Artificial Intelligence Driven Optoelectronic Data Mining for Advanced High-Integration Spectral Sensing

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School of Integrated Circuit Science and Engineering

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2024 Peking University "Boya M-Talents" International Doctoral Students Academic Forum2024

Sub forum 2 **Latest Research Report on Optoelectronic Materials**

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1 Miniaturized Spectrometer Background

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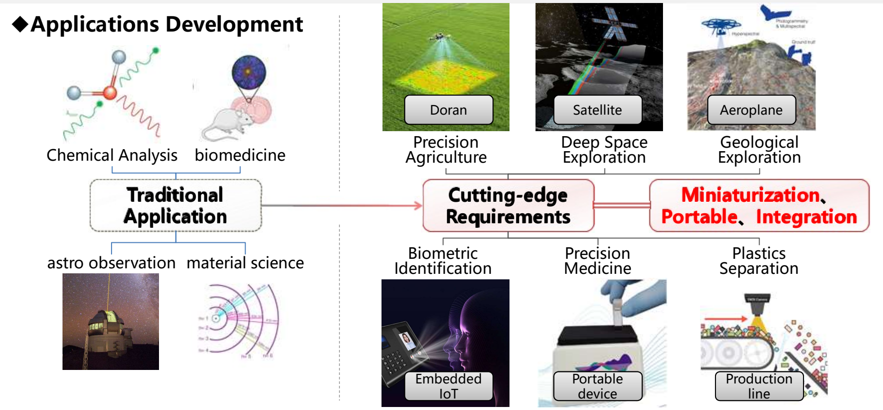
◆Applications Development



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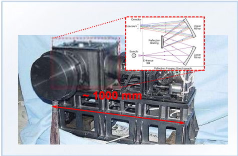
1 Miniaturized Spectrometer Background

◆Miniaturization Development

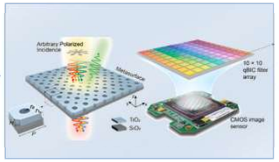
Traditional Benchtop Spectral Detector



➢**Tech. Adv.:**
- High spectral resolution
- Mature optical spectroscopy techniques

➢**Perennial Problem:**
- Large and heavy optical components
- Supports only push-broom imaging

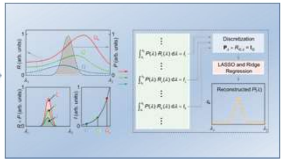
Miniaturized Integrated Optical Structure Spectrometer



➢**Tech. Adv. :**
- Enables snapshot imaging
- Optical components miniaturized

➢**Perennial Problem:**
- Micro-nano optics add cost
- Integration challenges in mass production.

Optical Structure Free Micro-spectrometer

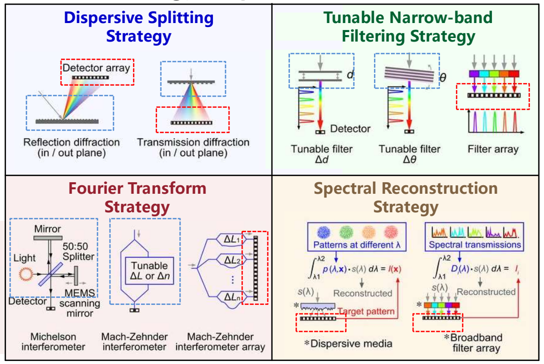


➢**Tech. Adv. :**
- No extra micro-nano steps
- Scalable to large 2D arrays

➢**Perennial Problem:**
- Limited modulation, singular spectral response. Error-prone reconstruction, low accuracy.

1 Miniaturized Spectrometer Background

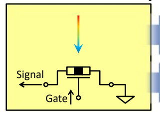
◆Technical strategy of spectrometer miniaturization



Array detector Dependence | **Micro-nano optical Dependence**

Integration Limited
Complicated Process

Single Point Reconstruction Spectrometer

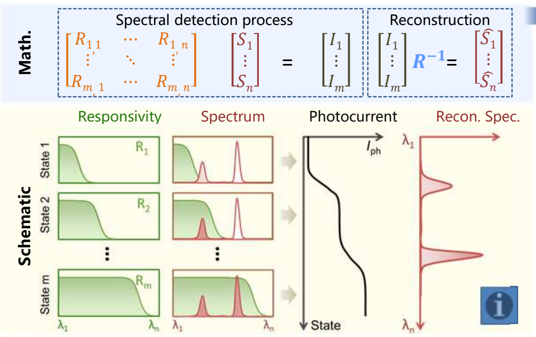


✓ Optical Module Free
✓ Single Detector

※ Xia FN. *Nat. Photon.* **15**, 601–607 (2021)
※ Sun ZP. *Science.* **378**,296-299 (2022)

1 Miniaturized Spectrometer Background

◆Basic principle of single-point reconstructed spectrometer

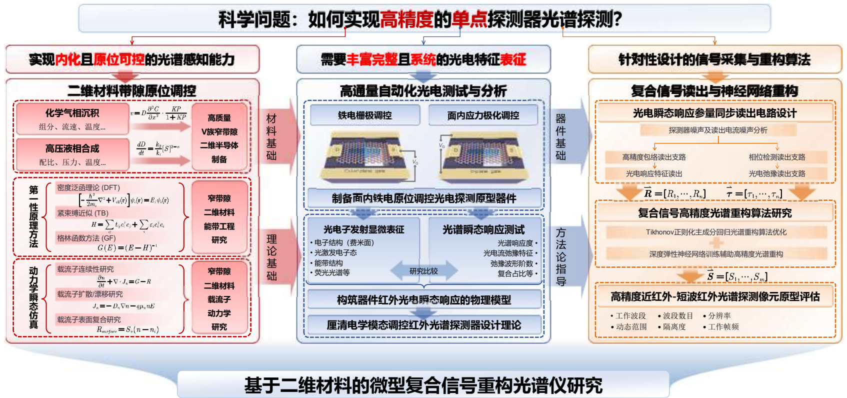


Singular Matrix -> Ill-posed Problem

Method	Pro.	Con.
Tikhonov Reg.	Suppress noise and reduce errors	Need right parameters
SVD	Stable for ill-conditioned	High computational complexity
M-P pseudo inverse	Stable for non-full rank matrices	Complexity for dense matrices
QR decomposition	Numerical stability is good	Not suitable for direct inversion
iterative	Suitable for large-scale problems	Dependent on initial values, converge slowly.

Core **How to improve precision in S.P. detection?**

1 Miniaturized Spectrometer Background



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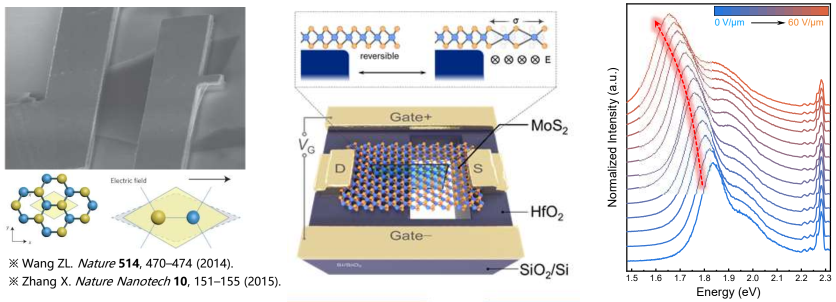
2 S.P. Spectrometer Device

◆**Design of semi-suspended 2D MoS_2 devices.**



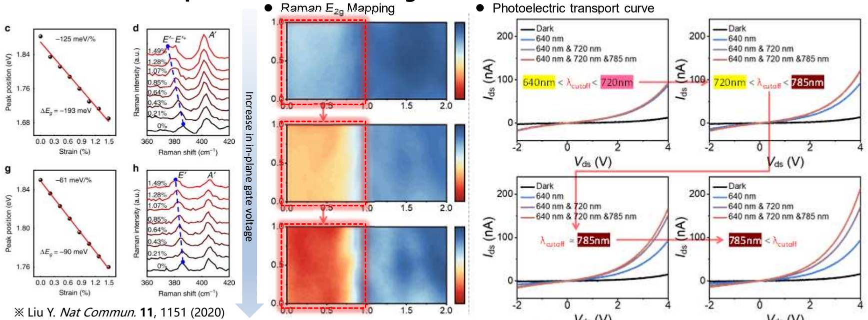
※ Wang ZL. *Nature* **514**, 470–474 (2014).
※ Zhang X. *Nature Nanotech* **10**, 151–155 (2015).

In-plane piezoelectric control technology, based on the symmetry breaking of single-layer structures.

Strain -> band structure: bandgap compression and evolution towards indirect bandgap.

2 S.P. Spectrometer Device

◆**Control the response cutoff wavelength**



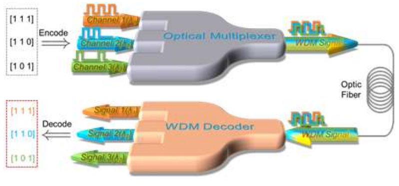
※ Liu Y. *Nat Commun.* **11**, 1151 (2020)

In-plane gate-induced lattice distortion (Raman characteristic peak shift). → Bandgap Compression → Extended Response Cutoff Wavelength

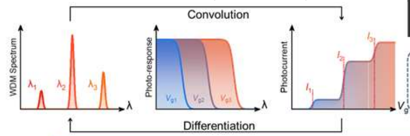
2 S.P. Spectrometer Device

◆**Realization of WDM detection**

- WDM Scheme



- Wave decomposition multiplexing detection diagram



- Mathematical procedure

V_G gradual increase → Series of photocurrents $I(V_G)$
Differential $I(V_G)$ → Spectrum curve

2 S.P. Spectrometer Device

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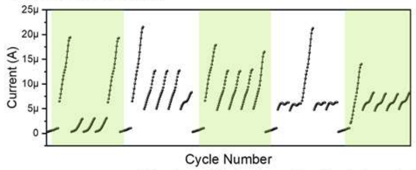
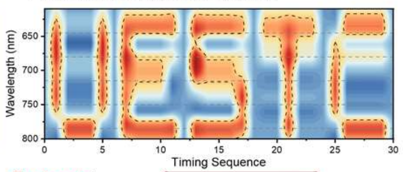
◆**Experimental Results**

- Photocurrent Signal
- Reconstructed Transient Spectrum





The demultiplexing of optical signals in five bands is realized in the wavelength range of 600-800 nm → **Lack of Precision**

Core — How to improve precision in S.P. detection.?

The spectrum is encoded in the photoelectric response → **Q1** Characteristic information of photoelectric response has not been fully mined

Jointly influenced by sampling accuracy and algorithm accuracy → **Q2** Optimize signal sampling and design reconstruction algorithm is important

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3 Automated High-throughput Testing

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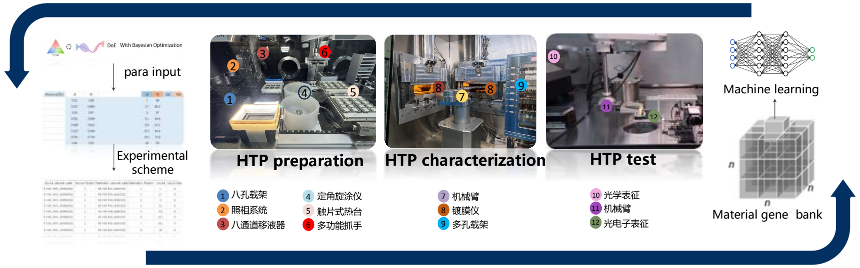

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3 Automated High-throughput Testing

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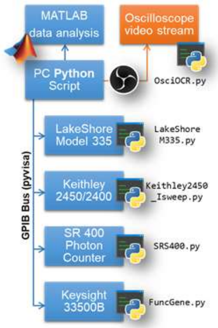
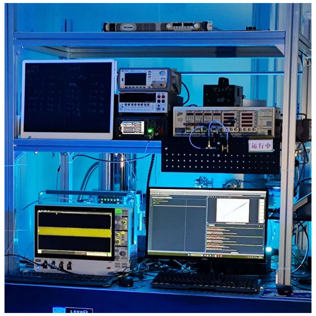
◆Automatic instrument control

- File tree
- Test platform





HTP platform's instruments are automatically controlled by the Python, could testing of device electrical transport (source-meter control), photoelectric response (light source and chopper control), and transient response characteristics (oscilloscope and photon counter).

Open source here!

3 Automated High-throughput Testing

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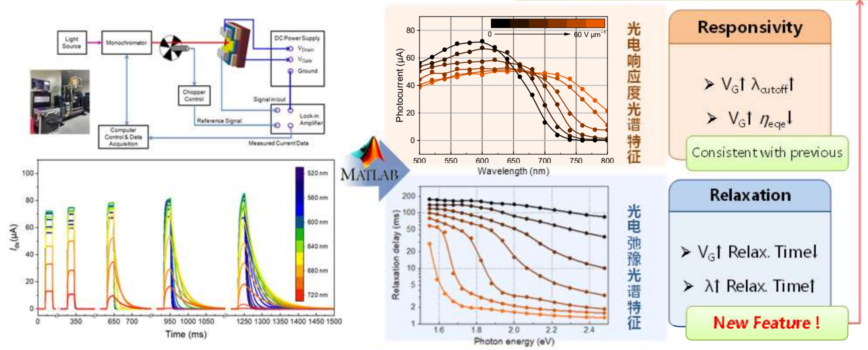
◆Transient response and analysis

Q1 Characteristic information of photoelectric response has not been fully mined



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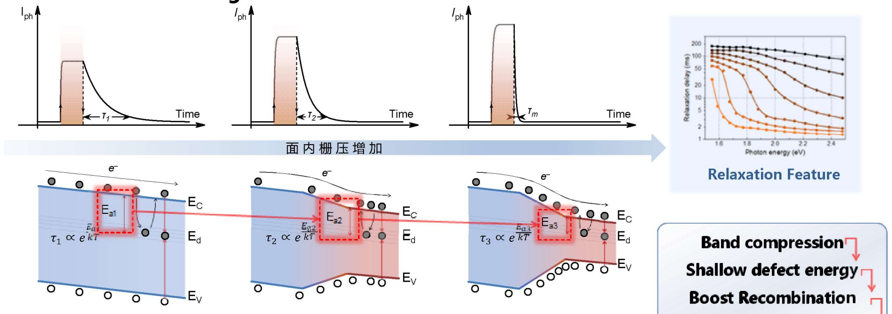
◆Carrier kinetic image for relaxation feature



$$\frac{dn_{free}}{dt} = k_{dc-trap} n_{trap} - k_{trap} n_{free} \left(1 - \frac{n_{trap}}{N_{trap}}\right) \quad \frac{dn_{trap}}{dt} = -k_{non-rad.} n_{trap} - k_{dc-trap} n_{trap} + k_{trap} n_{free} \left(1 - \frac{n_{trap}}{N_{trap}}\right)$$

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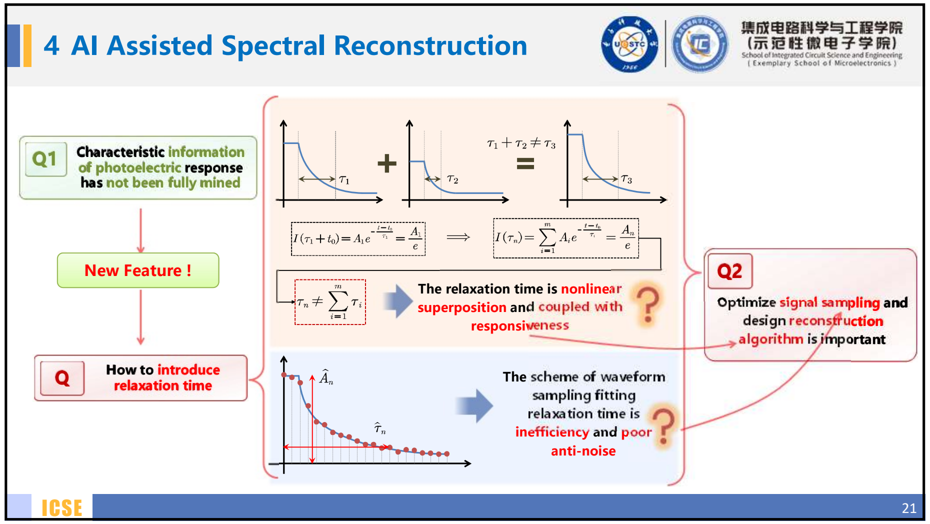
4 AI Assisted Spectral Reconstruction
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Q1
Characteristic information of photoelectric response has not been fully mined
New Feature !
Q
How to introduce relaxation time
The relaxation time is nonlinear superposition and coupled with responsiveness
The scheme of waveform sampling fitting relaxation time is inefficiency and poor anti-noise
Q2
Optimize signal sampling and design reconstruction algorithm is important
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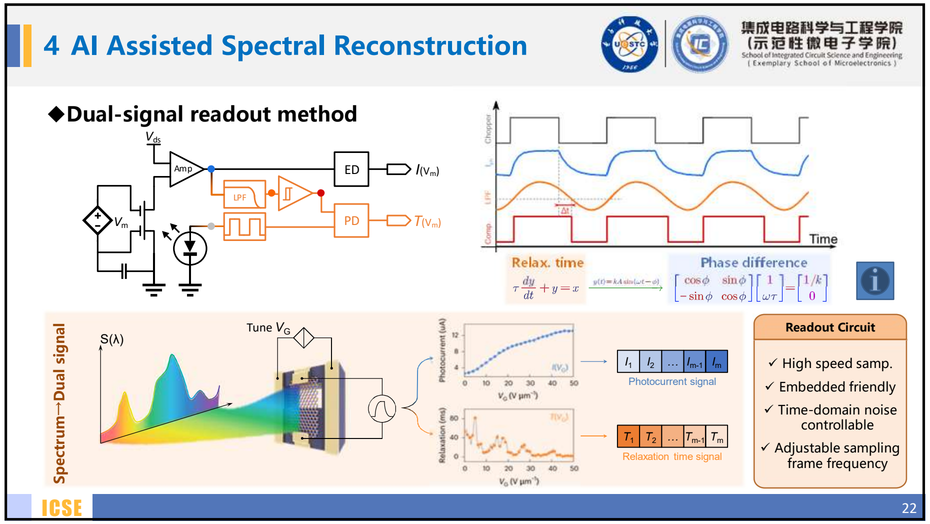
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◆Dual-signal readout method
Amp
LPF
ED
PD
Time
Relax. time
Phase difference
Spectrum→Dual signal
S(λ)
Tune V_G
Photocurrent signal
Relaxation time signal
Readout Circuit
✓ High speed samp.
✓ Embedded friendly
✓ Time-domain noise controllable
✓ Adjustable sampling frame frequency
ICSE
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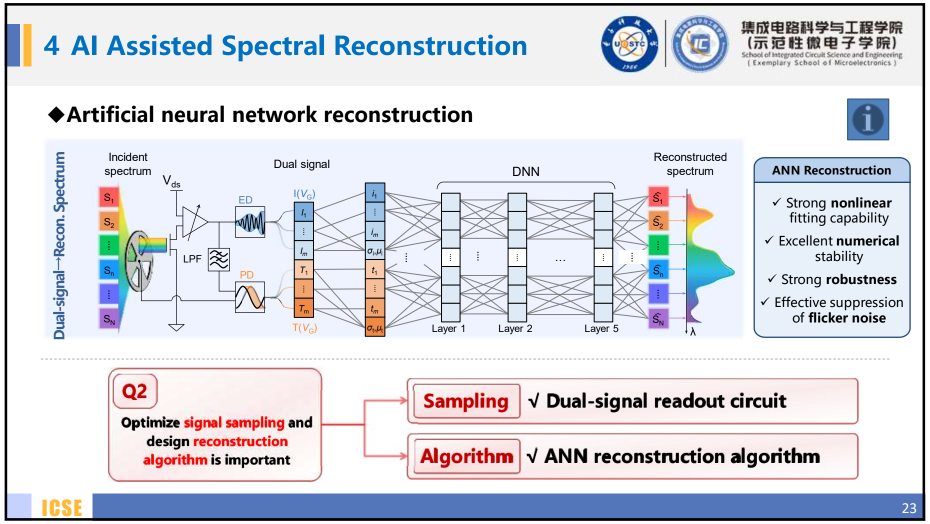
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◆Artificial neural network reconstruction
Dual-signal→Recon. Spectrum
Incident spectrum
Dual signal
DNN
Reconstructed spectrum
ED
LPF
PD
Layer 1
Layer 2
Layer 5
ANN Reconstruction
✓ Strong nonlinear fitting capability
✓ Excellent numerical stability
✓ Strong robustness
✓ Effective suppression of flicker noise
Q2
Optimize signal sampling and design reconstruction algorithm is important
Sampling √ Dual-signal readout circuit
Algorithm √ ANN reconstruction algorithm
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4 AI Assisted Spectral Reconstruction
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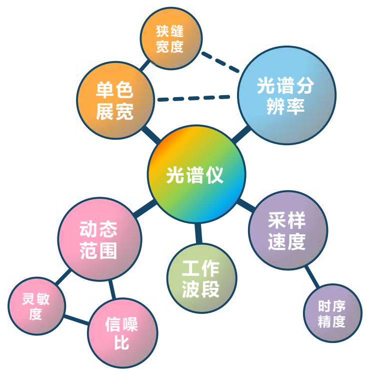

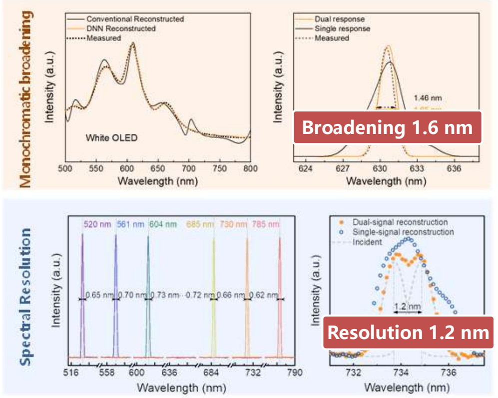

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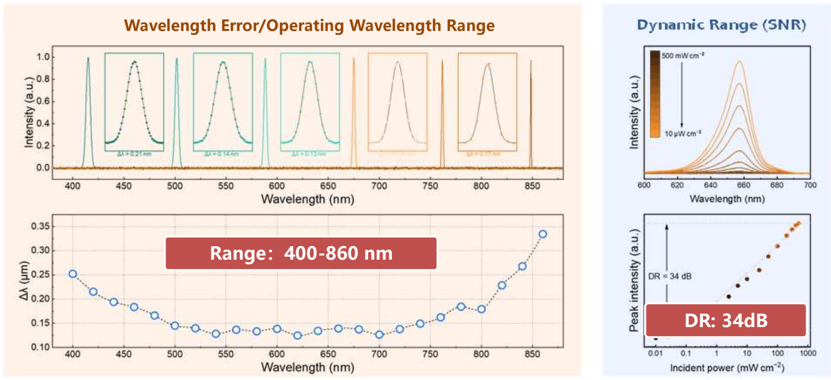

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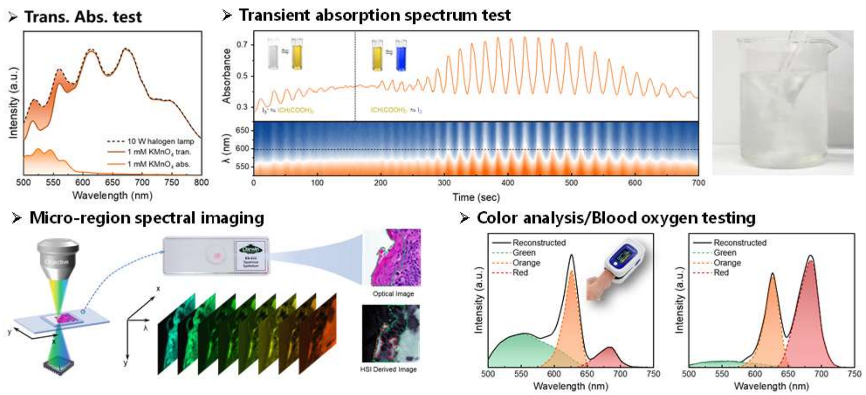

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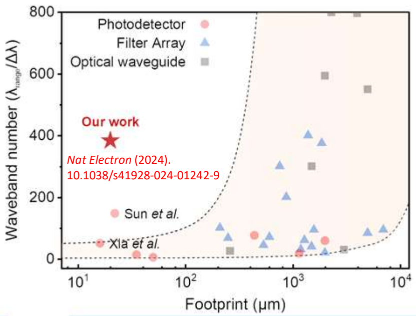
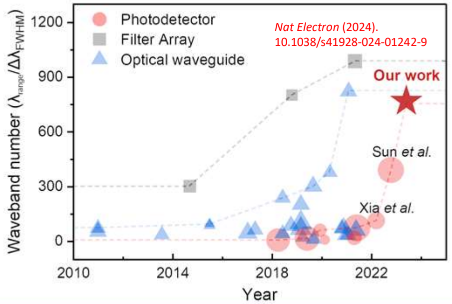
5 Tech. Prospect

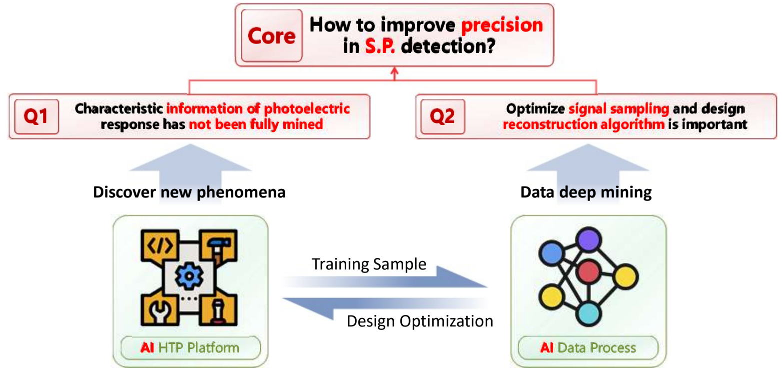
Tech. route perspective: single point spectral detector can effectively break through the trade-off between spectral detection volume and accuracy



Development process perspective: single point spectral detector can be experiencing rapid iteration and vigorous development of technology



5 Summary



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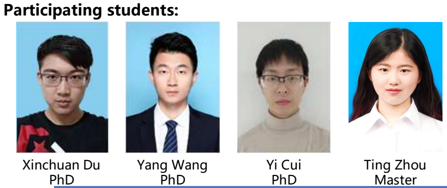
Participating students:



Xinchuan Du PhD | Yang Wang PhD | Yi Cui PhD | Ting Zhou Master

Funding Organization:

Laboratory team:

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谢 谢

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追求卓越 勇创先锋

Basic mechanism

Basic mechanism

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Basic mechanism

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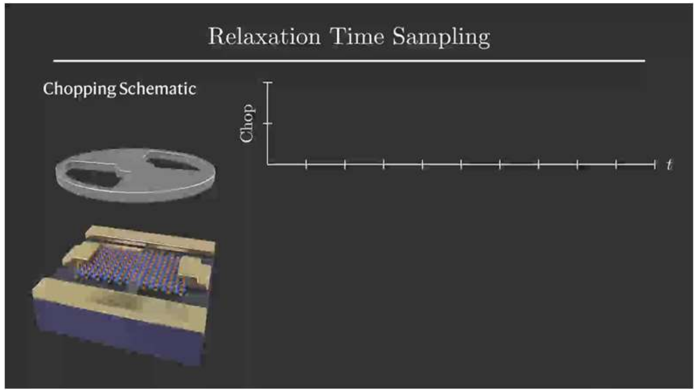
Relaxation Time Sampling



Neural Network Reconstruction