm) standard	E_i (cm^{-1})	E_k (cm^{-1})	Lower Level			Upper Level		
					Configuration	Term	J	Configuration	Term	J
H	656.3	656.279	82259.158	97492.304	2			3		
O I	715.3	715.67	102662.026	116631.094	$2s^22p^3(^2D^\circ)3s$	$^1D^\circ$	2	$2s^22p^3(^2D^\circ)3p$	^1D	2
O I	777.5	777.539	73768.2	86625.757	$2s^22p^3(^4S^\circ)3s$	$^5S^\circ$	2	$2s^22p^3(^4S^\circ)3p$	^5P	1
O I	788.4	788.627	115918.143	128594.916	$2s^22p^3(^2P^\circ)3s$	$^1P^\circ$	1	$2s^22p^3(^2P^\circ)3p$	^1D	2
O I	799.4	799.507	88631.146	101135.407	$2s^22p^3(^4S^\circ)3p$	^3P	2	$2s^22p^3(^2D^\circ)3s$	$^3D^\circ$	3
O I	844.7	844.636	76794.978	88631.146	$2s^22p^3(^4S^\circ)3s$	$^3S^\circ$	1	$2s^22p^3(^4S^\circ)3p$	^3P	2
O II	868.5	868.7153	246291.822	257799.93	$2s^22p^2(^3P)4p$	$^4S^\circ$	3/2	$2s^22p^2(^3P)5s$	^4P	3/2
F I	760.9	760.717	104731.05	117872.92	$2s^22p^4(^3P)3s$	^2P	3/2	$2s^22p^4(^3P)3p$	$^2D^\circ$	3/2
F I	782.7	782.259	115917.91	128697.89	$2s^22p^4(^3P)3p$	$^4P^\circ$	5/2	$2s^22p^4(^3P)3d$	^2F	5/2
C I	675.1	675.41	71385.40992	86185.2332	$2s^22p3p$	^3P	2	$2s^22p5d$	$^1D^\circ$	2
C I	707.2	707.4864	69689.49393	83820.1576	$2s^22p3p$	^3D	1	$2s^22p4d$	$^3D^\circ$	1
C I	750.8	750.567	75255.29373	88574.9	$2s2p^3$	$^3P^\circ$	2	$2s^22p(^2P^\circ_{1/2})7f$	$^2[5/2]$	2
C I	799.4	799.342	75255.29373	87762.23	$2s2p^3$	$^3P^\circ$	2	$2s^22p(^2P^\circ_{1/2})6f$	$^2[5/2]$	2

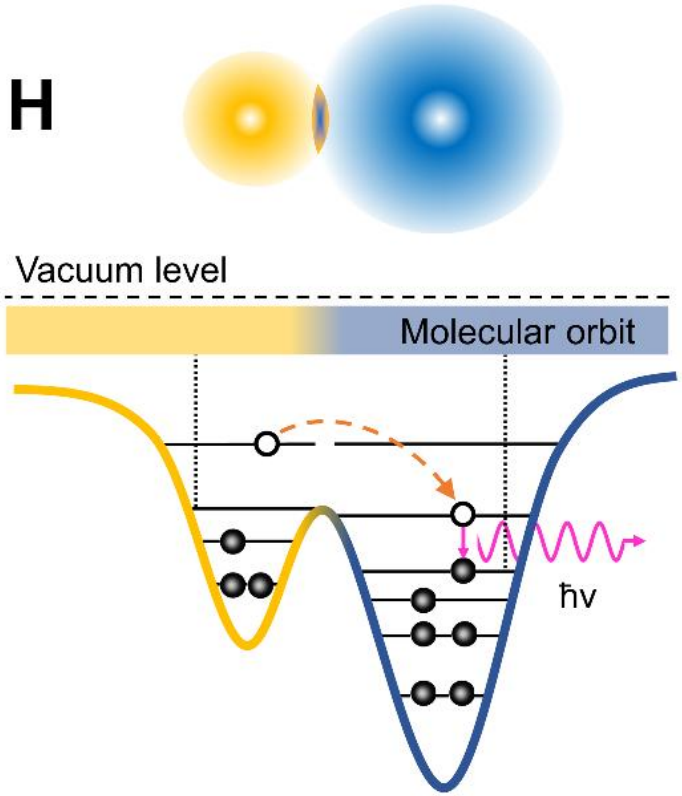
CEIIS-resonance transfer in He-Ne Laser



CEIIS-Interface Electron Transition Processes

During the CE, some of electrons are temporarily transmitted to excited states.



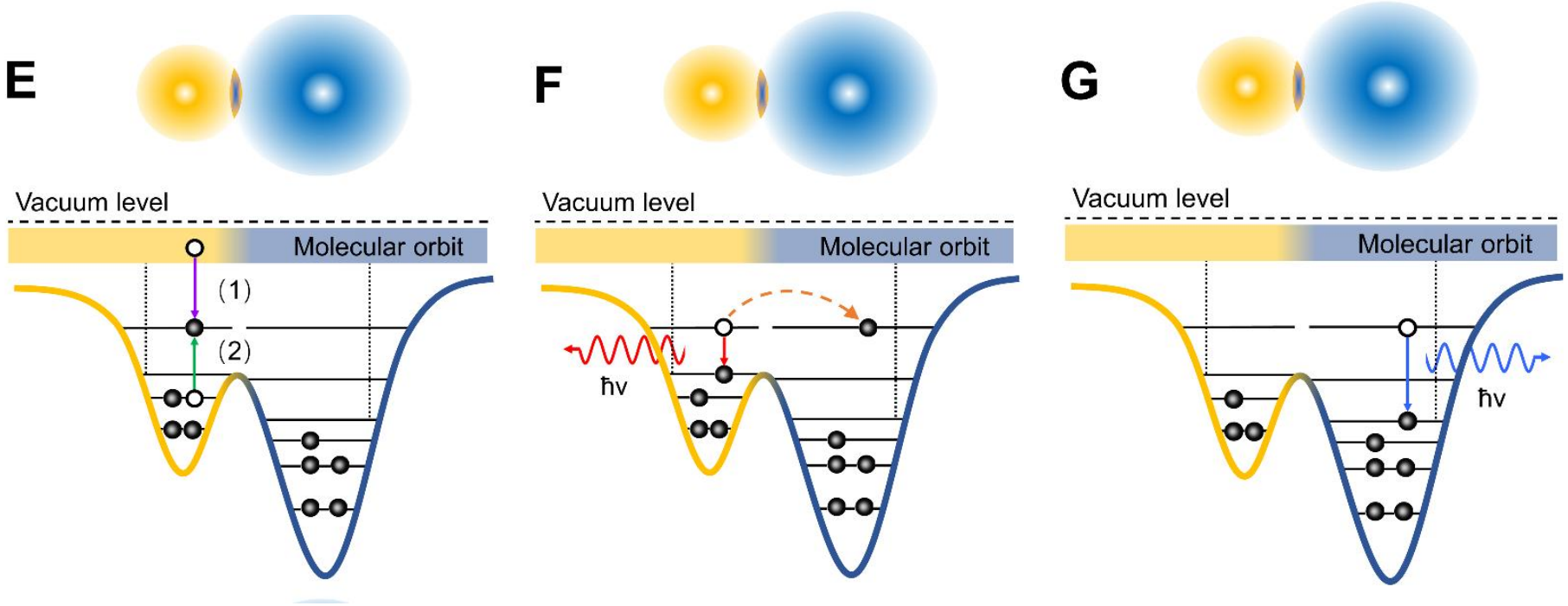


(1) The electron transit from molecular orbit to the excited state of an atom, during which it might experience nonradiative decay or radiative decay;
(2) the electron is excited from lower energy level to higher energy level inside an atom.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

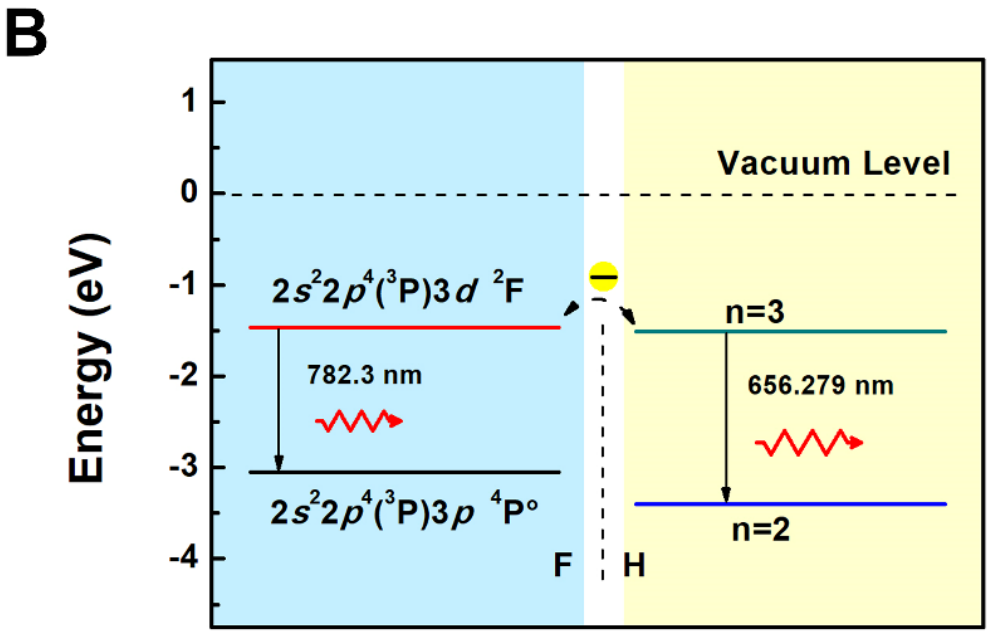
CEIIS-Interface Electron Transition Processes

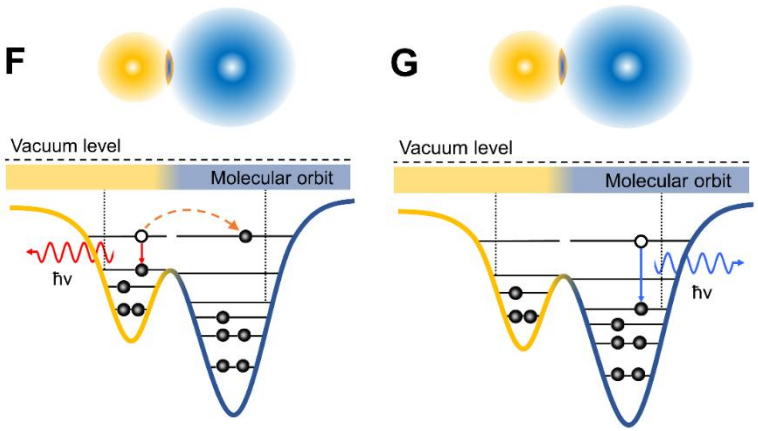
During the CE, some of electrons are temporarily transmitted to excited states.



Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS- F/H Interface Electron Transition Processes





Transitions between Hydrogen and Fluorine

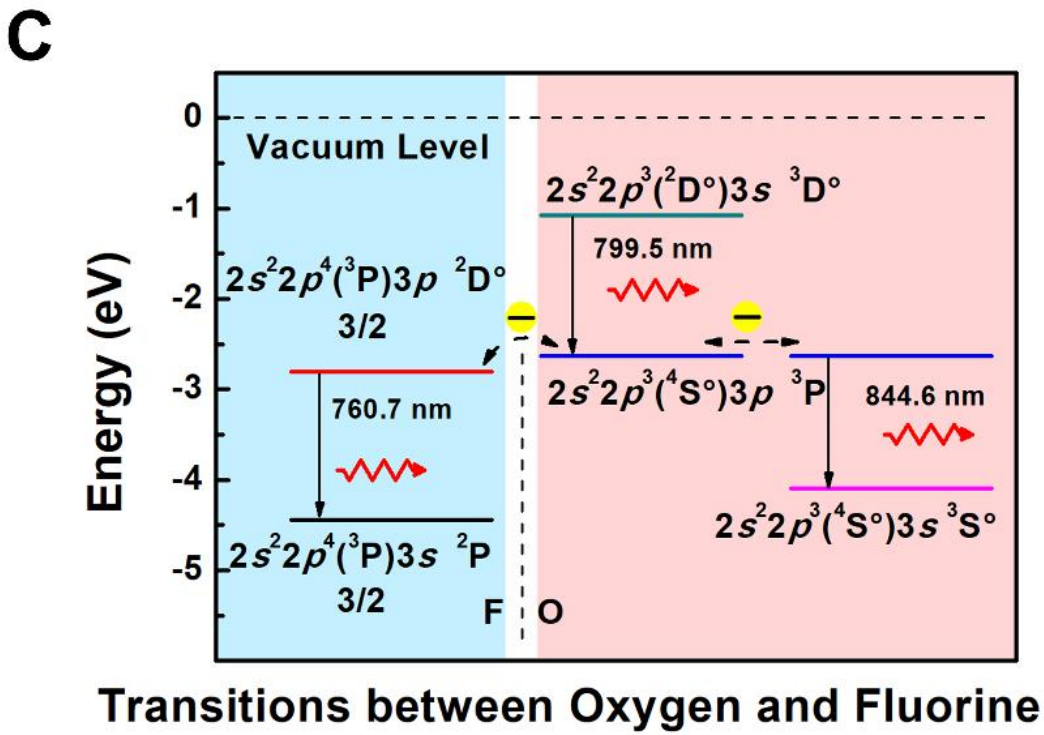
When the electron is at excited state, it could

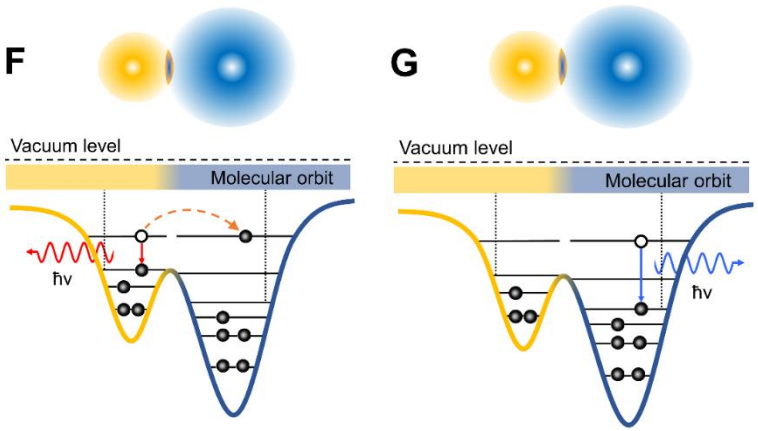
(1) transit to a lower energy level by emitting a photon.

(2) transit to the excited state of another atom (from atom A to atom B) through energy resonance transfer if the energy level of excited state in atom A is close to the one of another excited state in atom B.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS- F/O Interface Electron Transition Processes



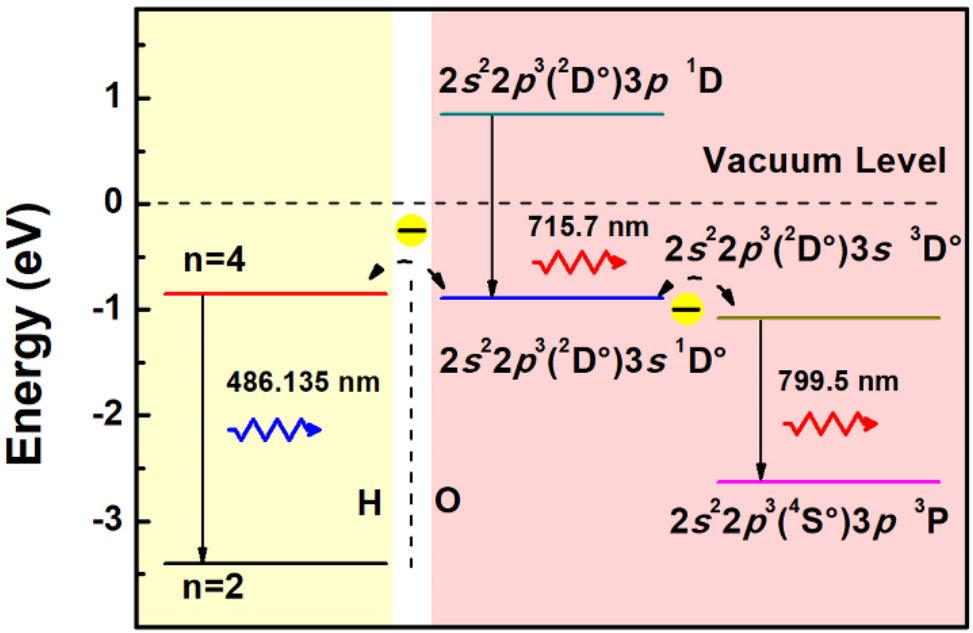


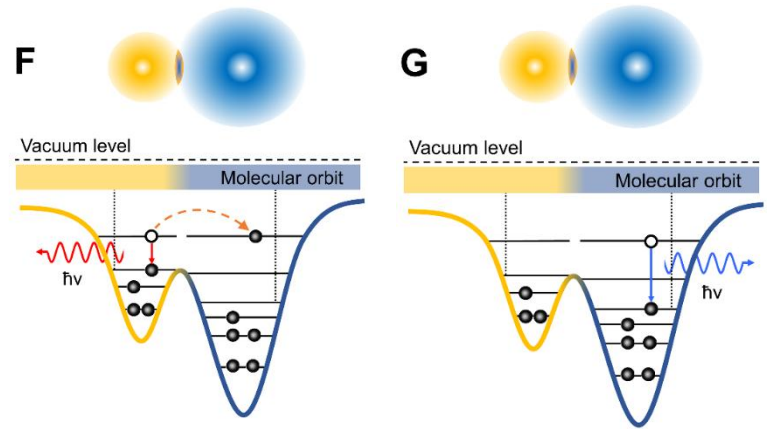
Then, the electron, transferring from atom A, could transit to a lower energy level in atom B emitting a photon.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

CEIIS-H/O Interface Electron Transition Processes

D





Transitions between Hydrogen and Oxygen

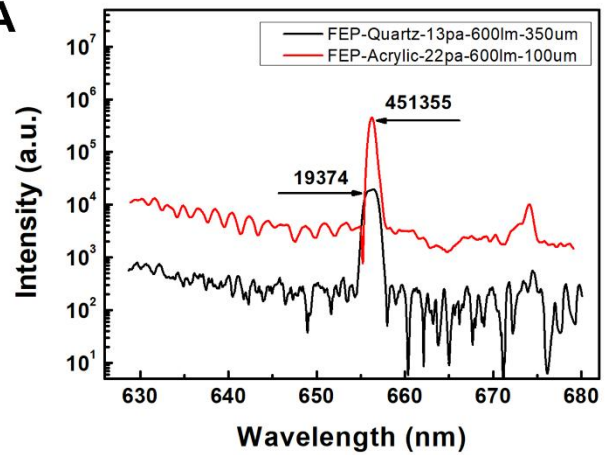
It is also possible, as revealed by previous theoretic analysis, that electron in atom A with a higher energy level could transit to a lower energy level in atom B. It is followed by a transition to an even lower energy level accompanied by a photon emission.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

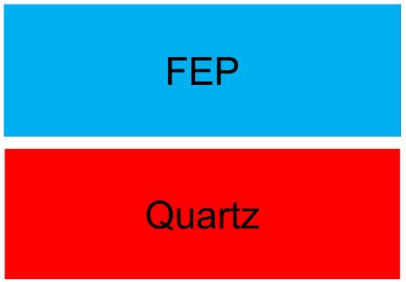
CEIIS-Role of H and O atom at CE

H atom holds the largest Bohr radius for excited states of electron among all the basic chemistry elements. Since H atom has the largest Bohr radius for excited states, it would be easier to overlap electron wave functions with other atoms in space

A



B

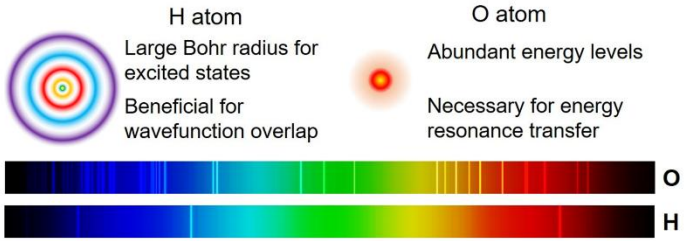


~ 5 × 10^{19} H atoms in 1 mol Quartz

C

$$R_{\text{H line intensity}} = \frac{I_{\text{FEP-Quartz}}}{I_{\text{FEP-Acrylic}}} = \frac{9121}{451355} \approx 2\times 10^{-2}$$

$$R_{\text{H atoms at interface}} = \frac{H_{\text{Quartz interface}}}{H_{\text{Acrylic interface}}} \approx 2\times 10^{-2}$$



D

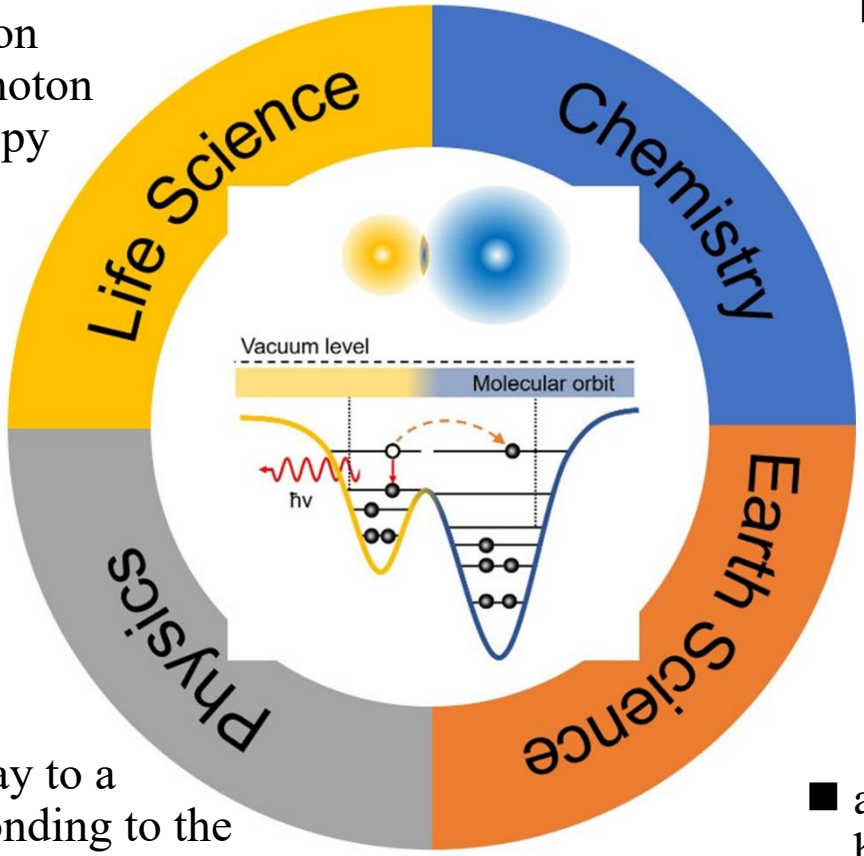
~ 8 × 10^{21} H atoms in 1 mol Acrylic

O atom has abundant energy levels, and the chances for energy resonance transfer are relatively high.

Li *et al.*, *Sci. Adv.* 2021; **7** : eabj0349

Summery

- This process is the contact-electrification induced interface photon emission spectroscopy (CEIIPES).



- the first atomic featured photon emission spectra during CE between two solid materials. The photon emissions are the evidences that electrons transfer takes place at the interface from one atom in one material to another atom in the other material during CE.

- It naturally paves a way to a spectroscopy corresponding to the contact-electrification at an interface, which might have fundamental impacts to understand the interaction among solids, liquids and gases.

- a general field that may be termed as contact electrification induced interface spectroscopy (CEIIS).

Recommended Key Papers

- Zhong lin Wang and Aurelia Chi Wang, “On the origin of contact electrification” (Review), *Materials Today*, 30(2019) 34.

  https:/doi.org/10.1016/j.mattod.2019.05.016

- Shiquan Lin, Xiangyu Chen, and Zhong Lin Wang, “Contact Electrification at the Liquid−Solid Interface", *Chem. Rev.*,online (2021). https://doi.org/10.1021/acs.chemrev.1c00176

- Zhong Lin Wang, “From contact electrification to triboelectric nanogenerators", *Reports on Progress in Physics*, 2021, 84 096502 (68pp).

  https://doi.org/10.1088/1361-6633/ac0a50.

- Zhong Lin Wang, “On the first principle theory of nanogenerators from Maxwell’s equations” *Nano Energy,* 68(2020)104272

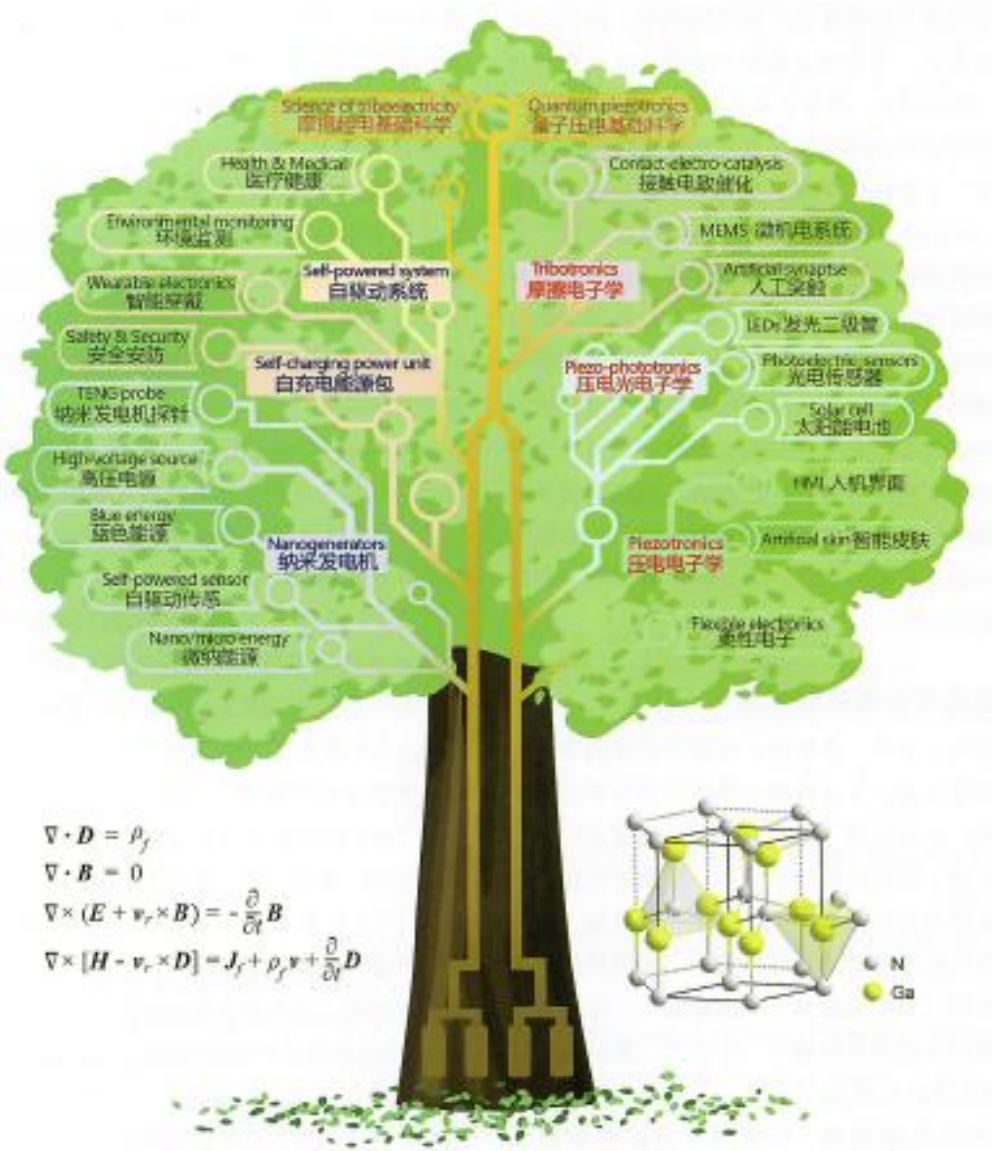
  https:/doi.org/10.1016/j.nanoen.2019.104272

- Zhong Lin Wang, “On the expanded Maxwell’s equations for moving charged media system – general theory, mathematical solutions and applications in TENG” *Materials Today*, to appear.

Content

- **Introduction for Dr. Ding Li**
- **The third-generation semiconductor and the Piezo-Phototronics**
- **Inter-atomic Electron-transition Induced Photon Emission in Contact-electrification (CEIIS)**
- **Welcome to BINN, CAS**

Welcome to BINN



Welcome to BINN

研究所招生——依托单位及学科专业

- **招生依托单位：中国科学院大学纳米科学与工程学院**
- **学院代码：80212**
- 2017年9月10日，纳米科学与技术学院在国科大雁栖湖校区举行揭牌仪式，正式成立。
- 2023年更名为纳米科学与工程学院
- 由中国科学院北京纳米能源与系统研究所和国家纳米科学中心承办。
- 纳米学院首任院长：王中林院士

研究生招生专业	研究方向示例
物理学科 070205凝聚态物理	纳米发电机及压电电子学 光电材料与器件 纳米能源转换与存储材料 压电聚合物及器件 柔性电子学与自驱动系统 量子力学与压电学理论 压电电子学和压电光电子学
化学学科 070304物理化学	纳米能源与催化
化学学科 0703J1纳米科学与技术	纳米生物医学 纳米智能材料
生物学科 071011生物物理学	纳米生物医学
材料学科 080502材料学 0805J1纳米科学与技术 （博士）	纳米发电机及压电电子学 功能材料与器件 第三代半导体材料器件与界面光谱学 纳米功能材料与器件 微纳电子催化与传感 智能机械传感与微能源系统 自驱动与智能传感 智能纤维材料与器件 新型能源与传感材料及器件 纳米发电机的先进制造与流体动力学

Welcome to BINN

研究所招生——研招硕士主要时间节点

硕士研究生招生

- **推荐免试：**面对有校外推免资格的本科大三学生，可录取为硕士或直博学生，不需要参加全国研究生统一招生考试。
- **推免面试：**9月中下旬组织，10月中旬完成接收。
- **全国硕士研究生统考：**11月初确认报名、12月底统一入学考试、2月下旬公布初试成绩、3月中下旬至4月底进行复试和拟录取。

中国研究生招生信息网
https://yz.chsi.com.cn/

Welcome to BINN

研究所招生——研招博士主要时间节点

博士研究生招生

- **春季**入学：九月底报名（仅限在读硕士转博）次年三月入学。
- **秋季**入学：秋季硕转博（仅限在读硕士转博），“申请-考核”制博士（普博），11月底至1月报名。

Welcome to BINN

研招工作者的温馨提示——研究招生专业目录

想去哪个专业方向、
大概招多少人、
考什么科目

国科大招生信息网
https://admission.ucas.ac.cn/

中国科学院大学 招生信息网

博士目录

首页 | 博士招生 | 硕士招生 | 本科招生 | 港澳台招生 | 留学生招生 | 政策法规 | 大学生夏令营 | 宣传专栏 | 联系我们

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硕士招生

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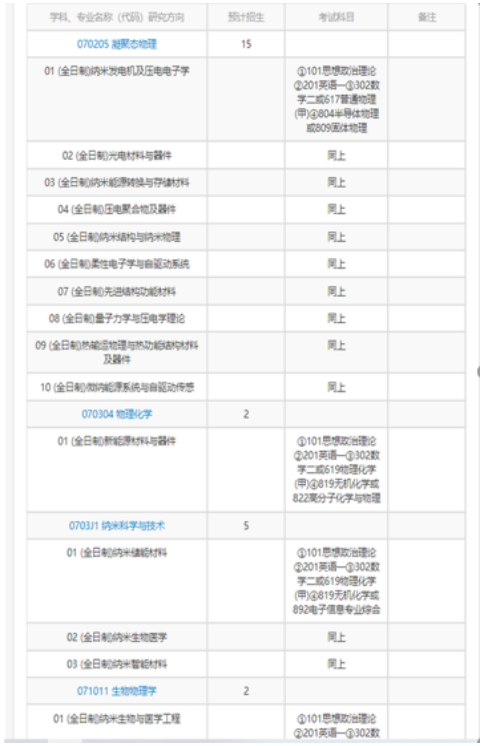
- 校内预报制
- 推免目录
- 招生目录
- 招生专业
- 考试大纲
- 报考流程
- 网上报名
- 录取查询
- 历年分数线
- 历年真题
- 资料下载
- 我要提问
- 常见问题

纳米科学与工程学院

中国科学院大学纳米科学与工程学院（School of Nano Science and Engineering，简称“纳米学院”）组建于2017年5月，由国家纳米科学中心和中国科学院北京纳米能源与系统研究所共同举办。中国科学院北京纳米能源与系统研究所（简称“纳米能源所”）筹建于2012年2月，是中国科学院和北京市共建的新型科研单元。纳米能源所招生依托纳米学院，纳米能源所聚焦于纳米领域的核心问题和发展方向，以纳米能源与纳米系统核心技术为研发目标，在压电电子学、压电光电子学及纳米发电机等相关领域开展基础和应用基础研究。截至2023年，纳米能源所拥有研究骨干人员110人，研究人员多在国际著名大学或科研机构接受过顶尖的学位教育与科研培训，他们为纳米学院的教育工作增添了国际化的视野和创新的理念。2024年，纳米学院招收35名硕士研究生，其中推免生约16人。（硕士各专业统考招生人数为计划下达人数减去推免实际招生人数）欢迎具有物理、化学、生物、材料、机械、电子、电气、能源、医药、半导体、自动化等专业背景的同学报考纳米学院研究生。

单位代码	80212	单位地址	北京市怀柔区雁栖经济开发区杨雁东一路8号院	邮政编码	101400
联系部门	人教办	联系电话	010-60688786	联系人	程老师
电子邮件	yanjiusheng@binn.cas.cn	目录类别	硕士		
网址	http://www.binn.cas.cn/				

学科、专业名称（代码）研究方向	指导教师	预计招生	考试科目	备注
070205 凝聚态物理		8		
01 (全日制)纳米发电机及压电电子学	王中林		①101思想政治理论 ②201英语 (一) ③302数学 (二) ④804半导体物理	
02 (全日制)光电材料与器件	胡卫国		同上	



学科、专业名称（代码）研究方向	预计招生	考试科目	备注
070205 凝聚态物理	15		
01 (全日制)纳米发电机及压电电子学		①101思想政治理论 ②201英语一 ③302数学二或617普通物理(甲) ④804半导体物理或809固体物理	
02 (全日制)光电材料与器件		同上	
03 (全日制)纳米能源转换与存储材料		同上	
04 (全日制)压电聚合物及器件		同上	
05 (全日制)纳米结构与纳米物理		同上	
06 (全日制)柔性电子学与自驱动系统		同上	
07 (全日制)先进结构功能材料		同上	
08 (全日制)量子力学与压电学理论		同上	
09 (全日制)热输运物理与热功能结构材料及器件		同上	
10 (全日制)微纳能源系统与自驱动传感		同上	
070304 物理化学	2		
01 (全日制)新能源材料与器件		①101思想政治理论 ②201英语一 ③302数学二或619物理化学(甲) ④819无机化学或822高分子化学与物理	
0703J1 纳米科学与技术	5		
01 (全日制)纳米储能材料		①101思想政治理论 ②201英语一 ③302数学二或619物理化学(甲) ④819无机化学或892电子信息专业综合	
02 (全日制)纳米生物医学		同上	
03 (全日制)纳米智能材料		同上	
071011 生物物理学	2		
01 (全日制)纳米生物与医学工程		①101思想政治理论 ②201英语一 ③302数	

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科学夏令营报名通知

中国科学院北京纳米能源与系统研究所2026科学夏令营报名通知

报名截止2026年7月1日

1、本届夏令营的招生对象为全日制普通高等学校本科大三、拟于2027年毕业的学生。

2、专业：物理、化学、生物、材料、机械、电子、电气、能源、自动化等相关专业。

3、本科期间学习成绩优秀。

4、英语水平达到国家四级。

5、对科研工作有浓厚兴趣，并有较强的或潜在的研究能力。