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Quantum Dot Intersubband Photodetectors for LWIR photons

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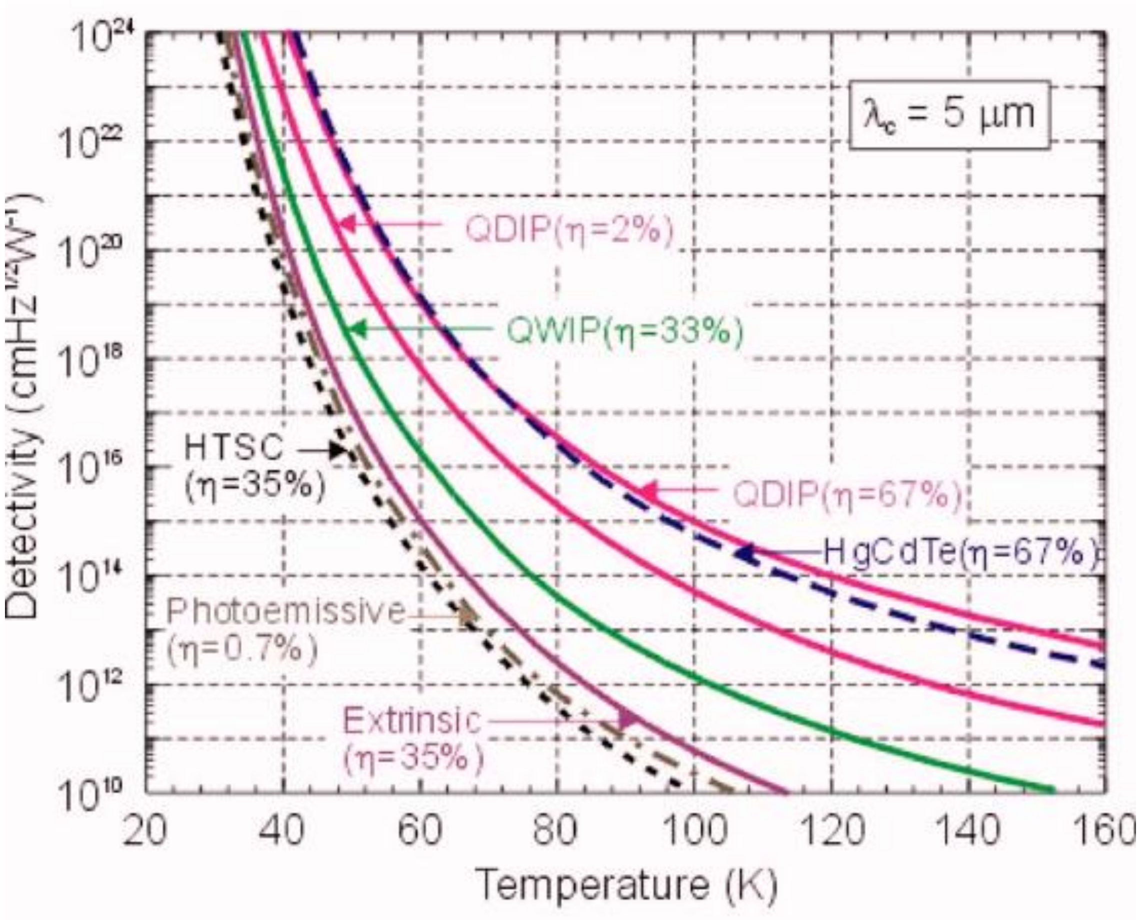
** L-NESS & CNR-IFN, Milano (Italy)

HgCdTe

- ✔ Mature technology
- ✔ High quantum efficiency (~70%)
- ✔ Can be tuned in the range 1-30 μm
- ✖ Low growth uniformity
- ✖ Extremely high cost



Rogalski et al., J. Appl. Phys. 105, 091101 (2009)

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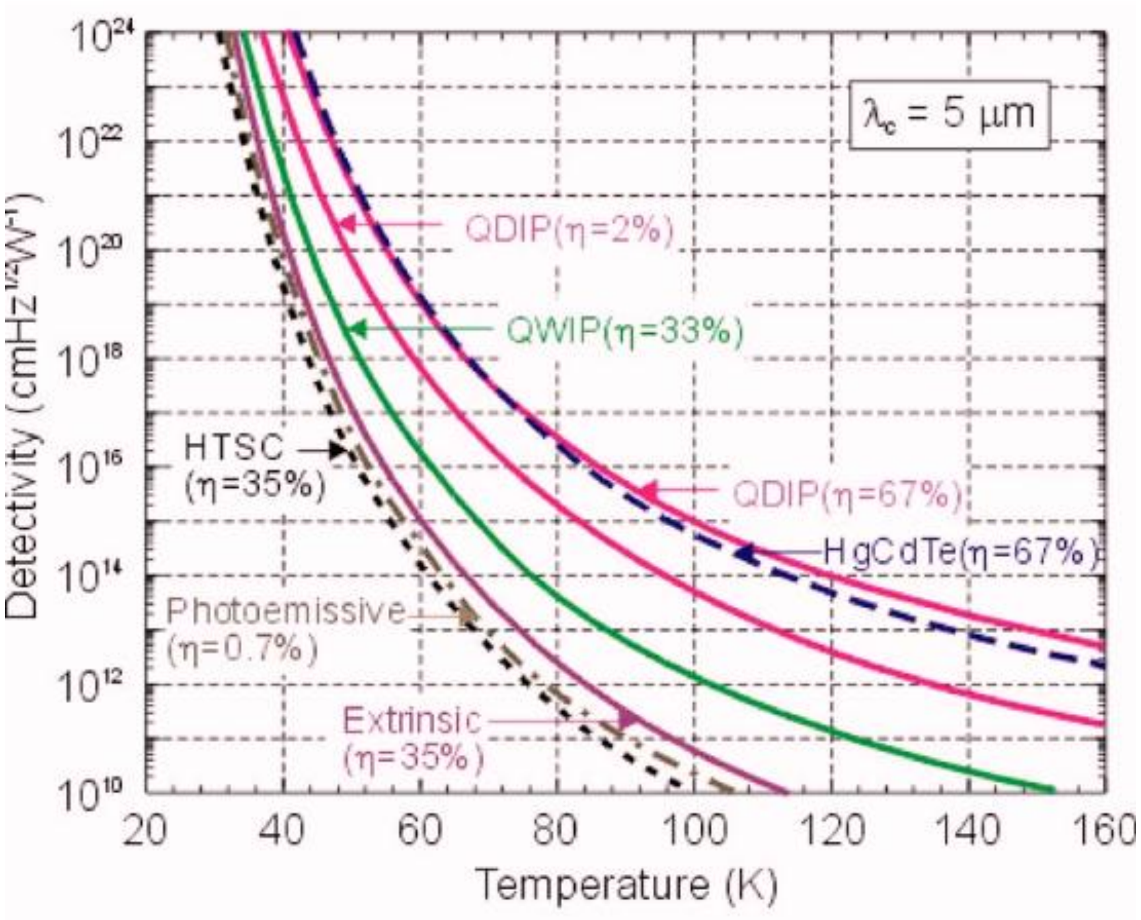
QWIP (Quantum Well)

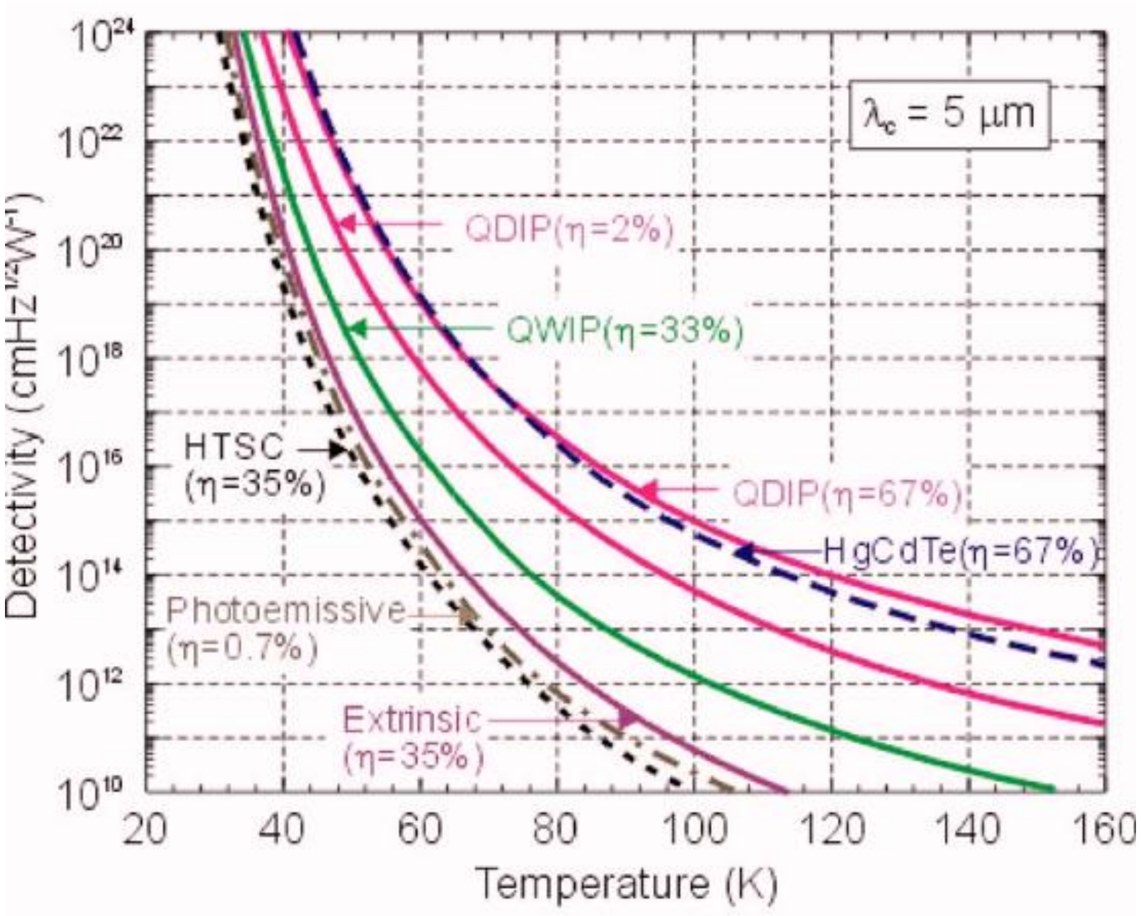
- ✓ Mature technology
- ✗ Short carrier lifetime (lower quantum efficiency)
- ✗ Only IR radiation parallel to the QW is detected
- ✓ High growth uniformity
- ✓ Lower cost



Rogalski et al., J. Appl. Phys. 105, 091101 (2009)

QDIP (Quantum Dot)

- Technology based on well estabilshed GaAs technology
- Low dark current due to lower thermal emission
- High optical absorption at normal incidence
- Possible high operating temperature (Peltier cooling -80°C)



Rogalski et al., J. Appl. Phys. 105, 091101 (2009)

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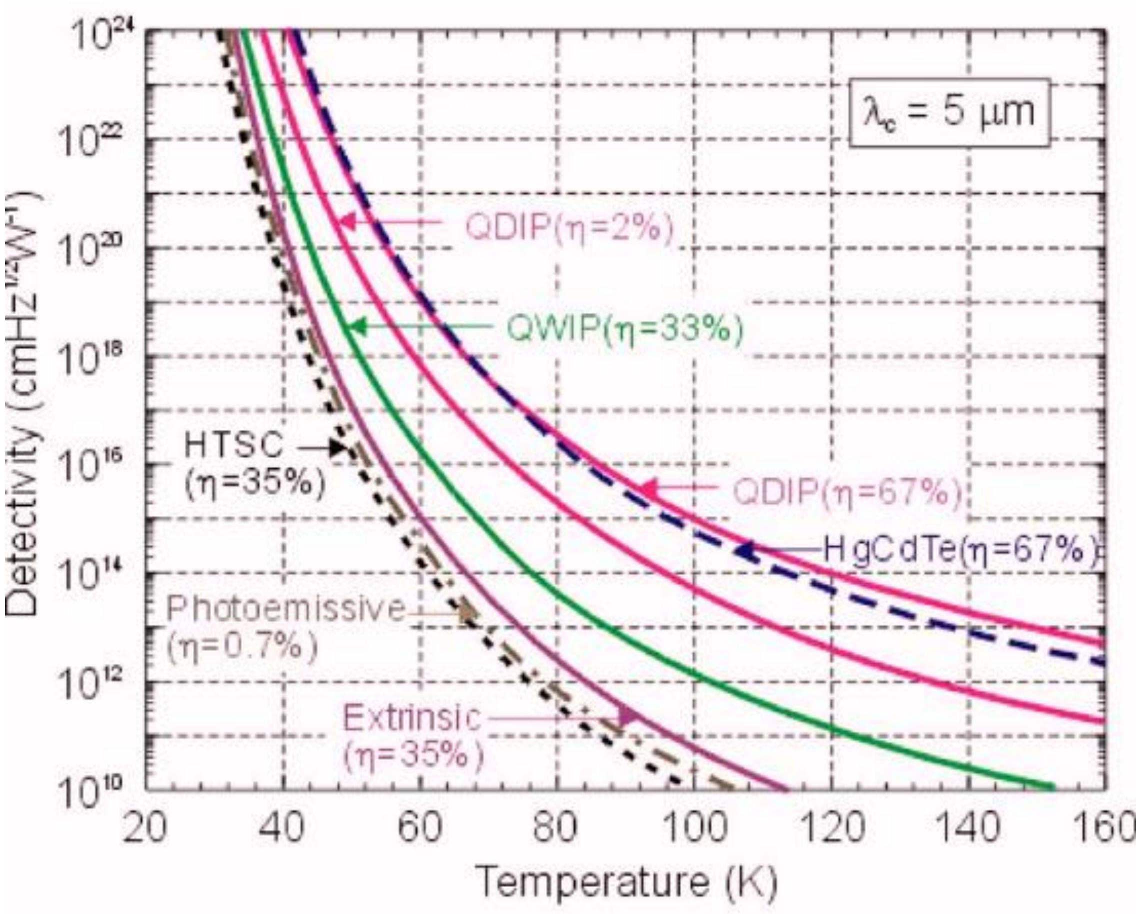
The decrease in **detectivity** with **temperature** is a crucial issue.

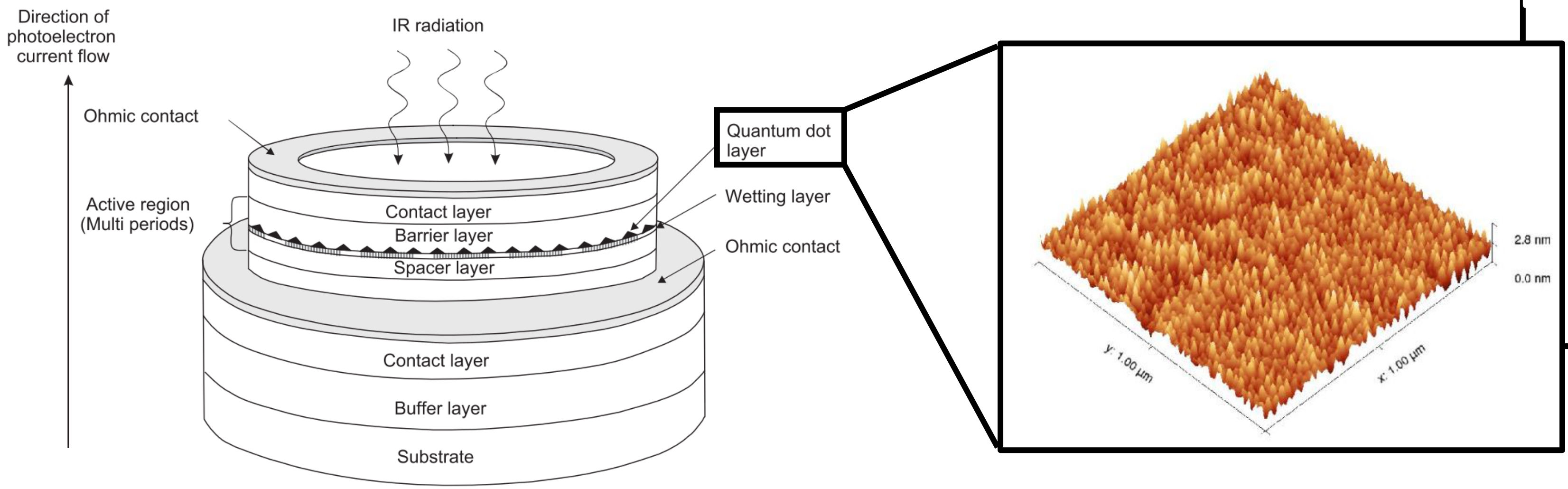
Up to now external cooling is always required to improve S/N ratio.

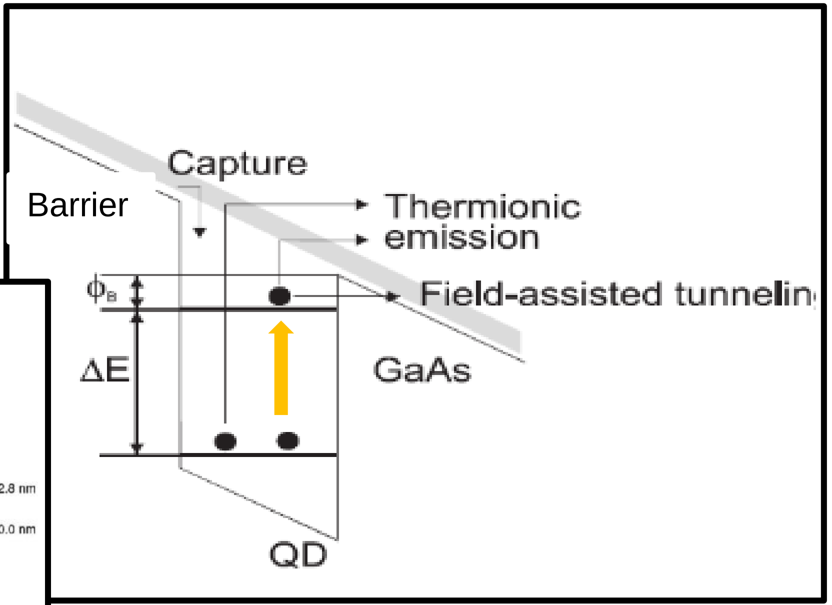
- Increased complexity
- Reduced device lifetime in space satellites



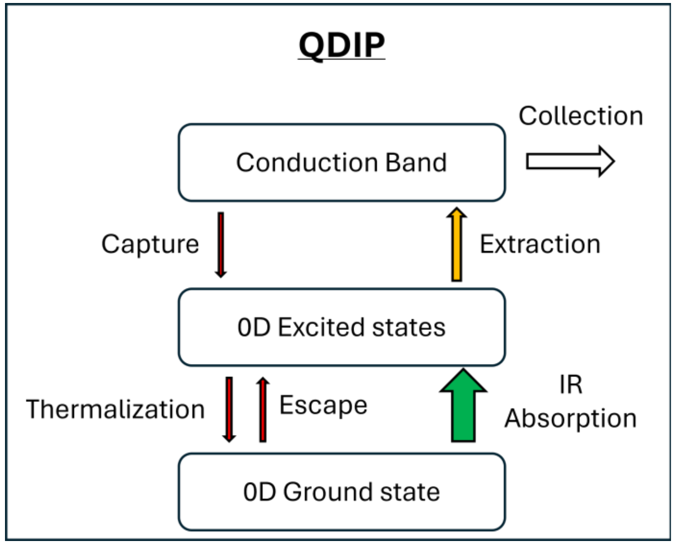
QDIP are **promising** but not yet competitive.

- Large dark current at room temperatures
- Low density of absorbers





Intraband transitions



- Small capture
- Low thermalization efficiency (phonon bottleneck)
- Low escape probability (phonon bottleneck)
- Large absorption coefficient
- Ok extraction (tunneling)

Increase capture and **thermalization** efficiencies without increasing the escape probability.

Capture and thermalization are very efficient in **2D nanostructures.**

0D nanostructures have low escape probability and high absorption coefficient.

What if we can combine these advantages?

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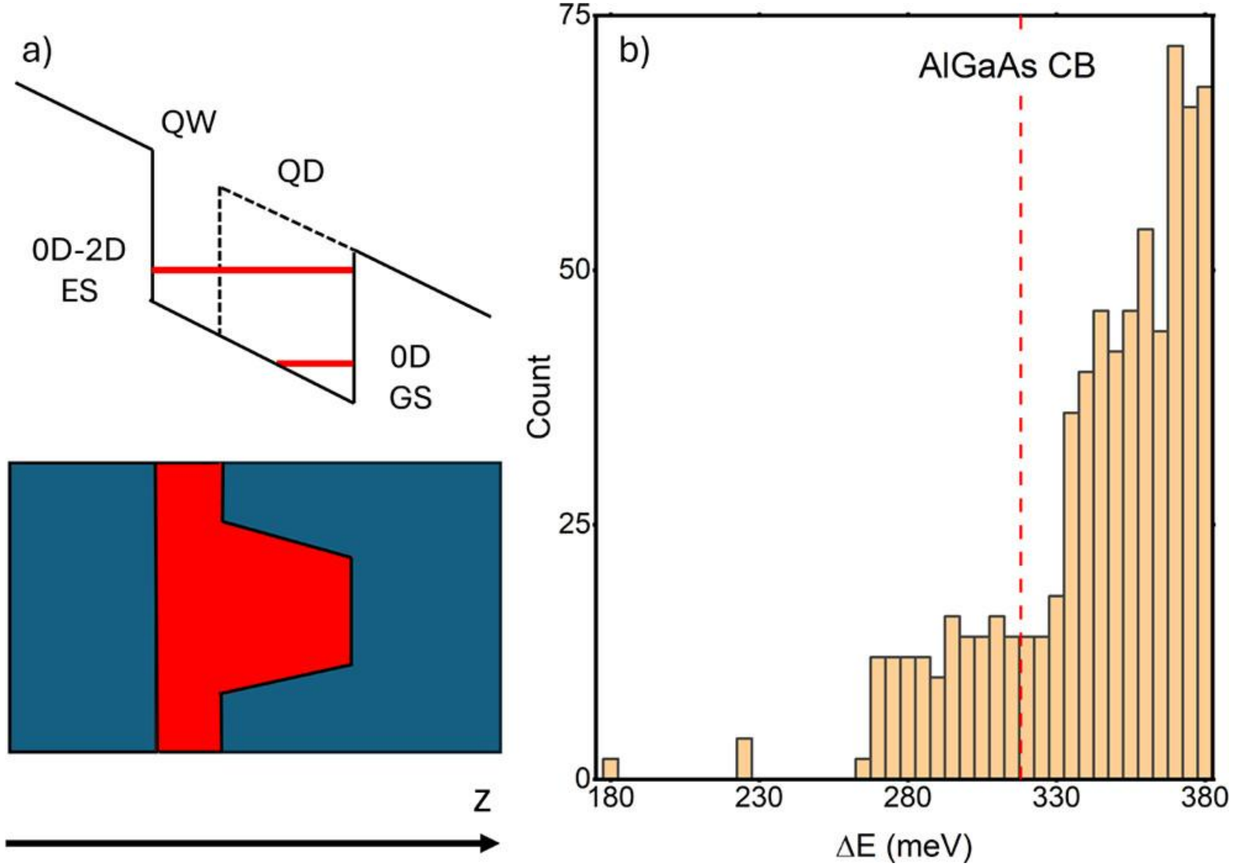
We designed and realized by **Droplet Epitaxy** a hybrid **0D-2D nanostructure** (QDs on top of a QW) made of GaAs/AlGaAs.

The absence of a potential barrier between 0D and 2D allows to spatially **modulate** the properties **quantum confinement**.

QD-like **low** energy states
QW-like **high** energy states



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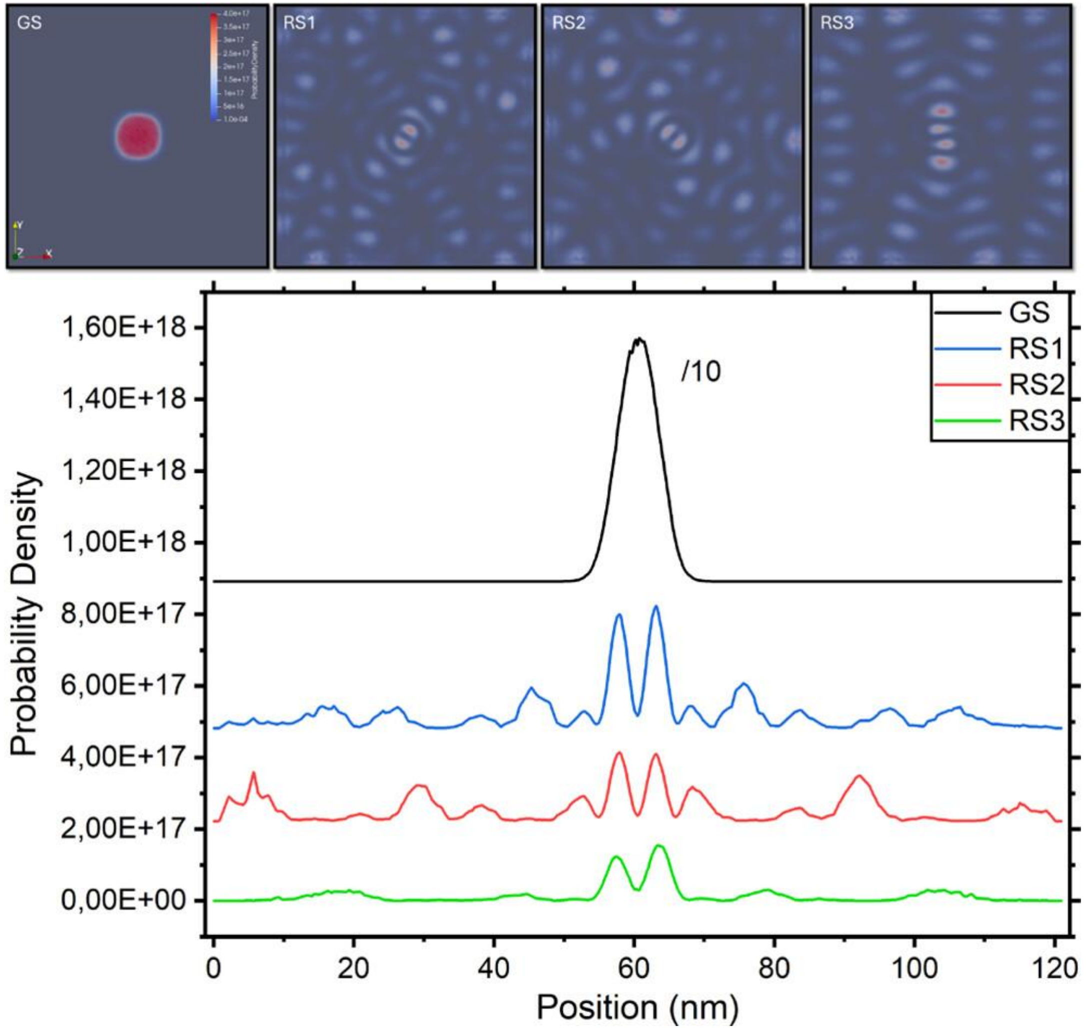
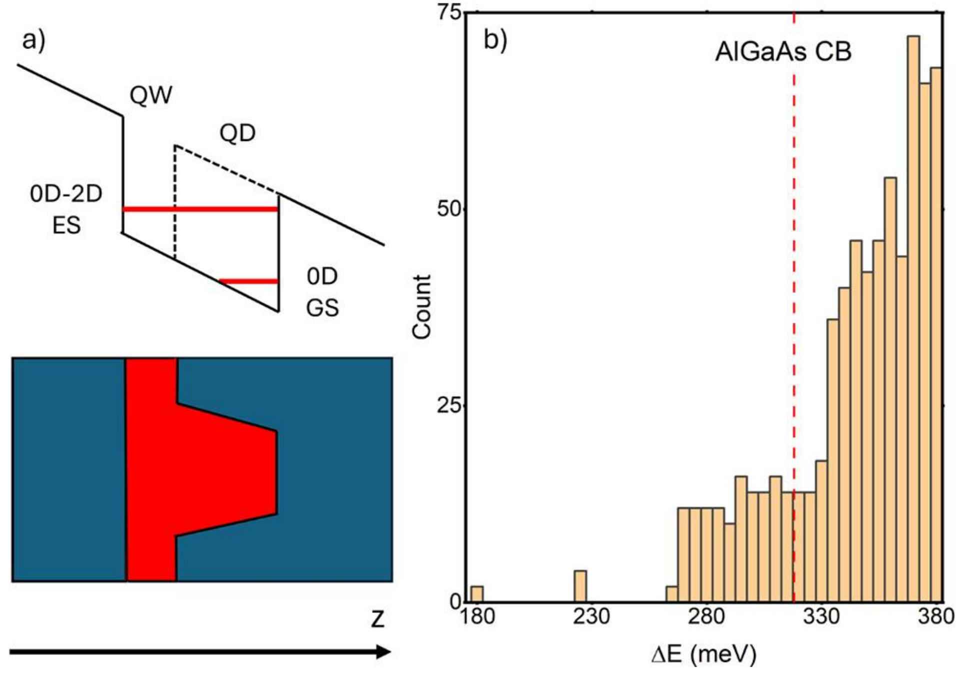


The QW introduces **resonant states** in CB, E>E_{CB} with a localization in the QD region -> large absorption probaility



Vichi et al., ACSPhotonics 12,447–456 (2025)

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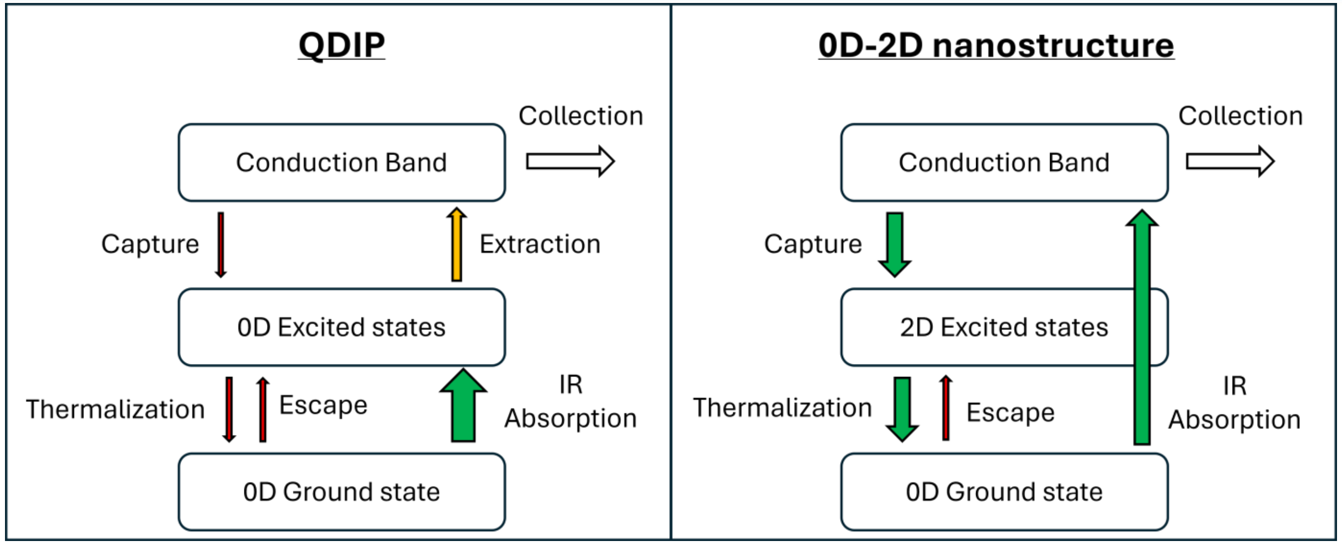
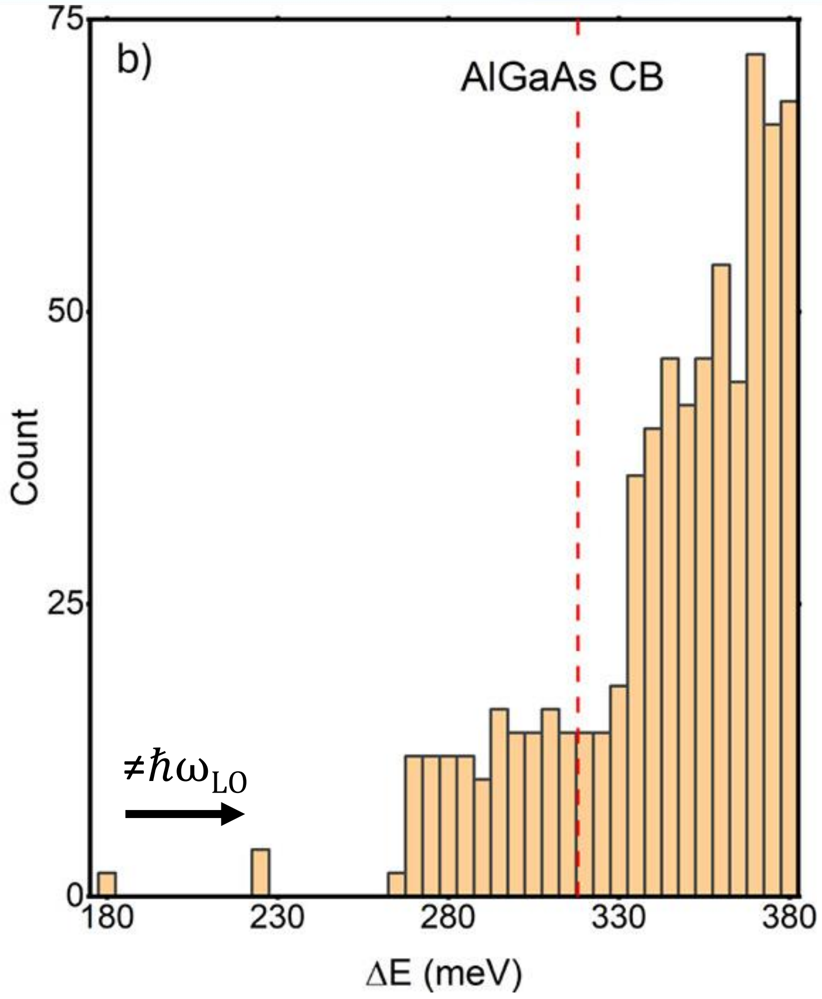


- Small capture
- Low thermalization efficiency (phonon bottleneck)
- Low escape probability (phonon bottleneck)
- Large absorption coefficient
- Ok extraction (tunneling)

- Large capture
- High thermalization efficiency (carrier-carrier scattering)
- Low escape probability (phonon bottleneck)
- Good absorption coefficient
- Large extraction (resonant states)



Vichi et al., ACSPhotonics 12,447–456 (2025)

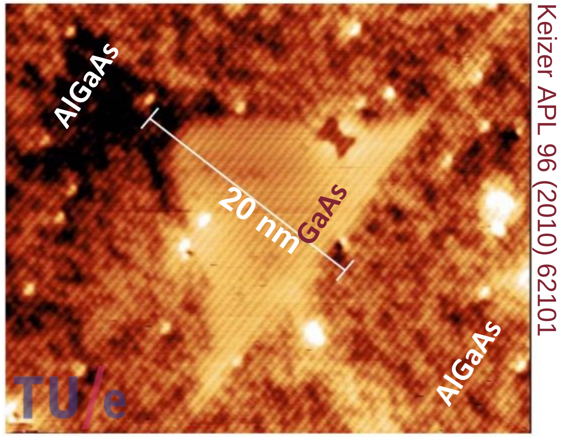
Droplet Epitaxy

Two-step growth of self-assembled QDs:

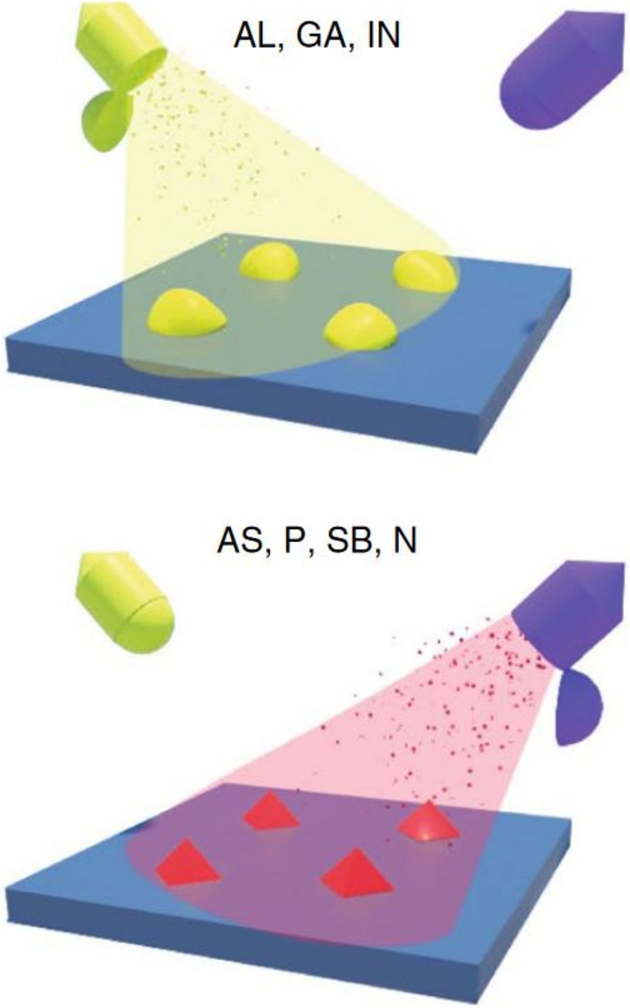
- Deposition of group III to form **metal droplets**
- **Crystallization** with group V flux

Advantages:

- **Strain-free** growth
- Independent **control** on QD **morphological parameters** (height, aspect ratio, shape)
- Narrow size **dispersion**

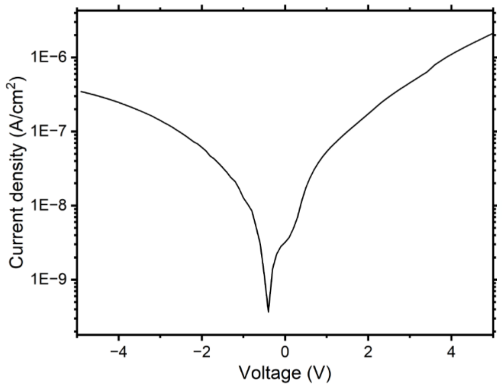


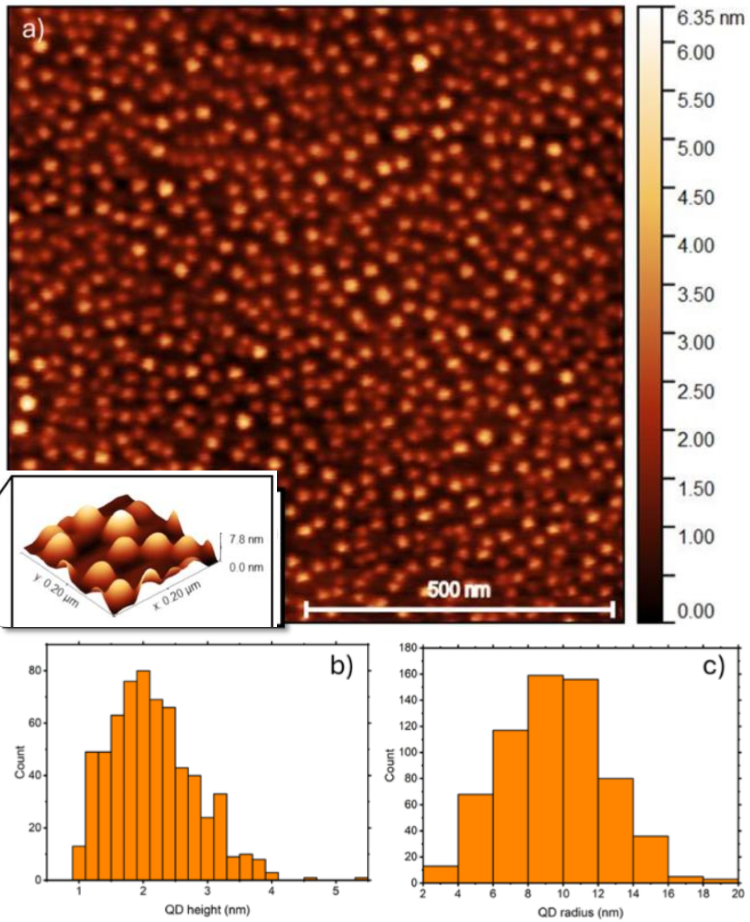
Keizer APL 96 (2010) 62101

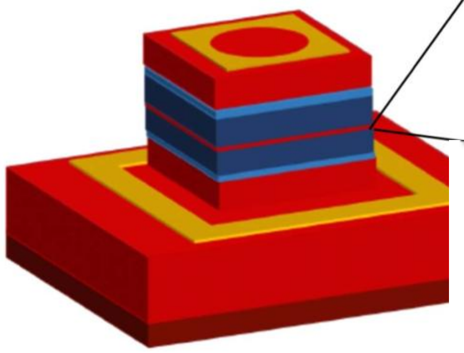


Gurioli et al., Nat. Mater. 18, 799 (2019)

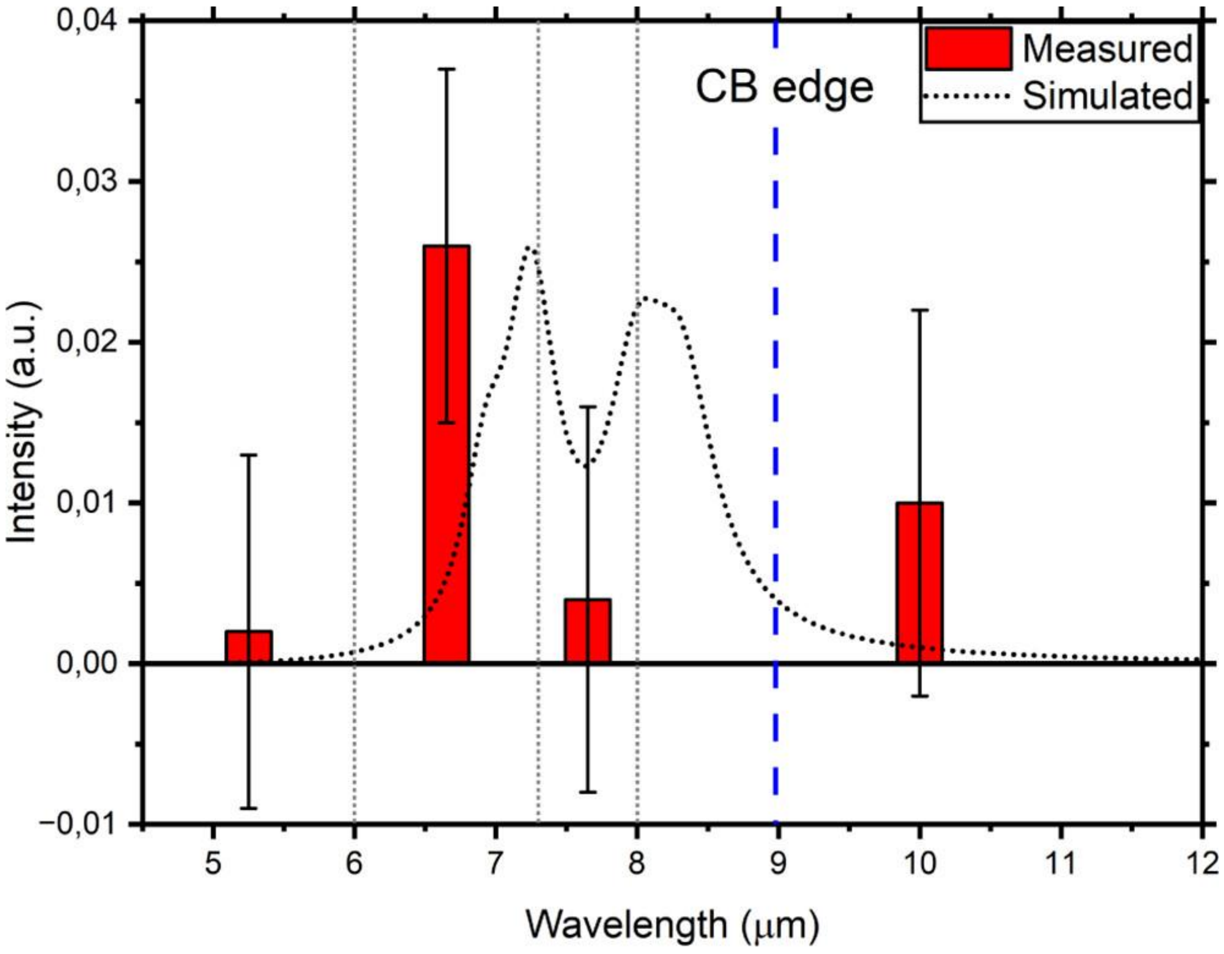
RT dark current







QD density = $7*10^{10}$ cm^{-2}



Room temperature absorption signal
detectivity = $2*10^{-4}$ A/W at -4 V

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CONCLUSIONS:

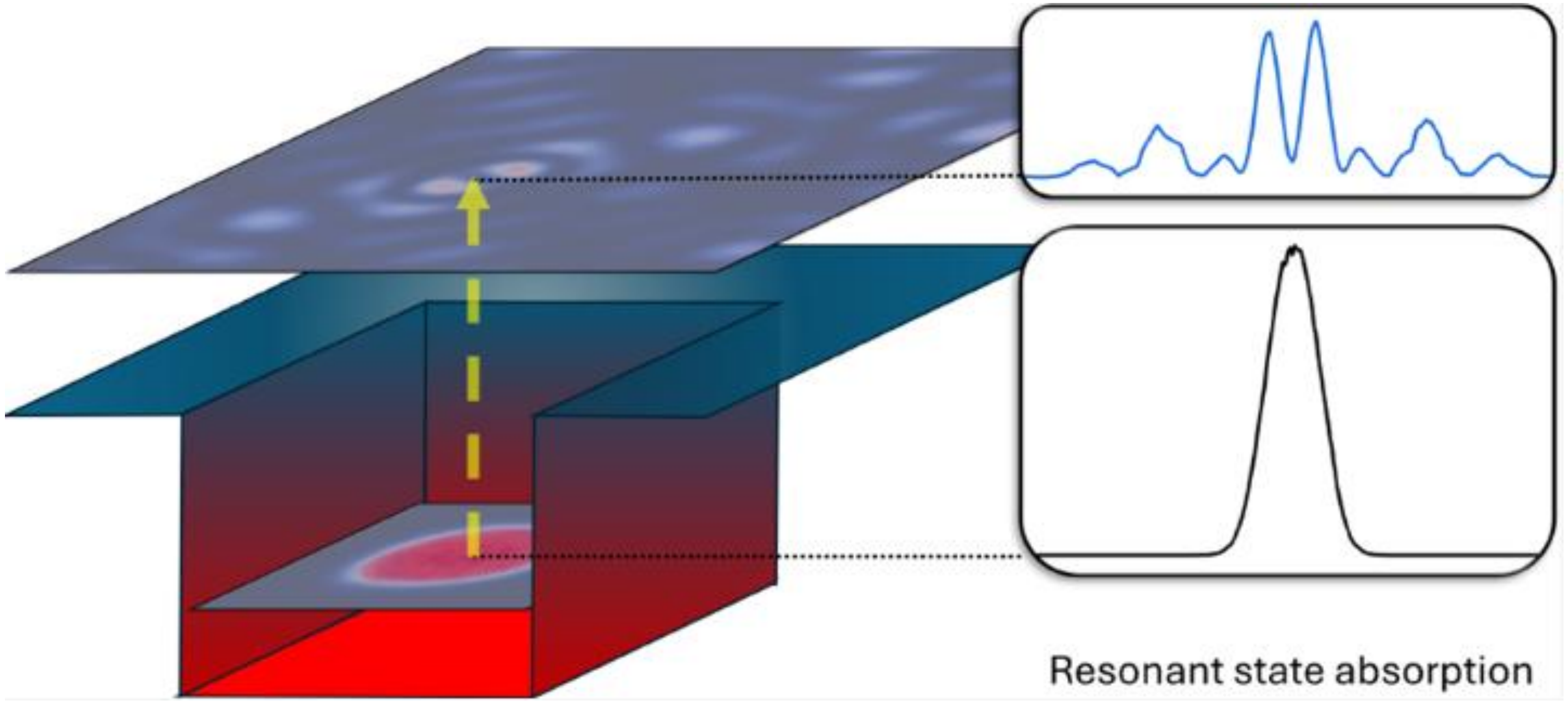
Innovative quantum state design to **modulate quantum confinement**:

- **0D** ground state
- **2D** excited states

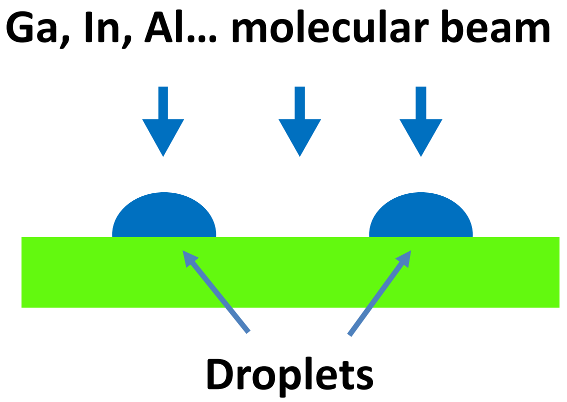
To exploit the advantages of both nanostructures.

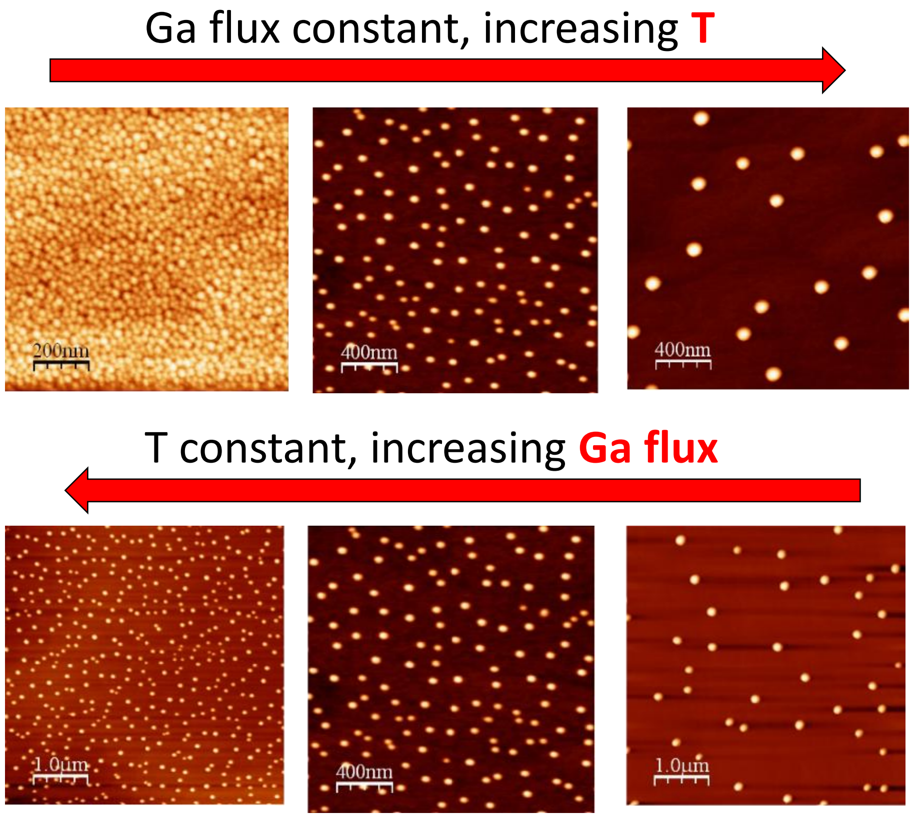
Achieved room temperature operation R = $2*10^{-4}$ A/W

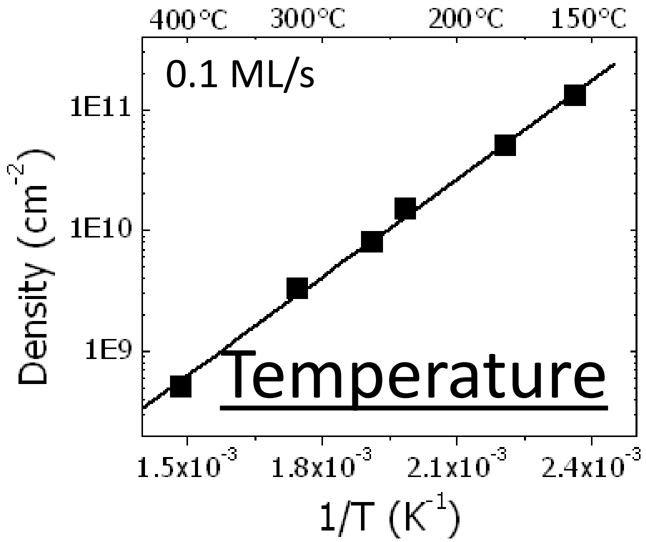
Vichi et al., ACS Photonics 12,447−456 (2025)

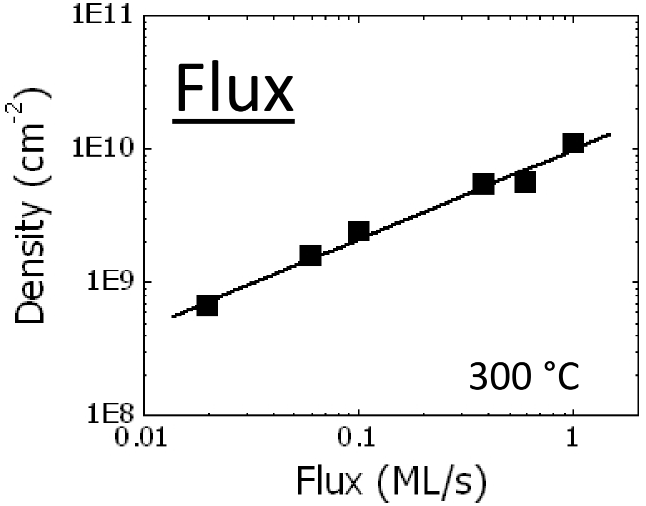


EXTRA SLIDES









Ga droplet deposition

Droplet deposition:
Ga amount --> droplet volume
Temperature --> droplet density

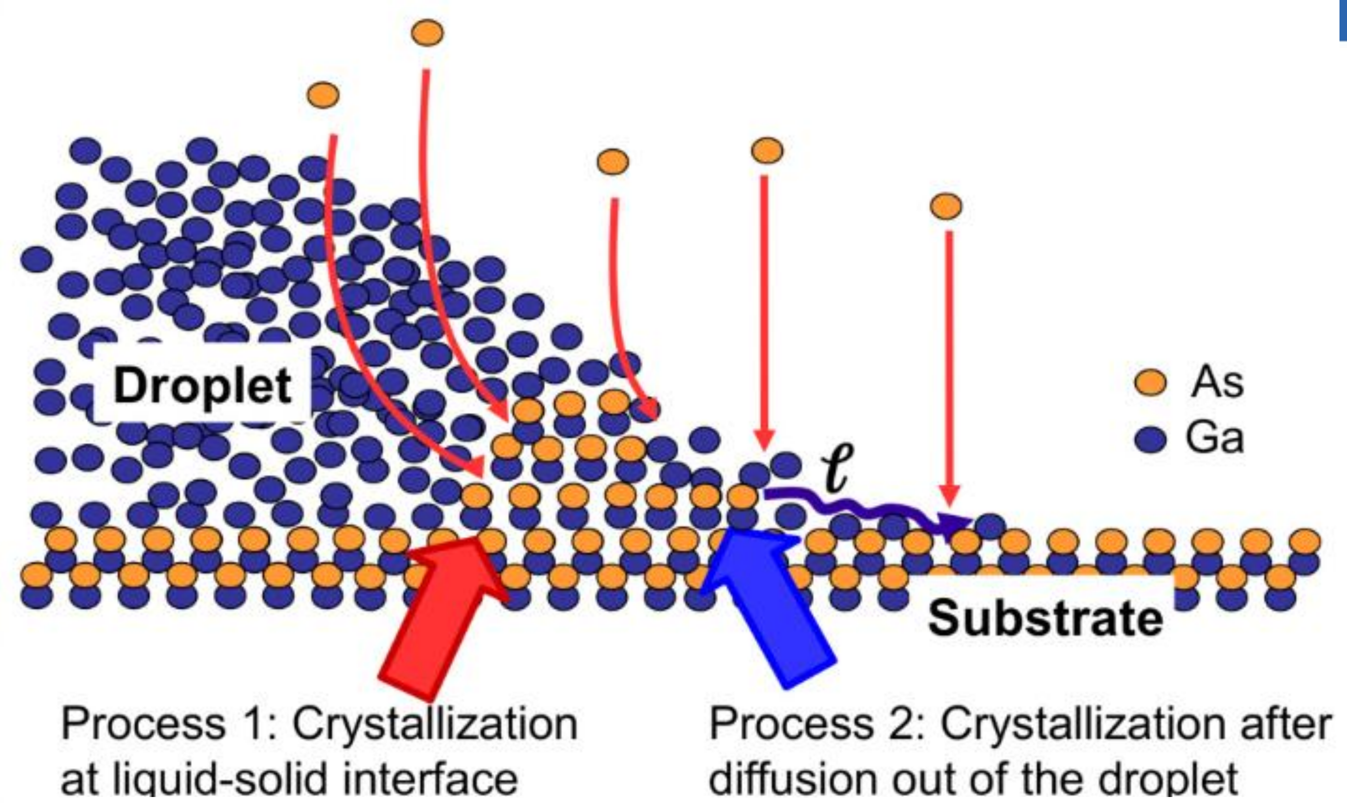
Crystalization controls geometry:

1) As incorporation in the droplet and crystalization at the **liquid-solid interface**
2) As adsorption on the surface and crystalization after **Ga out-diffusion**

$$\boldsymbol{l} = \sqrt{4D_{Ga}\tau}$$ Diff. length

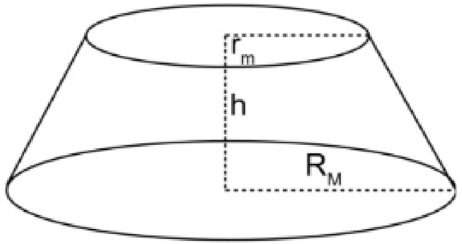
$$D_{Ga} = D_0 e^{-E_a/k\boldsymbol{T}}$$ Diffusivity

$$\tau = \frac{N_s}{\boldsymbol{J_{As}}}$$ Lifetime



DE-QDs formation

$$V_0 = \gamma R_0^3$$



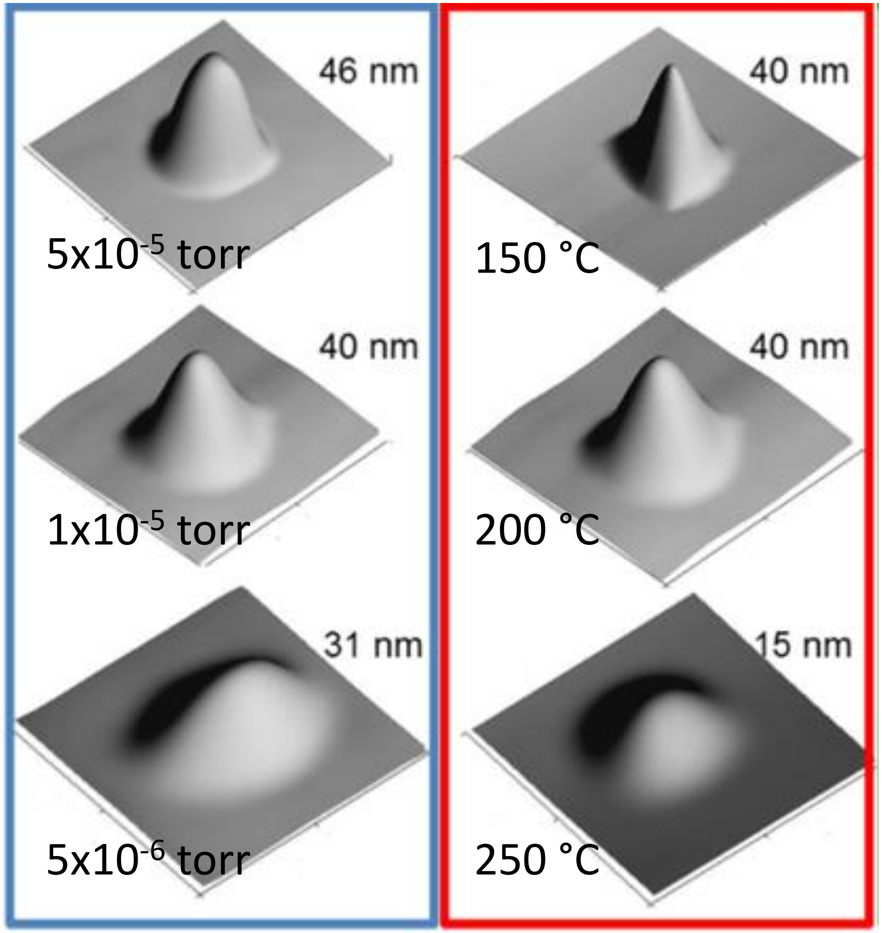
$$\boldsymbol{R_M} = R_0 + l$$

$$\boldsymbol{\rho} = \frac{h}{2R_M} = \frac{3}{2\pi}\frac{\beta\gamma}{(1+\alpha+\alpha^2)}\left(\frac{\boldsymbol{R_0}}{\boldsymbol{R_M}}\right)^{\boldsymbol{3}}$$

How to change **R** without changing h?
Increase **diffusion length**

How to change **h** without changing R?
Increase **droplet volume**

$$\boldsymbol{l} = \sqrt{4D_{Ga}\tau} \qquad \tau = N_s/\boldsymbol{J_{As}} \qquad D_{Ga} = D_0 e^{-E_a/k\boldsymbol{T}}$$



DE-QD shape engineering

Bietti et al., Phys Rev B 92, 075425 (2015)

QD-IBSC: engineering of carrier dynamics

QD: h≈3, 6 nm, D≈25

Aspect ratio $\rho = h/D$