SAND2020-4962PE

Accelerating scale-up of quantum processors with split accumulation gate quantum dots

Thesis defense

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UNIVERSITÉ DE SHERBROOKE

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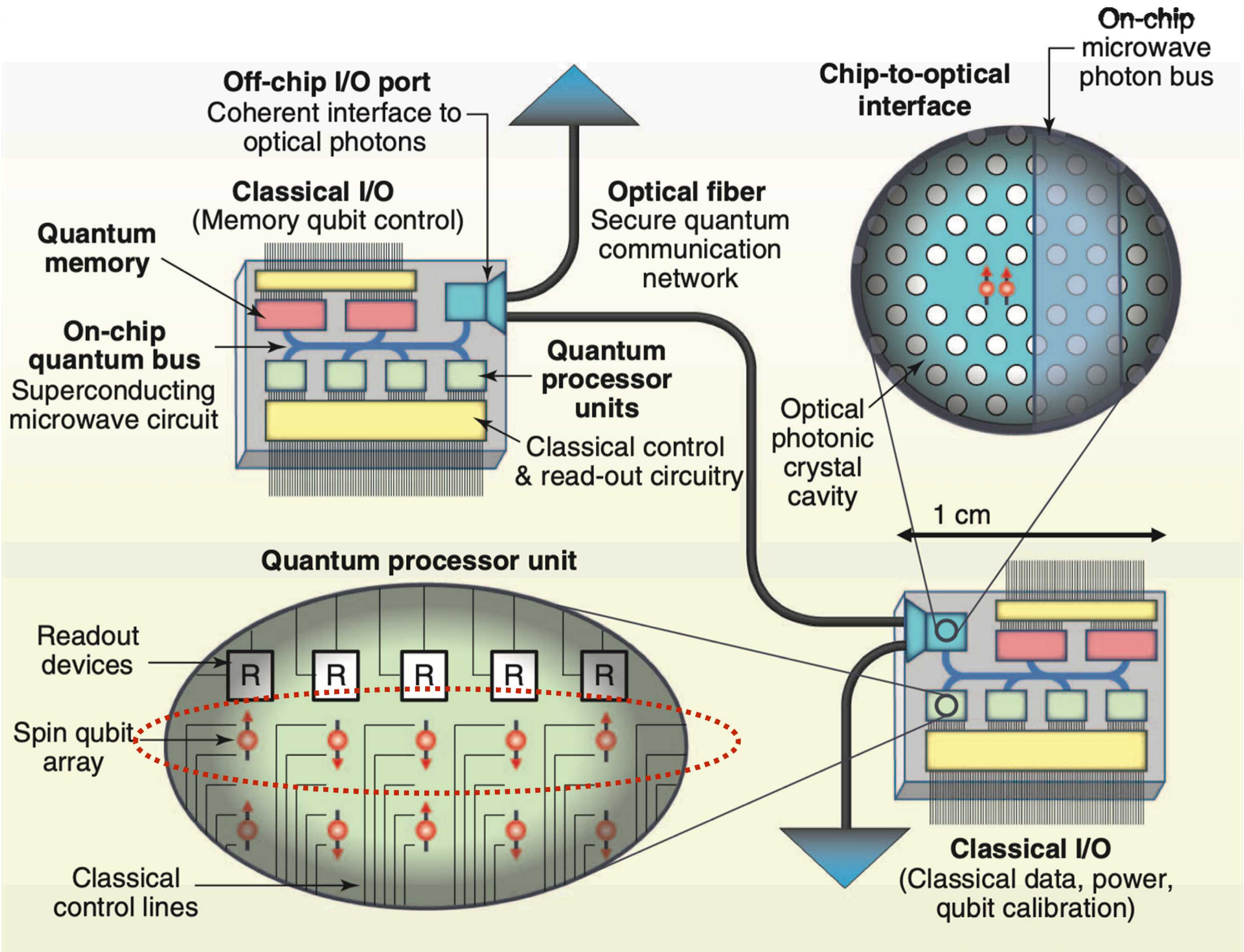
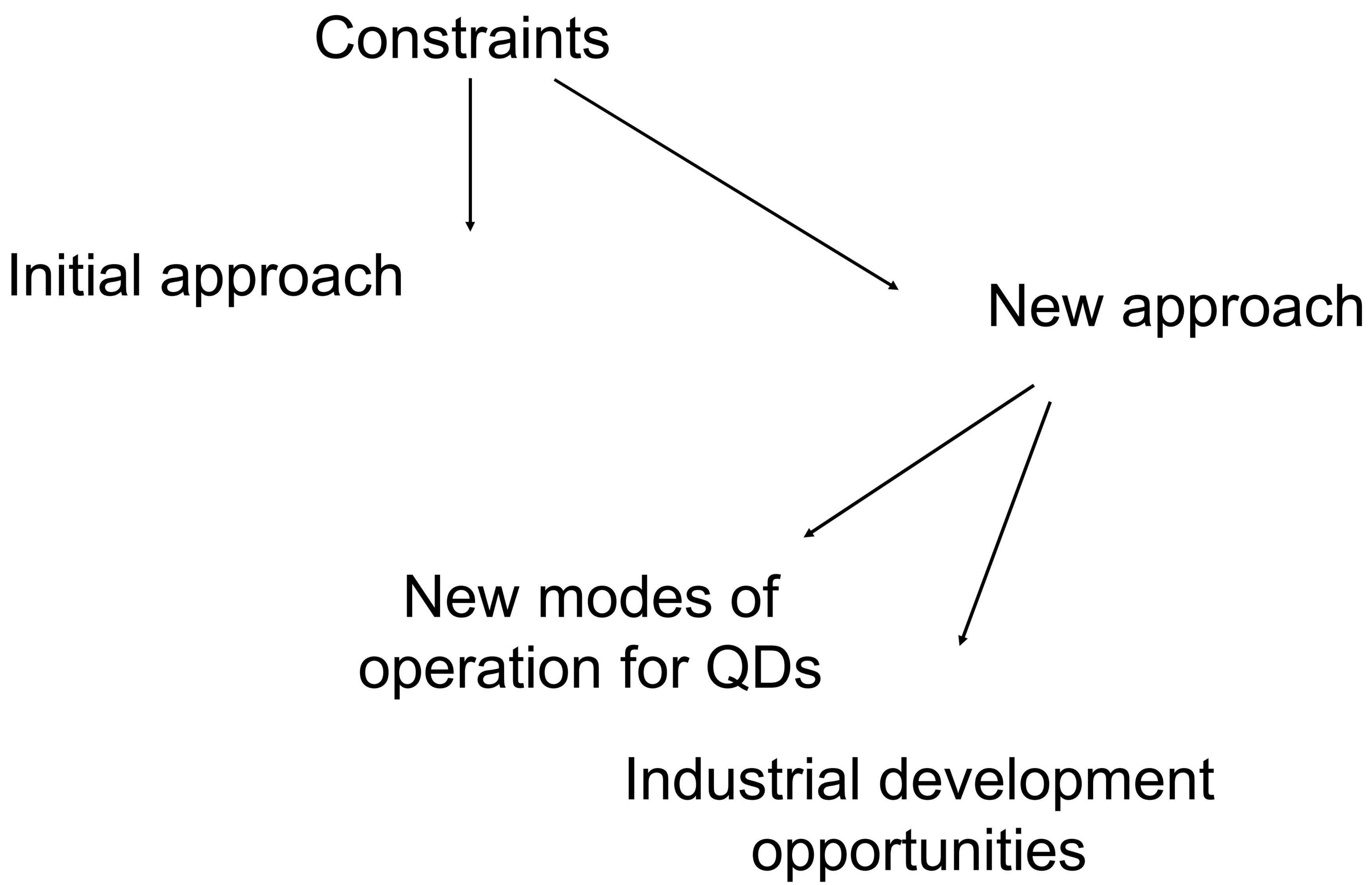
Next step for spin qubits: large-scale integration

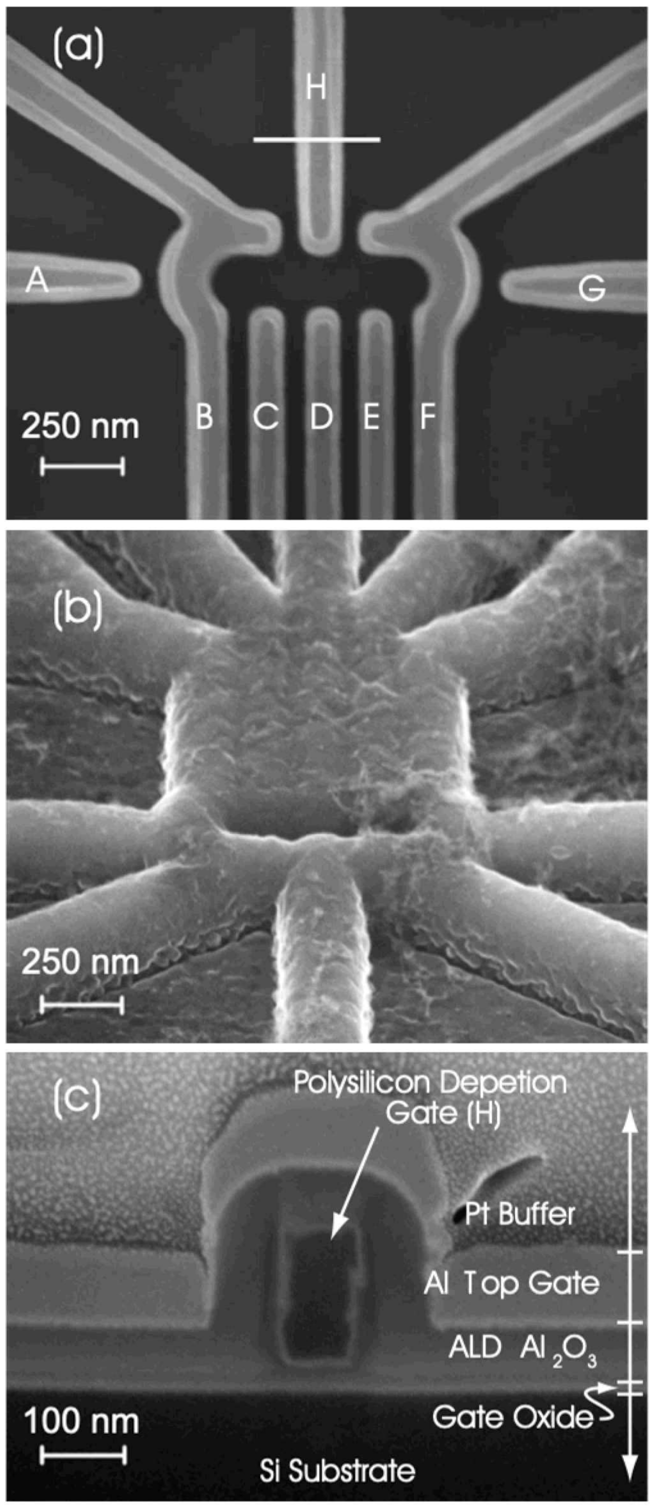


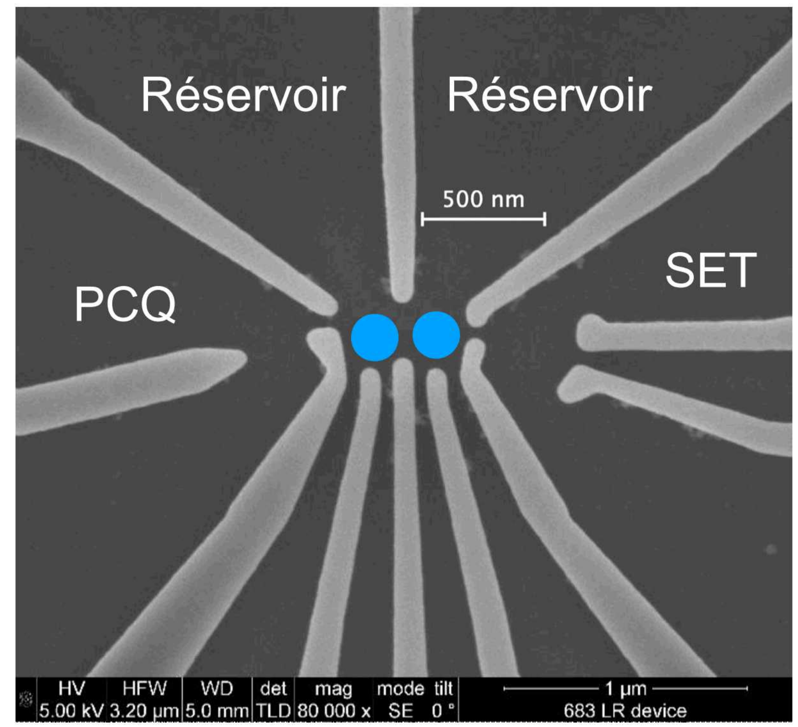
Awschalom et al., Science 339, 1174 (2013)

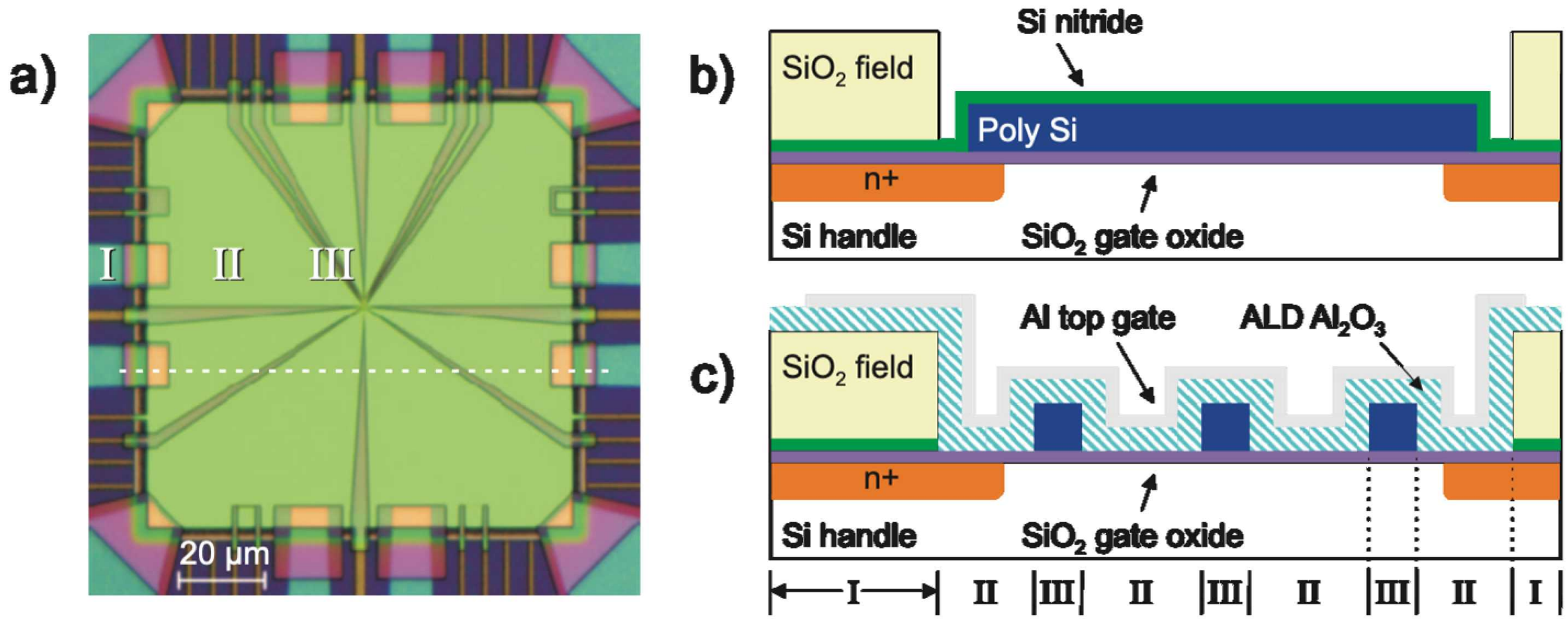
Thesis overview



Previous structure:
Multi-layers with global accumulation



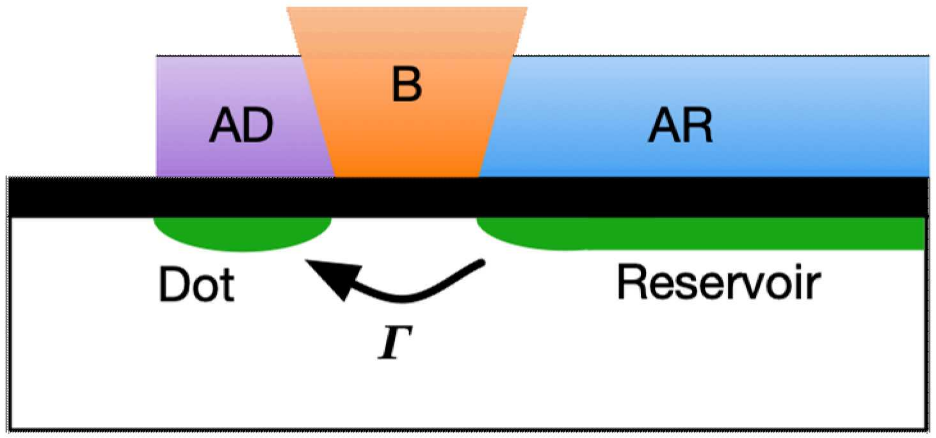




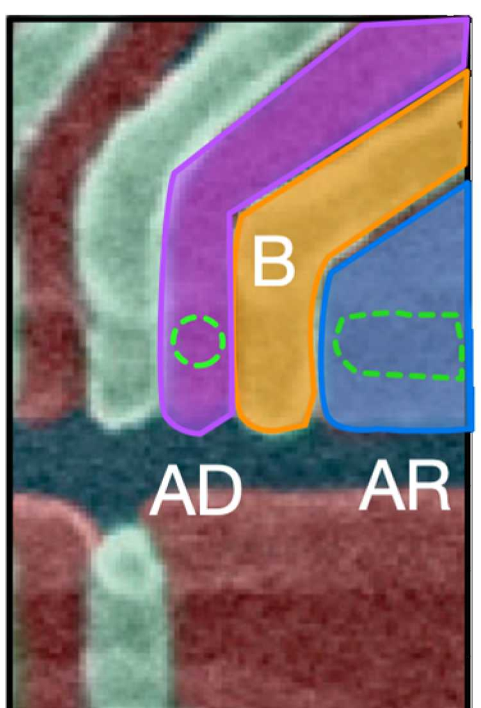
E. P. Nordberg *et al.*, PRB **80**, 115331 (2009)

BQ-reservoir tunnel barrier control methods

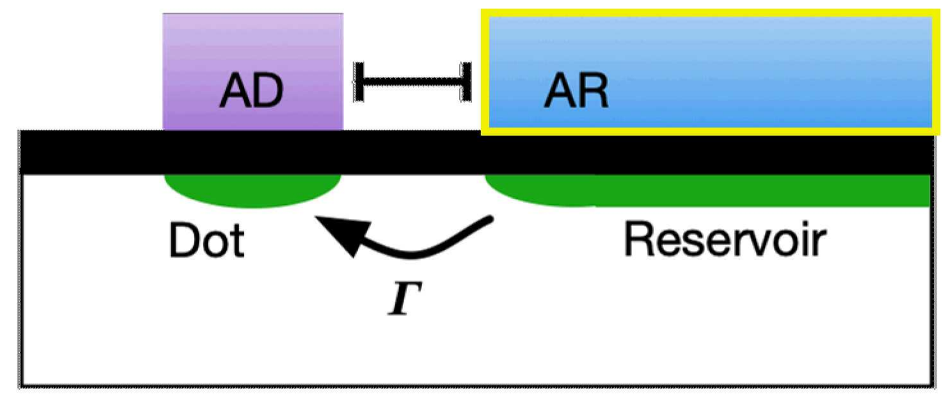
Local accumulation gates devices



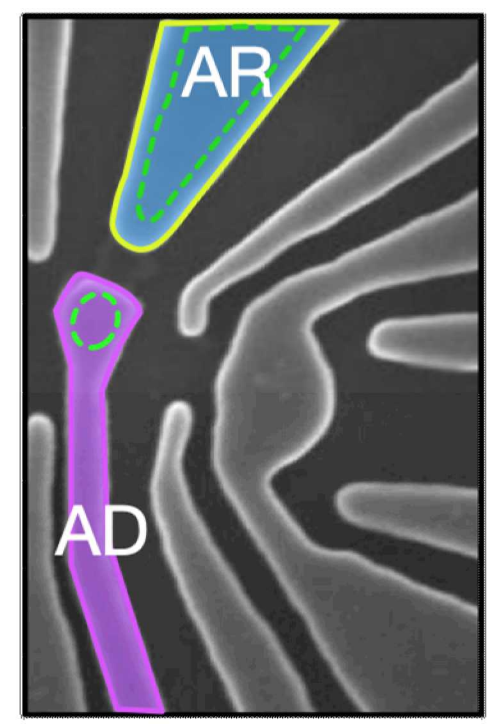
Dedicated barrier gate



Zajac *et al.*, 2016



No dedicated barrier gate



Objectives:

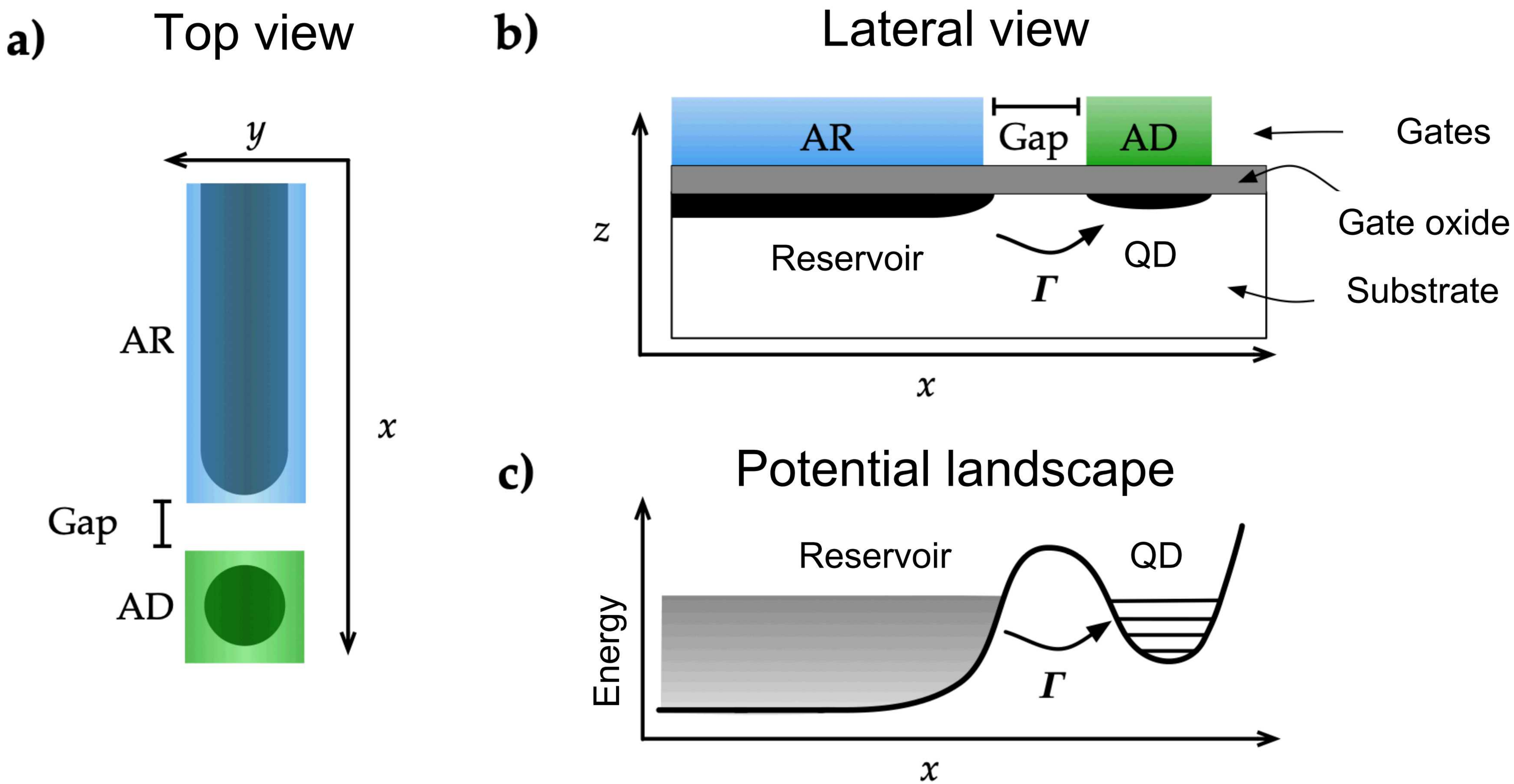
- Verify respect of minimal performance criterias for qubits;
- Demonstrate possible advantages of the split accumulation gate structure;
- Study particularities of the structure and develop new tools and models.

Structure of the talk

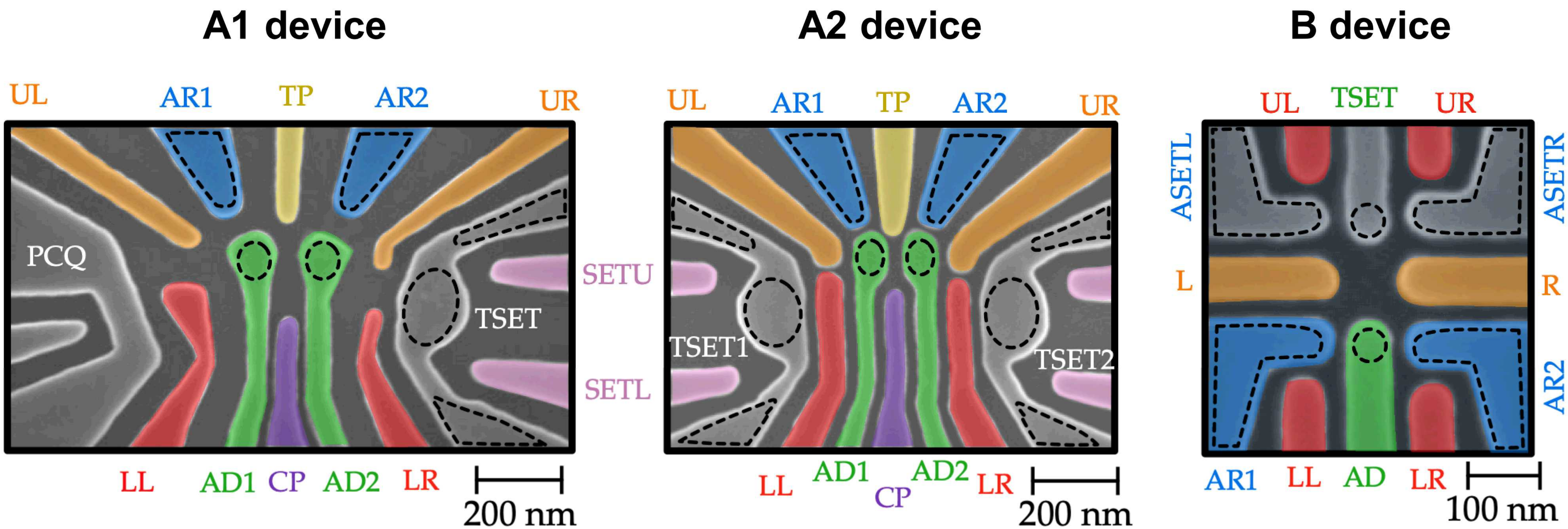
1. Elementary notions of quantum dots
2. Split accumulation gate devices
3. Single-electron regime and confinement
4. Control of the tunnel rate with the split accumulation gate structure
5. Role of the reservoir charge density in the split accumulation gate structure operation
6. Scaling: industrial approach
7. Conclusion

Split accumulation gate devices

Split accumulation gate structure



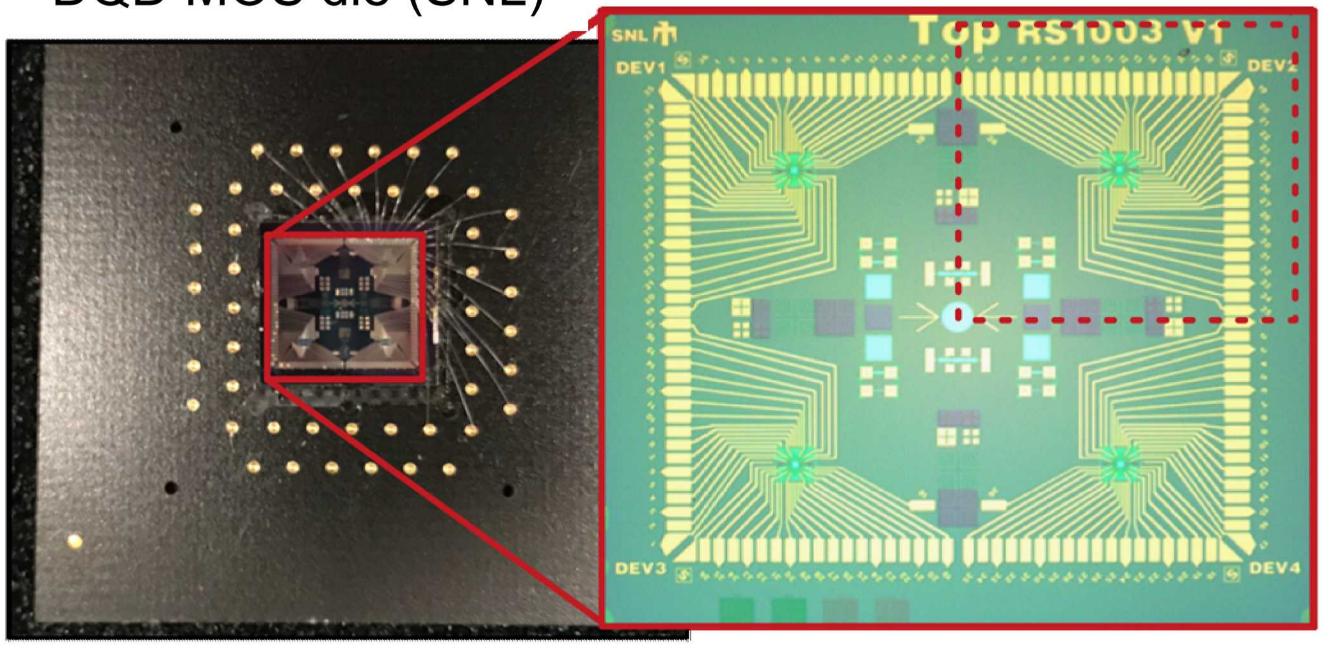
Devices



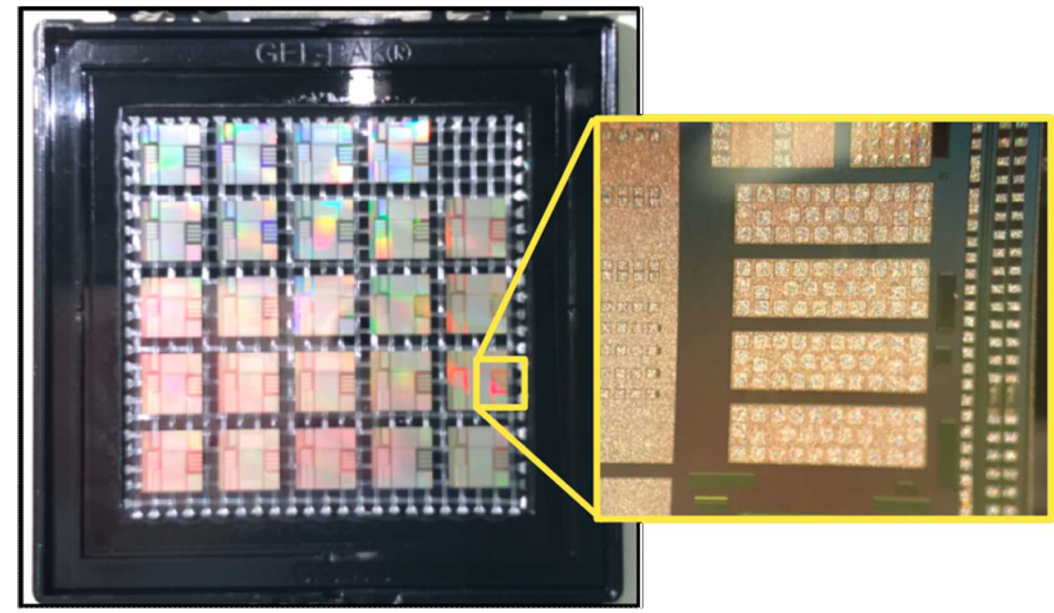
- Reservoir accumulation gate
- Quantum dot accumulation gate
- Accumulated electrons
- SET control gate
- Lateral depletion gates
- Inter-QD coupling and depletion gate
- Separation gate
- Inter-QD coupling and depletion gate

Devices

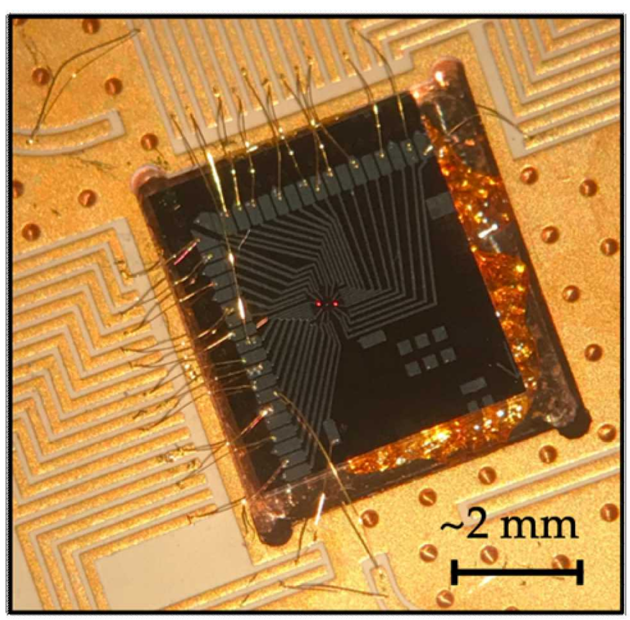
a) DQD MOS die (SNL)



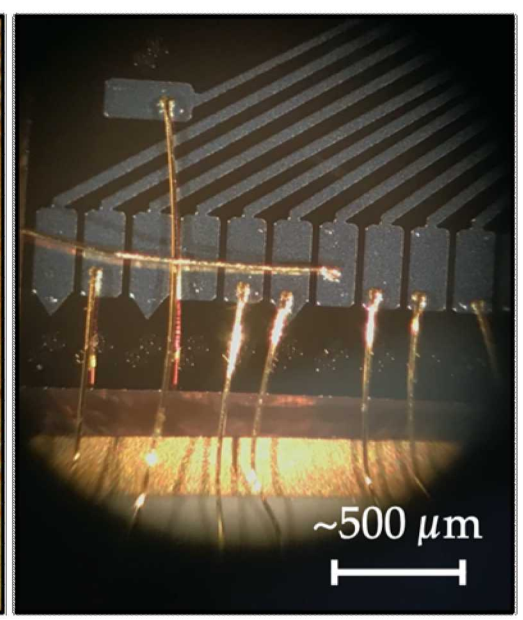
b) 2D FDSOI arrays die (STMicro)



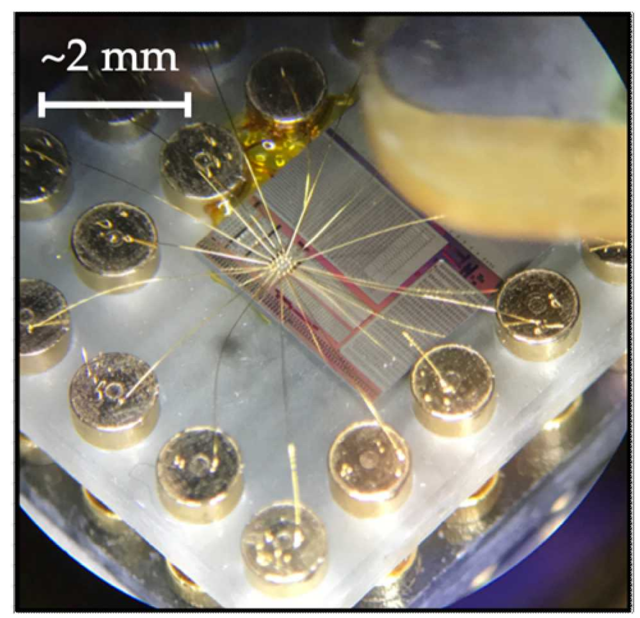
a)



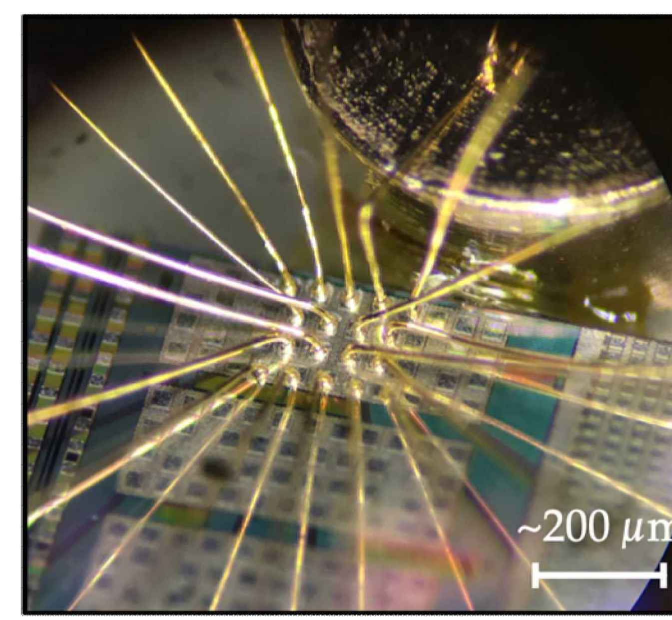
b)



c)

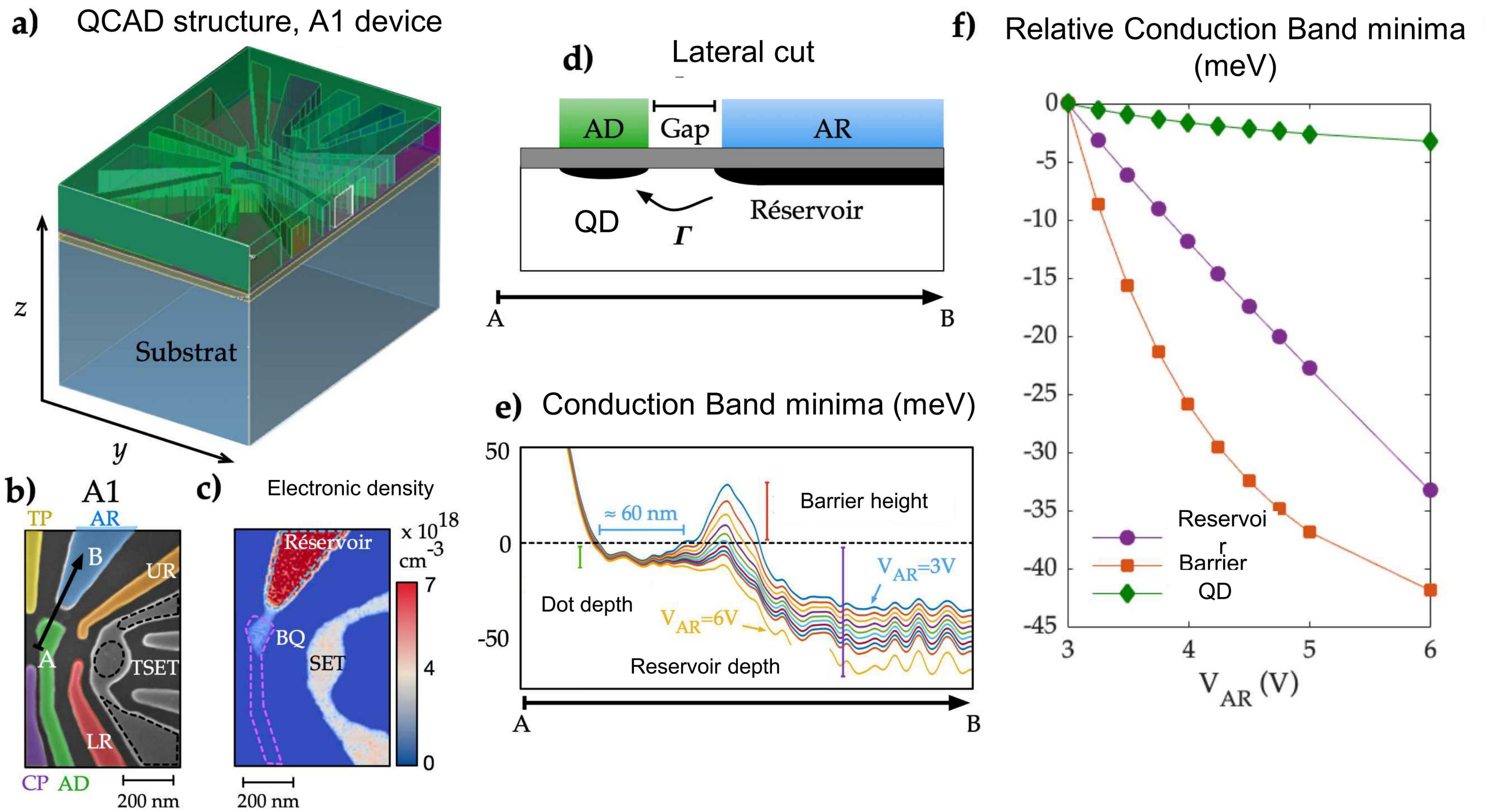


d)



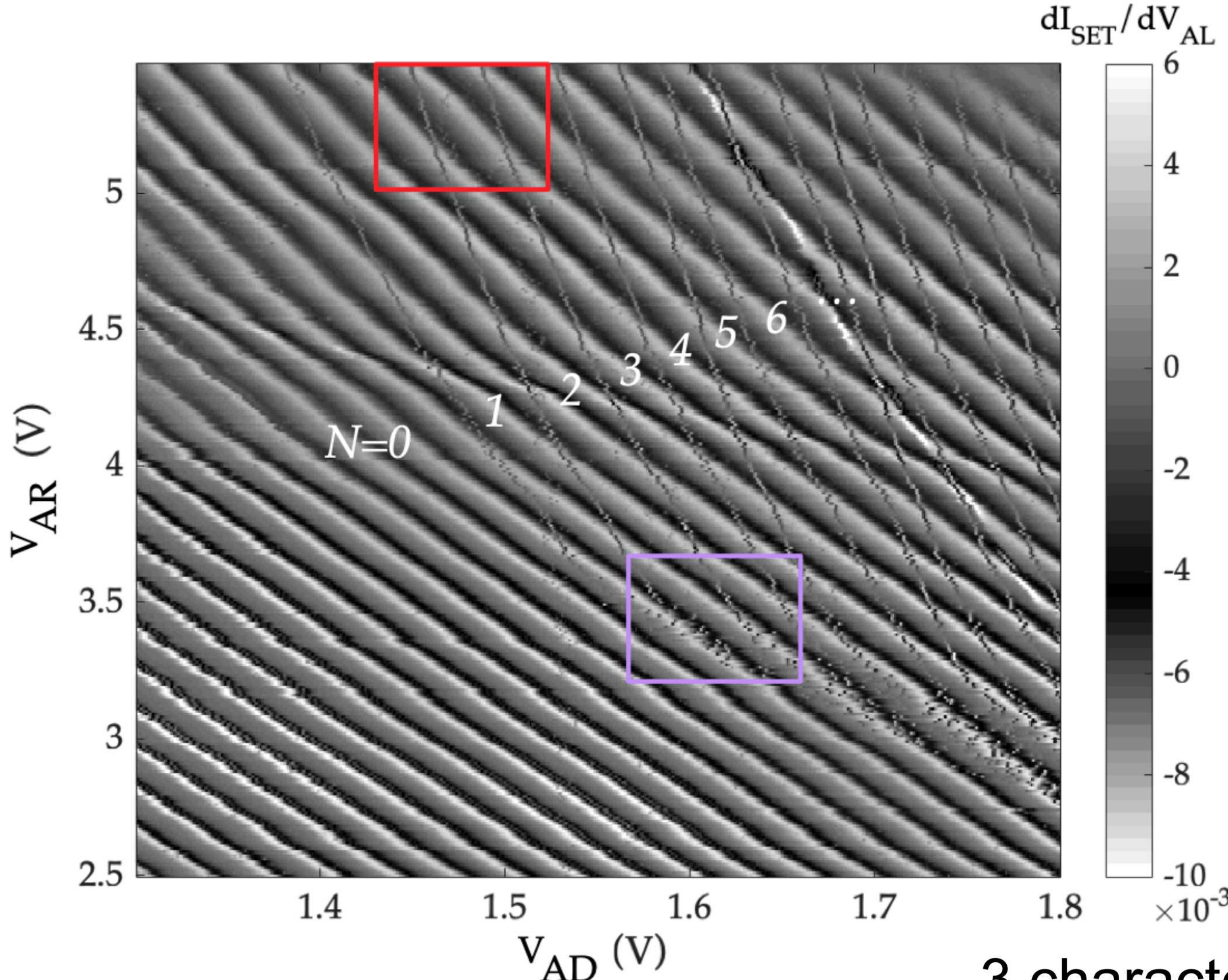
Single electron regime and confinement

Device operation

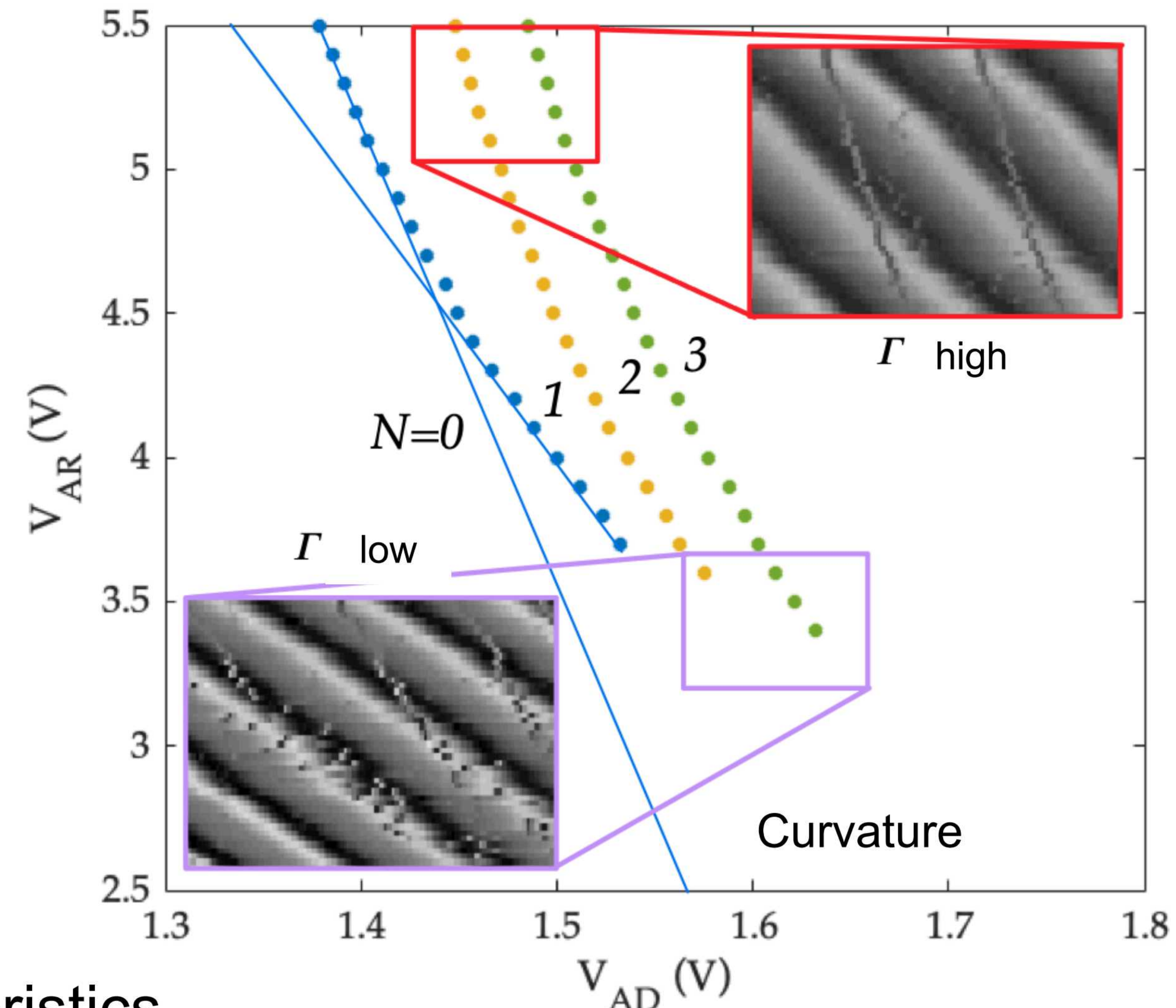


Single electron regime

a) A2 device stability diagram



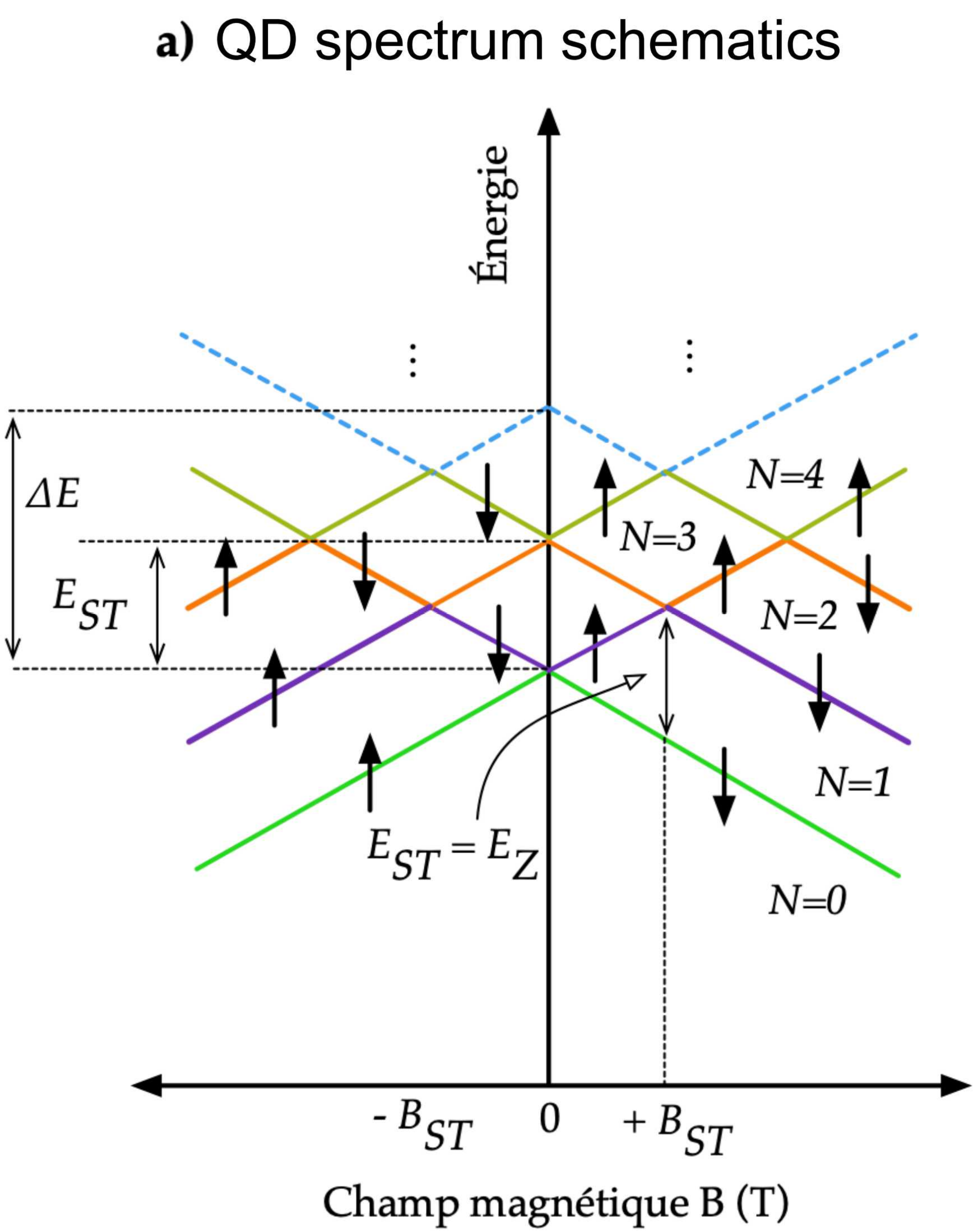
b) First 3 charge transition

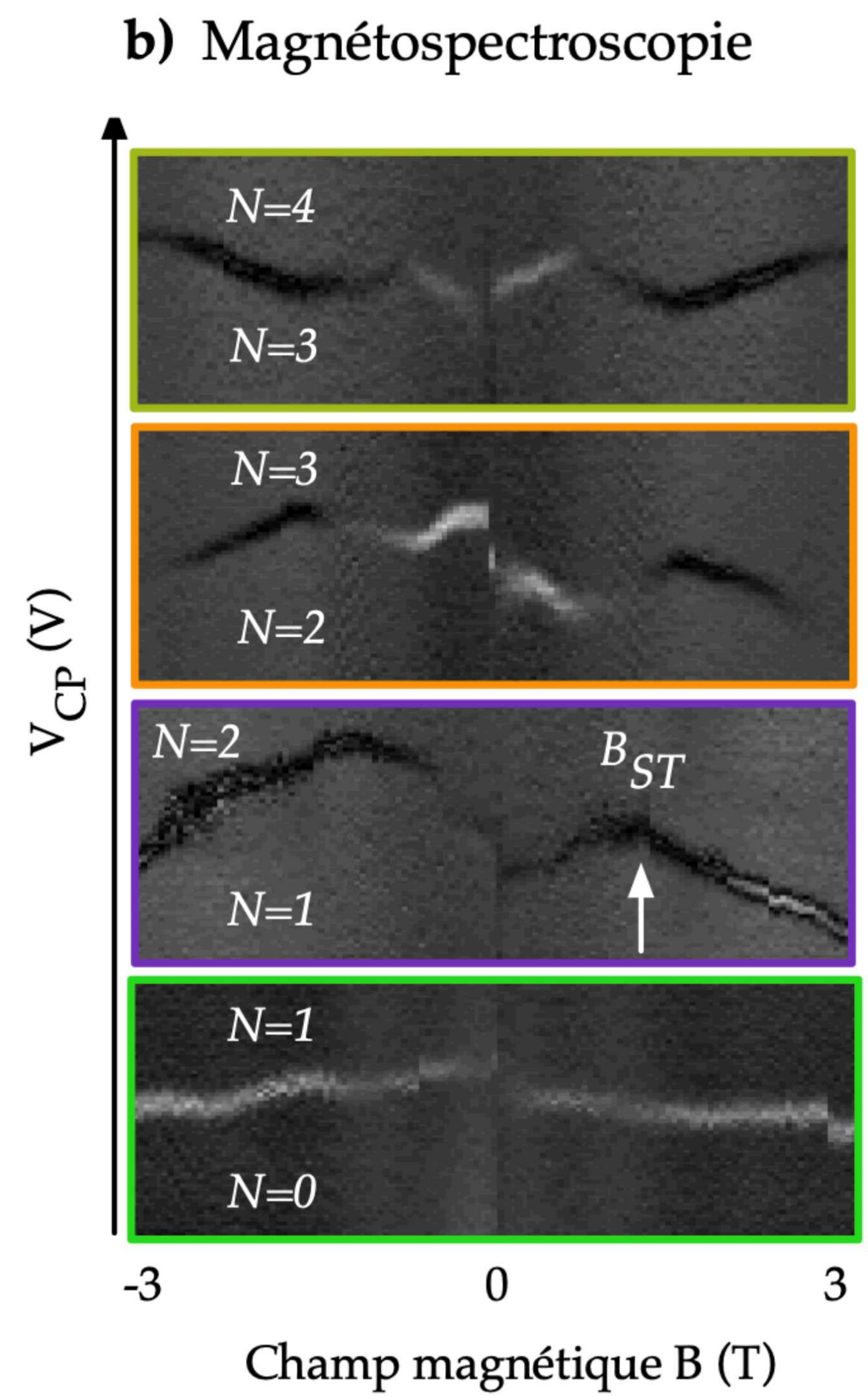


3 characteristics

1. Vanishing of transitions
2. Pixelisation vs widening transitions
3. Charge transitions curvature

Single electron regime

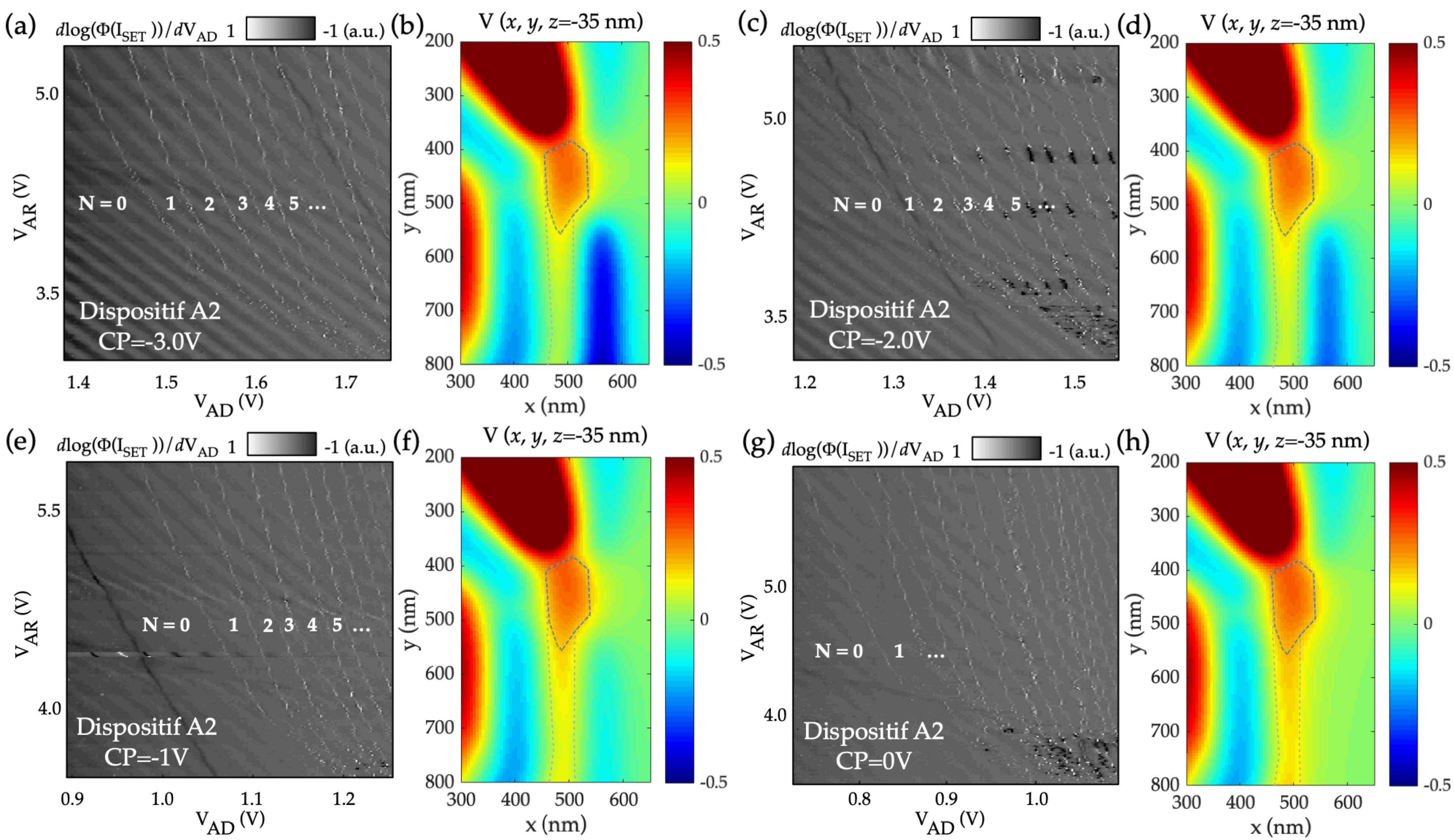




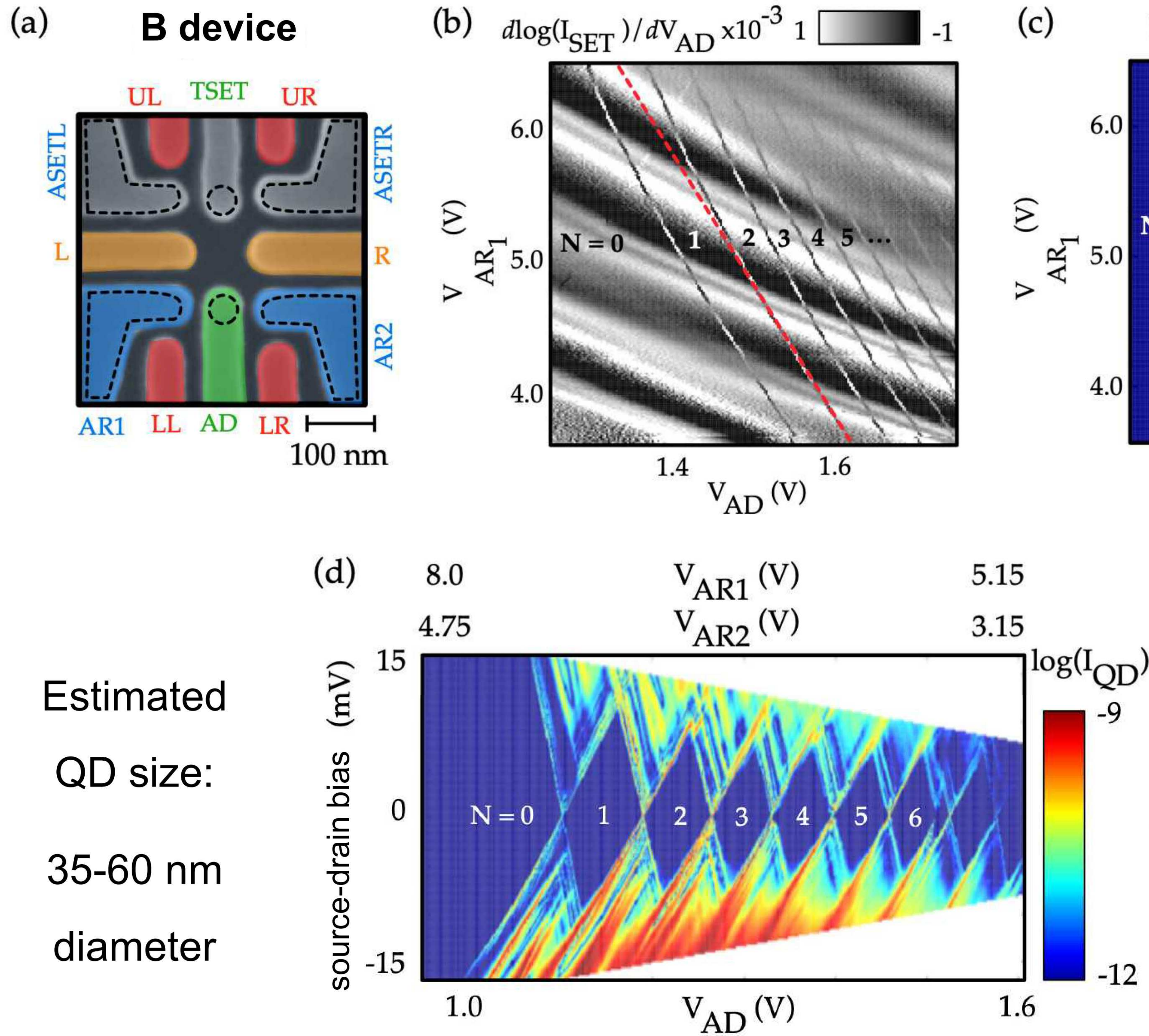
Behavior in magnetic field of the first transitions

consistent with 0 electrons

Electrostatic confinement



Single electron regime



Estimated

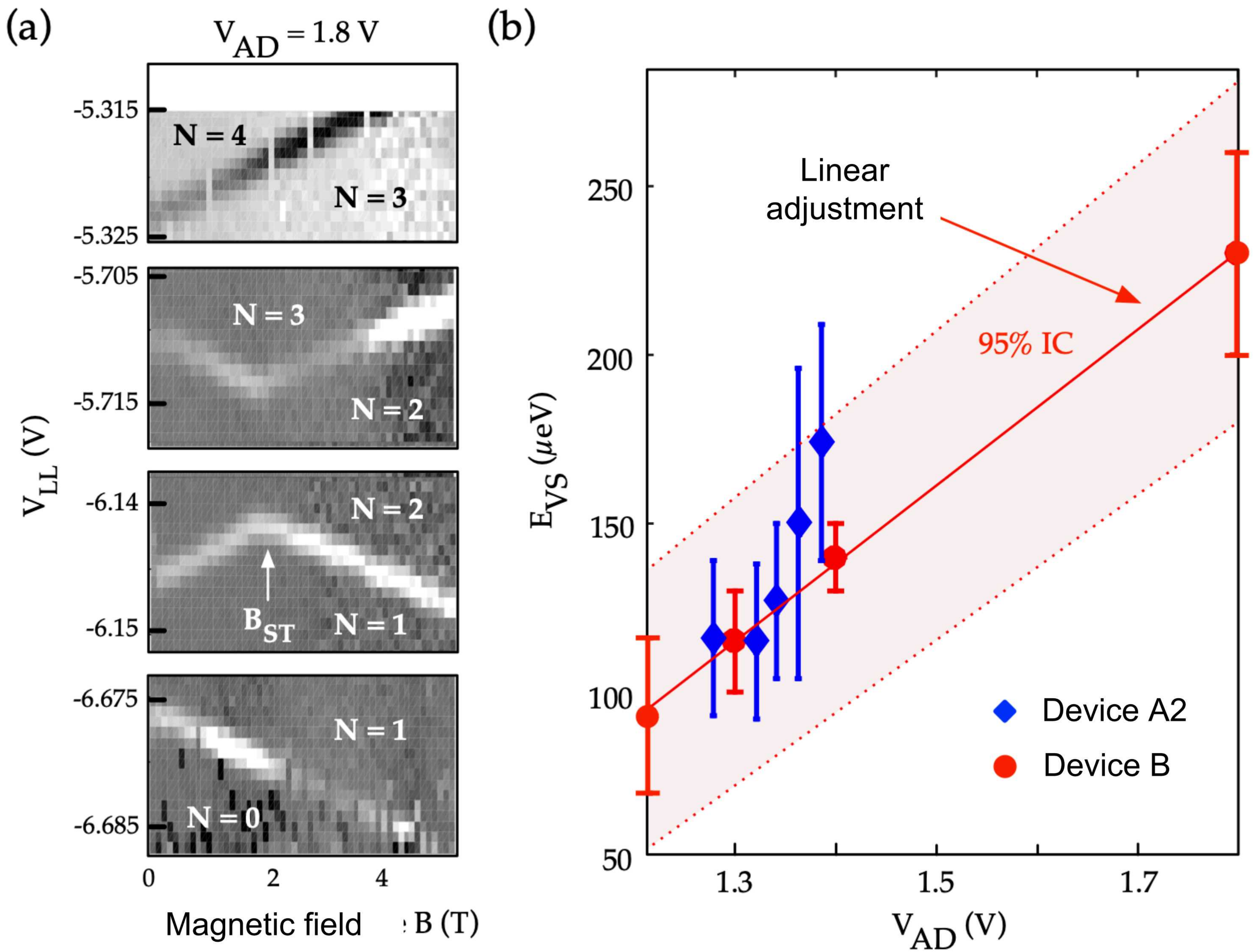
QD size:

35-60 nm

diameter

Reproducibility of typical characteristics in double-reservoir geometry

Valley splitting control



VS controlability

8.1 ± 0.6 μeVm/MV,

Between 5 and 11 μeVm/MV when considering error bars.

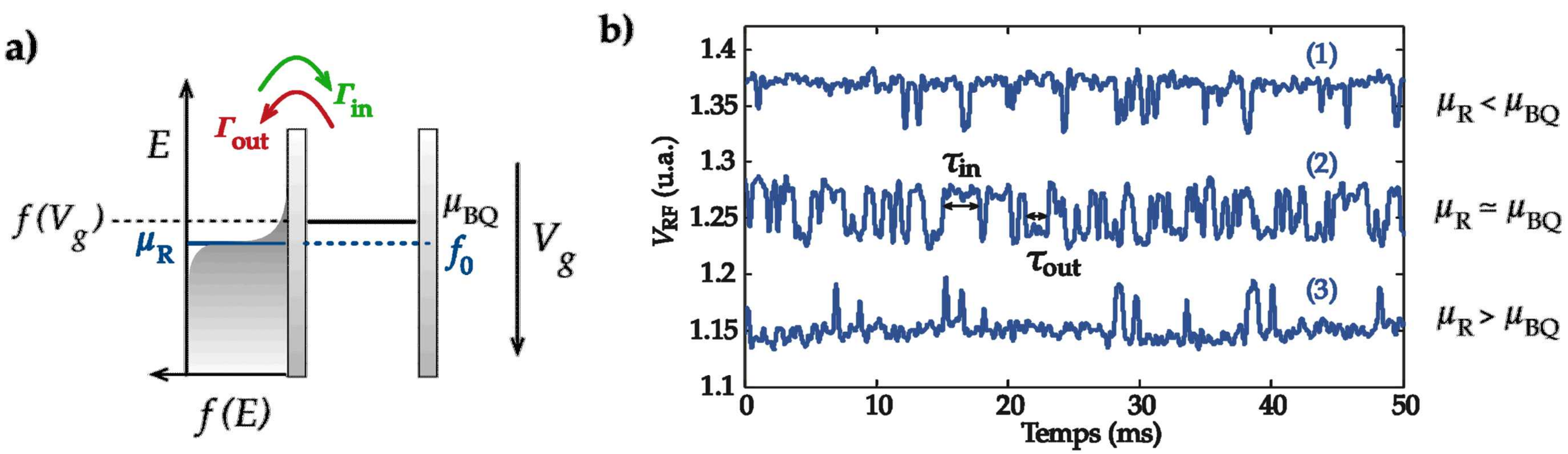
Multi-layers MOS (Yang *et al.* 2013): 5.12 μeVm/MV

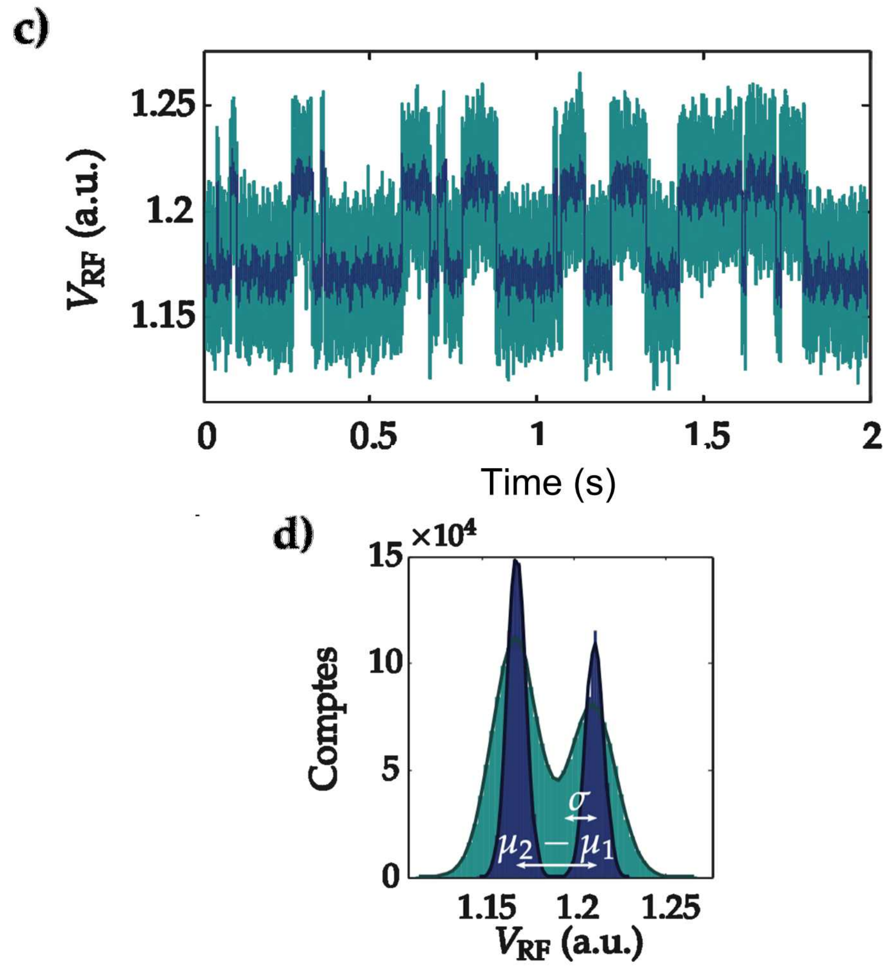
Tunnel rate control
in the split accumulation gate structure

Tunnel rate measurement

Method 1:

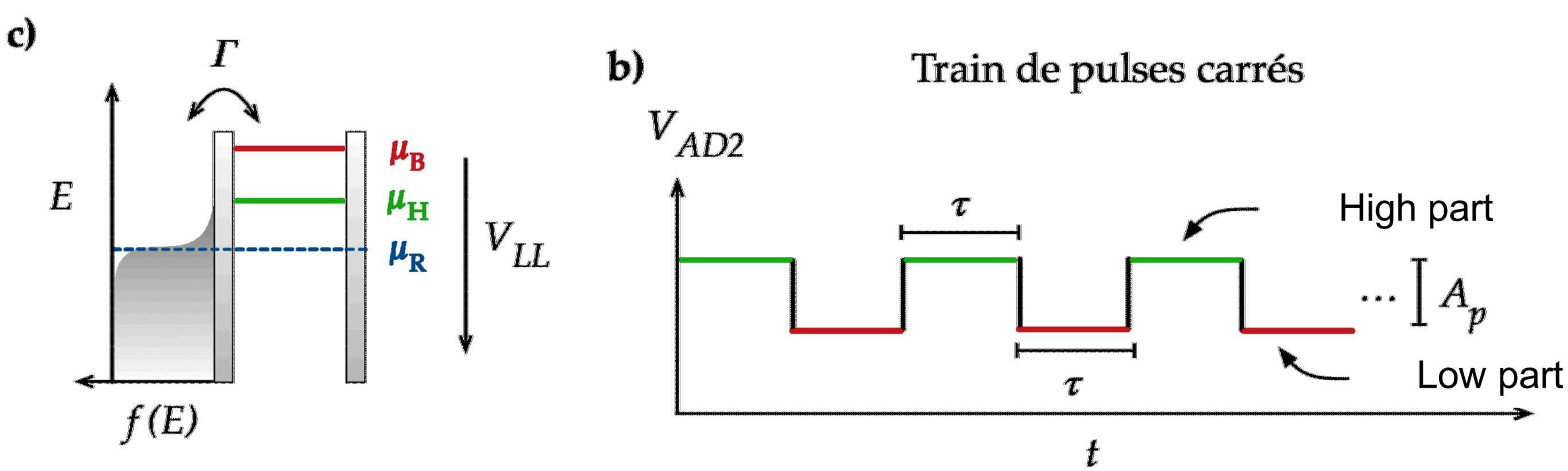
Real-time single shot statistics

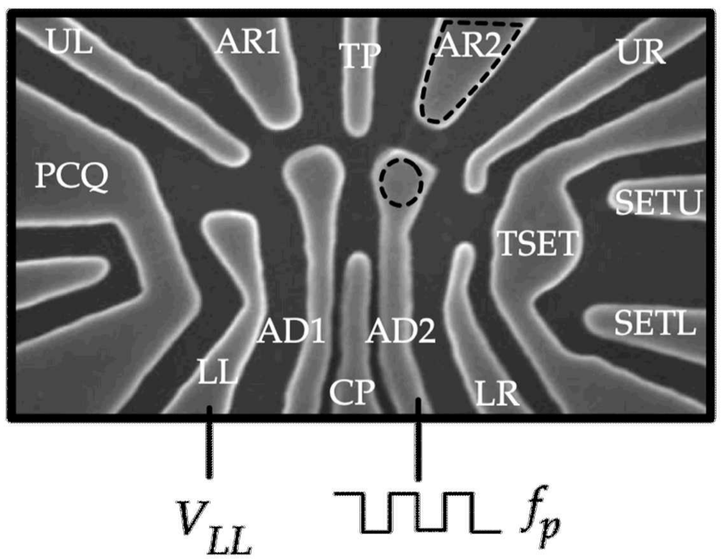




Method 2:

Single-frequency pulse spectroscopy

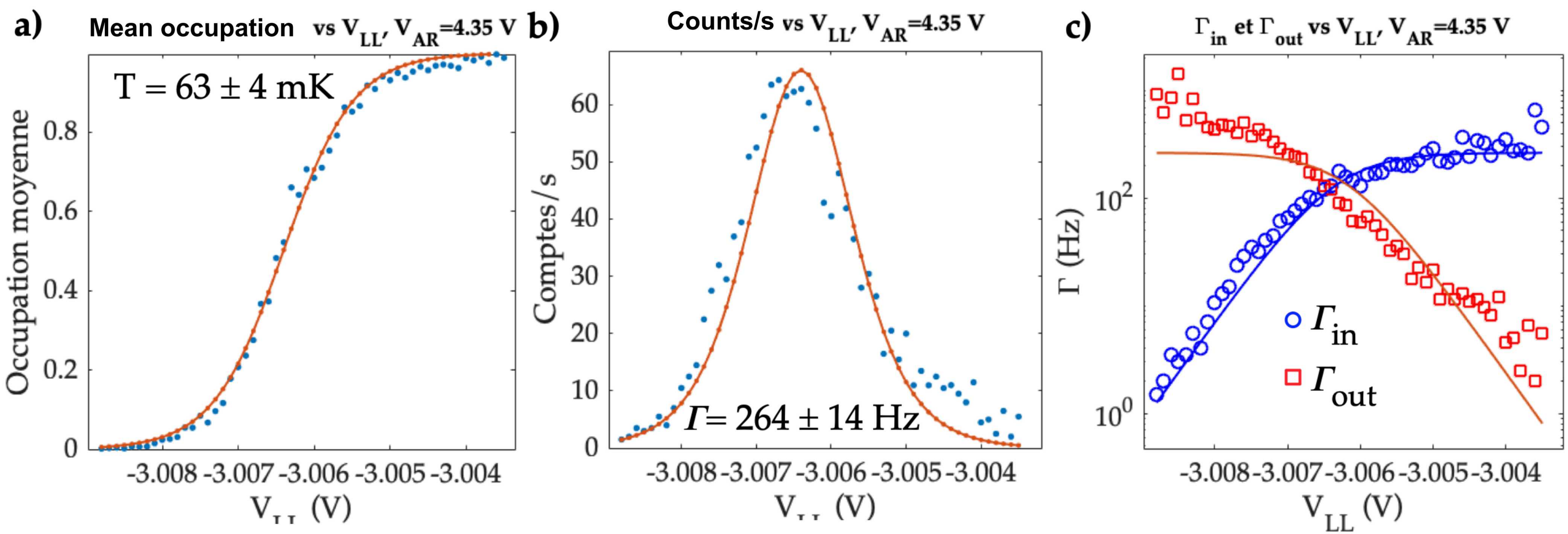




Tunnel rate measurements

Method 1:

Real-time single shot statistics



$$f(\mu_{BQ}) = \frac{<\tau_{out}>}{<\tau_{in}> + <\tau_{out}>}.$$

$$f(\mu_{BQ}) = \frac{1}{1 + e^{\frac{\mu_{BQ}-\mu_R}{k_B T}}}$$

$$r_E = \frac{1}{<\tau_{in}> + <\tau_{out}>}.$$

$$r_E = \Gamma f(1-f)$$

$$\Gamma_{in} = \Gamma f(\mu_{BQ}),$$

$$\Gamma_{out} = \Gamma(1 - f(\mu_{BQ})),$$

Electronic temperatures:

30-73 mK

Γ increases with V_{AR}

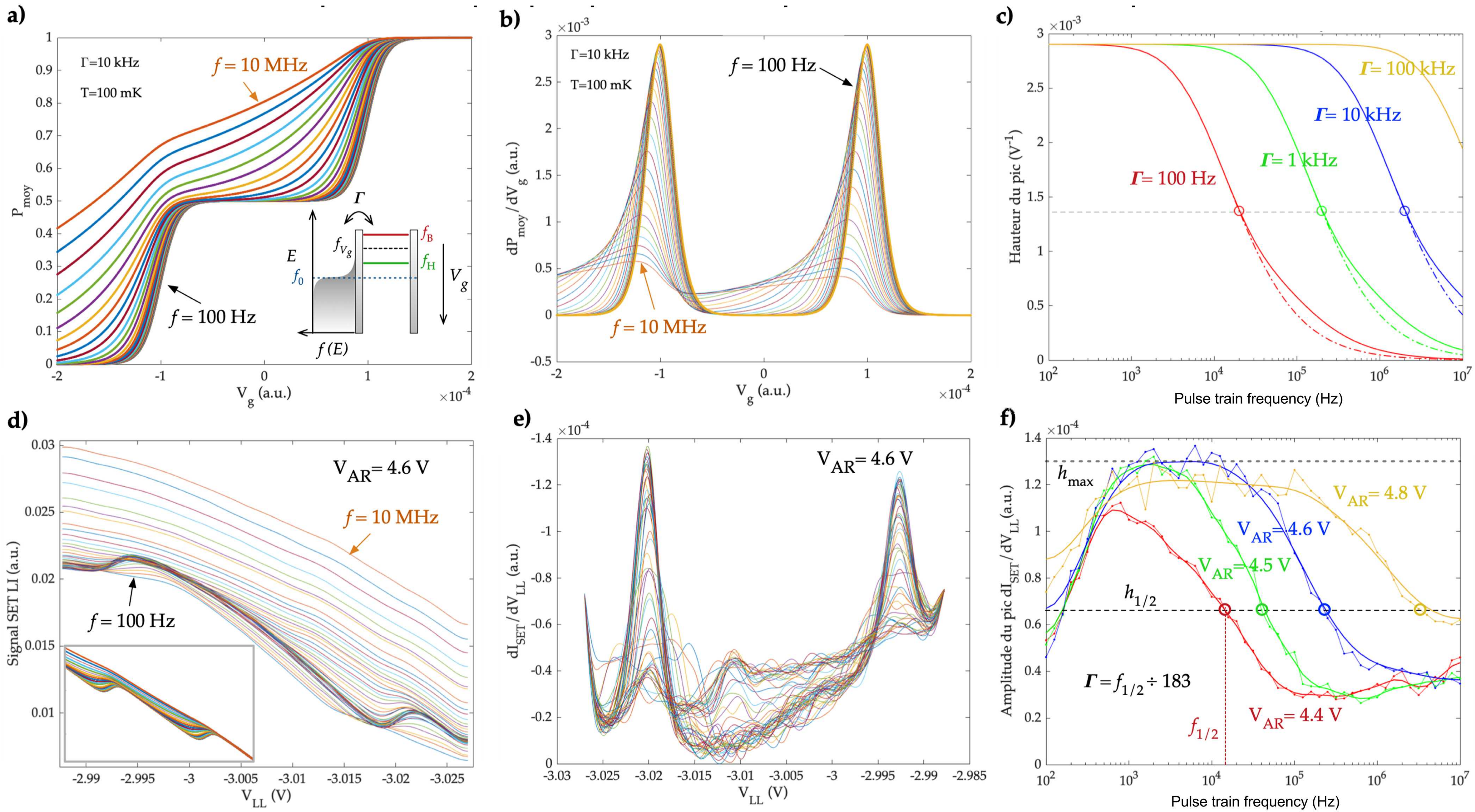
Excited states

contribution neglected

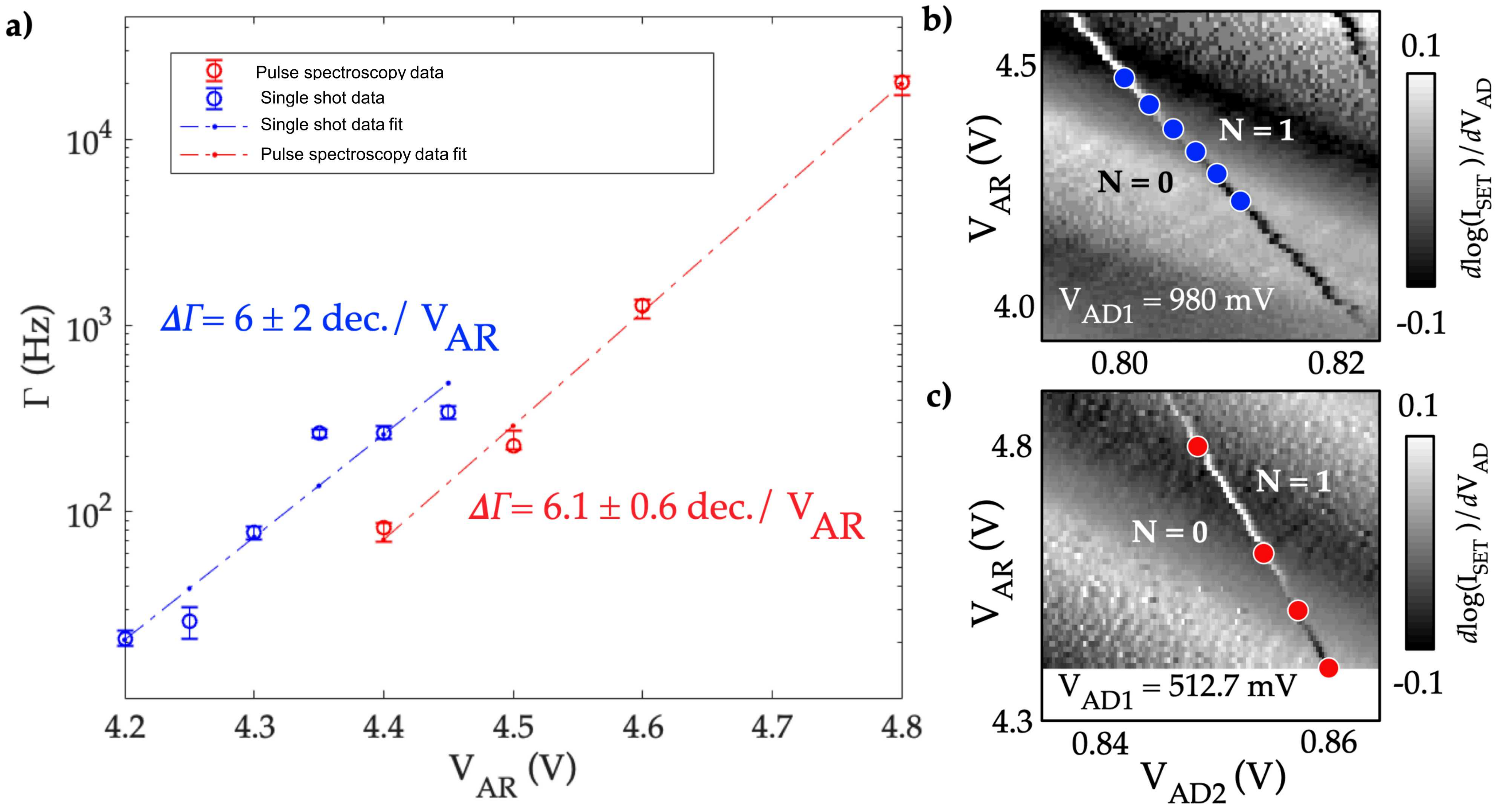
Tunnel rate measurement

Method 2:

Single-frequency pulse spectroscopy



Tunnel rate control using the reservoir accumulation gate



Tunnel rate control with the reservoir accumulation gate

Tunnel rate variation in decades

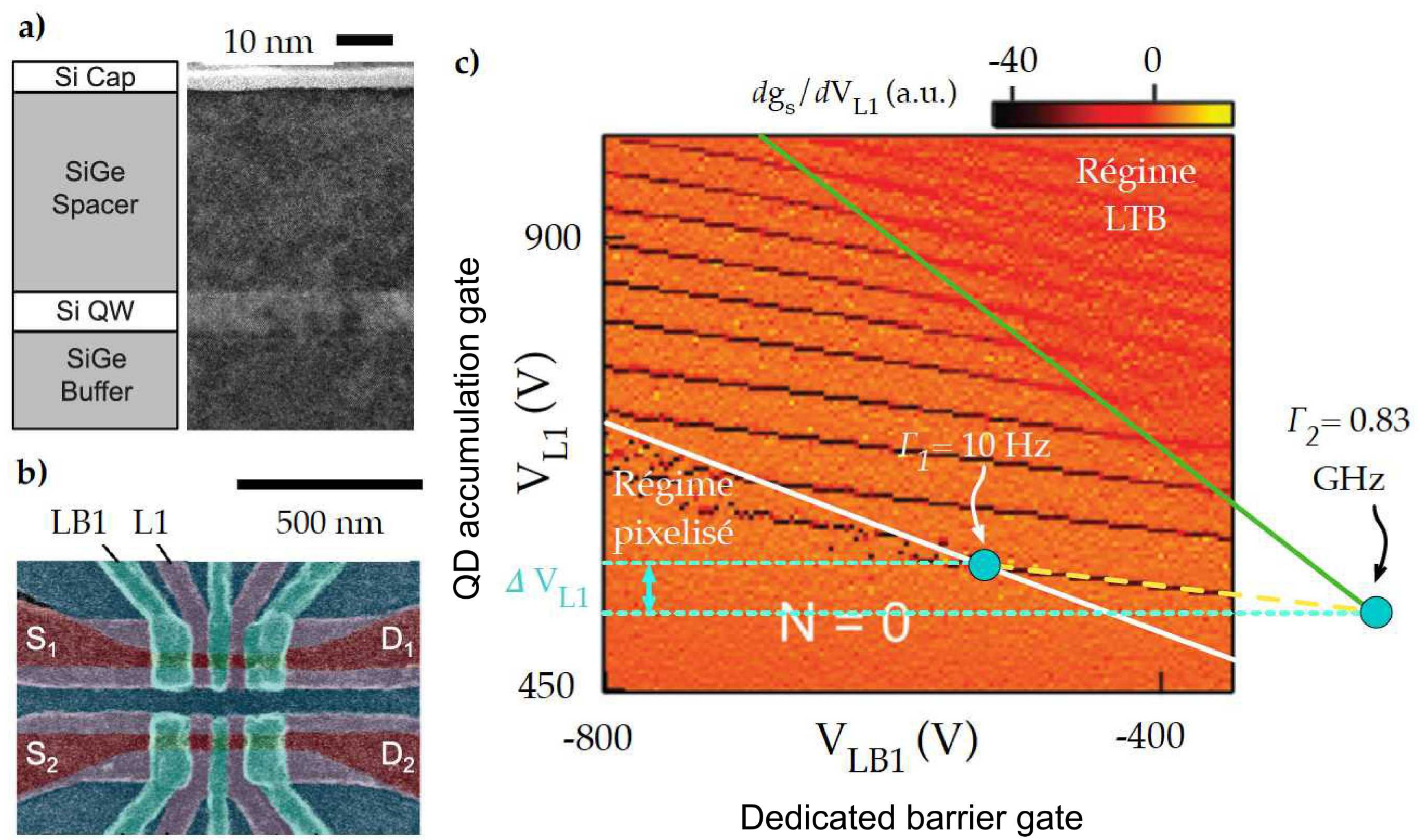
$$\beta_{g1,g2} \equiv \beta_{g1} - \beta_{g2} = \frac{\Delta\Gamma_{g1,g2}}{\Delta\mu_g 1},$$

Chemical potential variation in meV

Measure of the *control orthogonality*:

Level of control independance between tunnel rate and QD occupation

Allows comparison between different devices



3 performance criterias

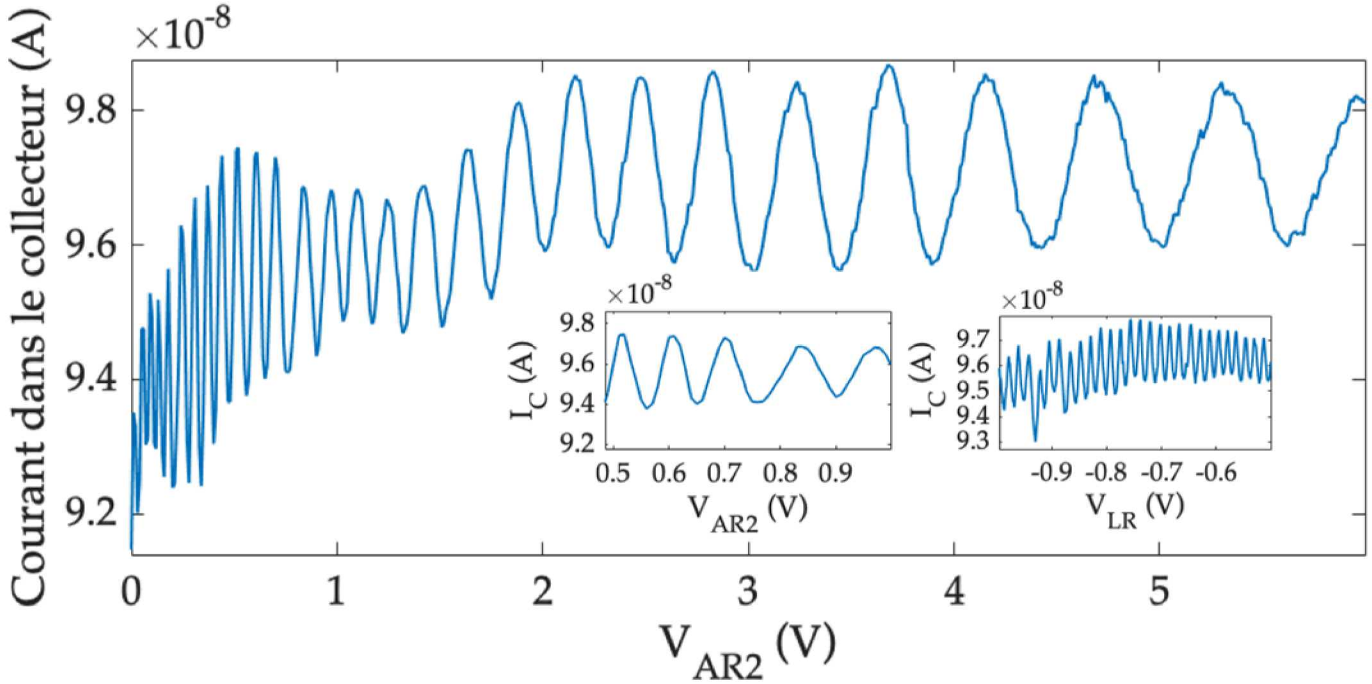
Device:	A1	A2	B	Litterature
QD diamenter	-	48-77 nm	35-60 nm	20-58 nm [1,2,3,4,5]
Valley splitting	-	-	β = [5, 11] μeVm/MV	β = 5.12 μeVm/MV [6]
Tunnel rate	β = 0.9 ± 0.3 dec/meV	-	-	β = [1.0, 2.4] dec/meV [1]

[1]: D. M. Zajac et al., APL 106, 223507 (2015)
[2]: S. J. Angus et al., Nano Letters 7, 2051-5 (2007)
[3]: M. Veldhorst et al., Nat. Nano., 1-5 (2014)
[4]: C. H. Yang et al., Nat. Electronics 2, 151 (2019)
[5]: M. Veldhorst et al., Nature, 1-5 (2015)
[6]: C. H. Yang et al., Nat. Comm., 3069, 2013

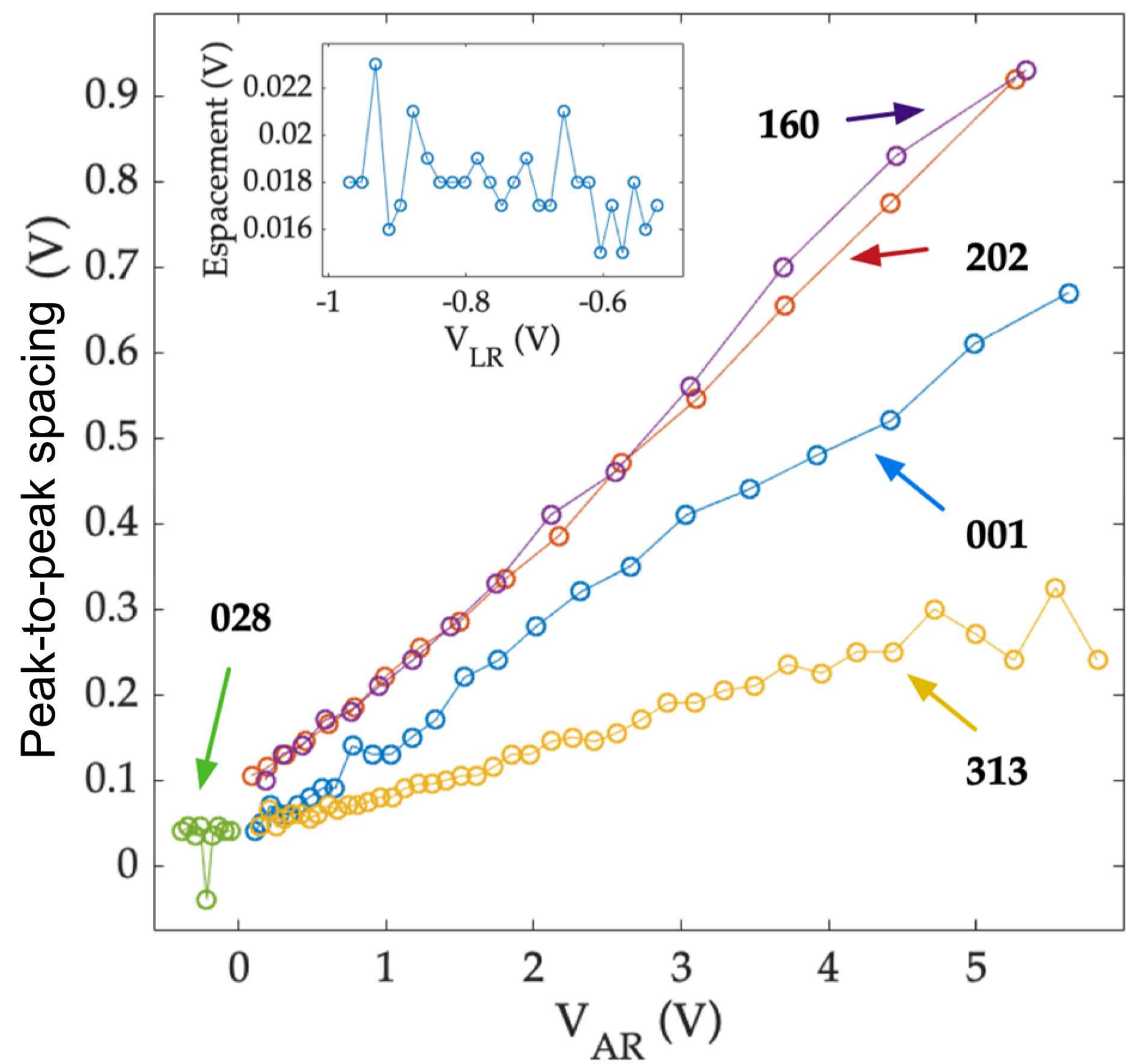
Role of the reservoir charge density in split accumulation gate structure operation

A model for the charge transition curvature

a) **SET2 oscillations for a reservoir accumulation gate**



b) **Peak-to-peak spacing vs V_{AR}**



Linear increase of

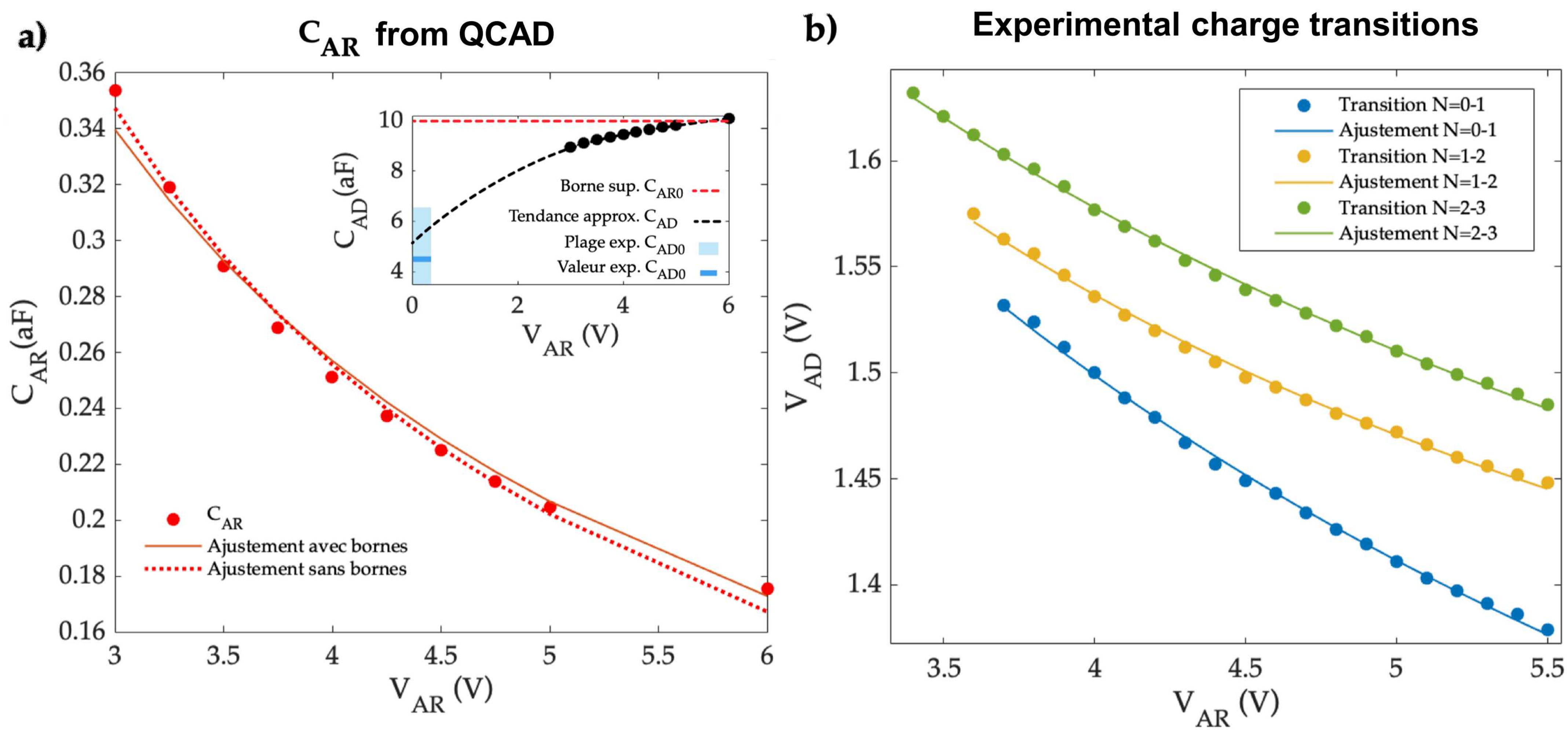
oscillation period:

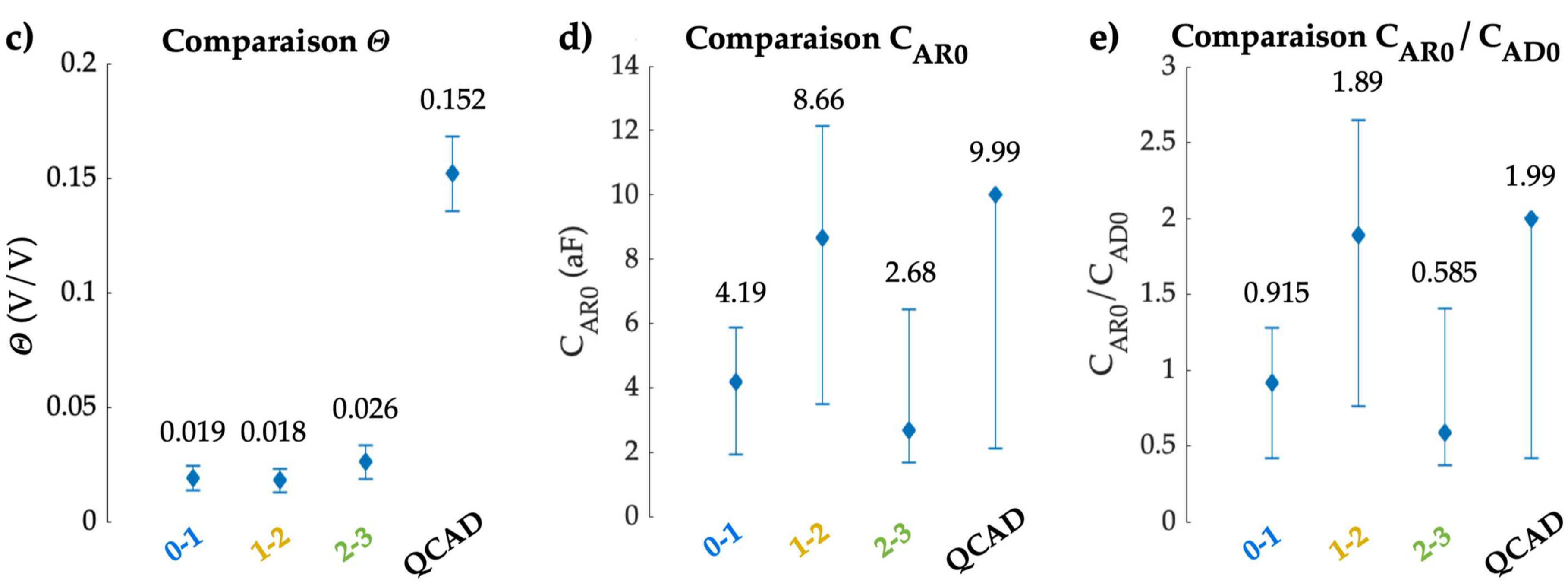
$$P_{AR\to SET} = \Theta V_{AR} + P_{AR\to SET_0}$$

Gate-island capacitance vs voltage:

$$C_{AR\to SET} = \frac{1}{\frac{\Theta V_{AR}}{e} + \frac{1}{C_{AR\to SET_0}}}.$$

Application to data



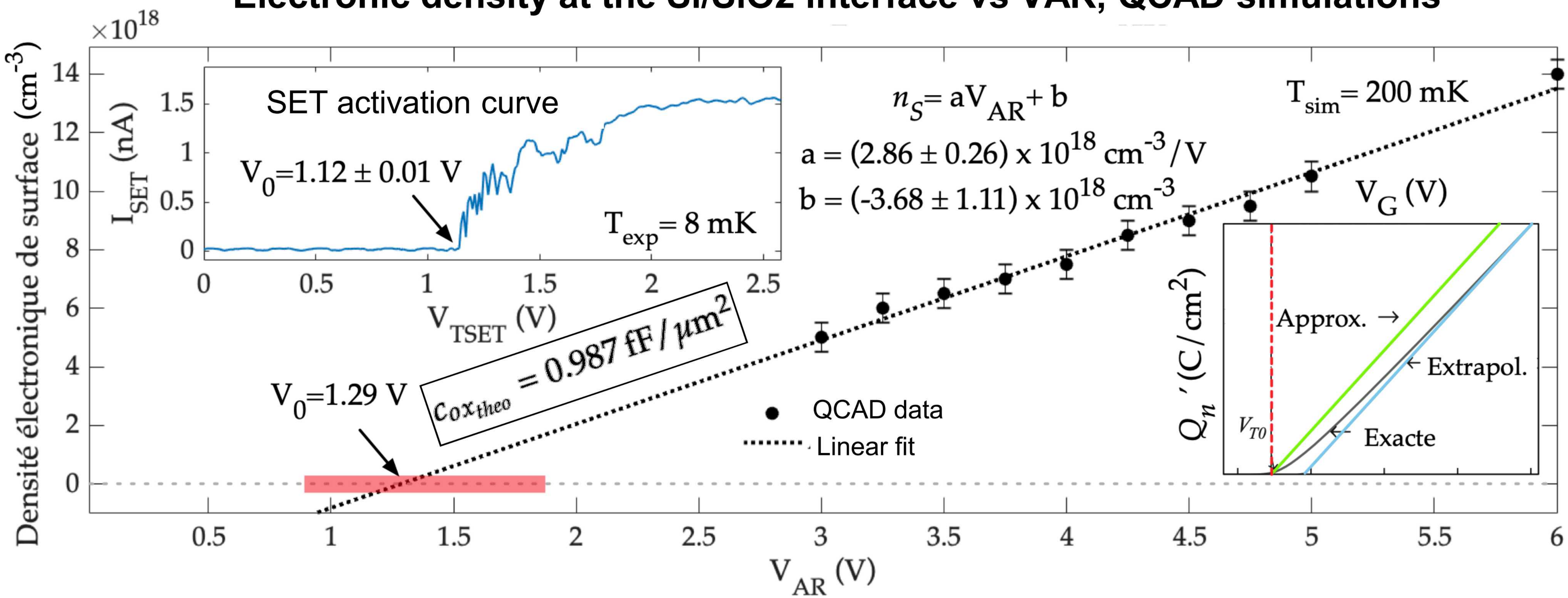


Charge transition condition:

$$V_{AD} = -\frac{1}{C_{AD_0}}\left[\frac{V_{AR} + \frac{(\mu_N - \eta_N)}{e}}{\frac{\Theta}{e}V_{AR} + \frac{1}{C_{AR_0}}}\right] + \Omega_N$$

Role of the reservoir charge density

Electronic density at the Si/SiO2 interface vs VAR, QCAD simulations



Effective gate voltage caused by adding charges in the reservoir:

$$N_R = \Delta n_S S_R d_{inv.}$$

$$\delta V_{AR(+N_R)} = \frac{-eN_R}{C_{Rtot}} \frac{C_{R\to SET}}{C_{AR\to SET_0}}.$$

$$V_{AReff} = V_{AR} + \delta V_{AR(+N_R)}.$$

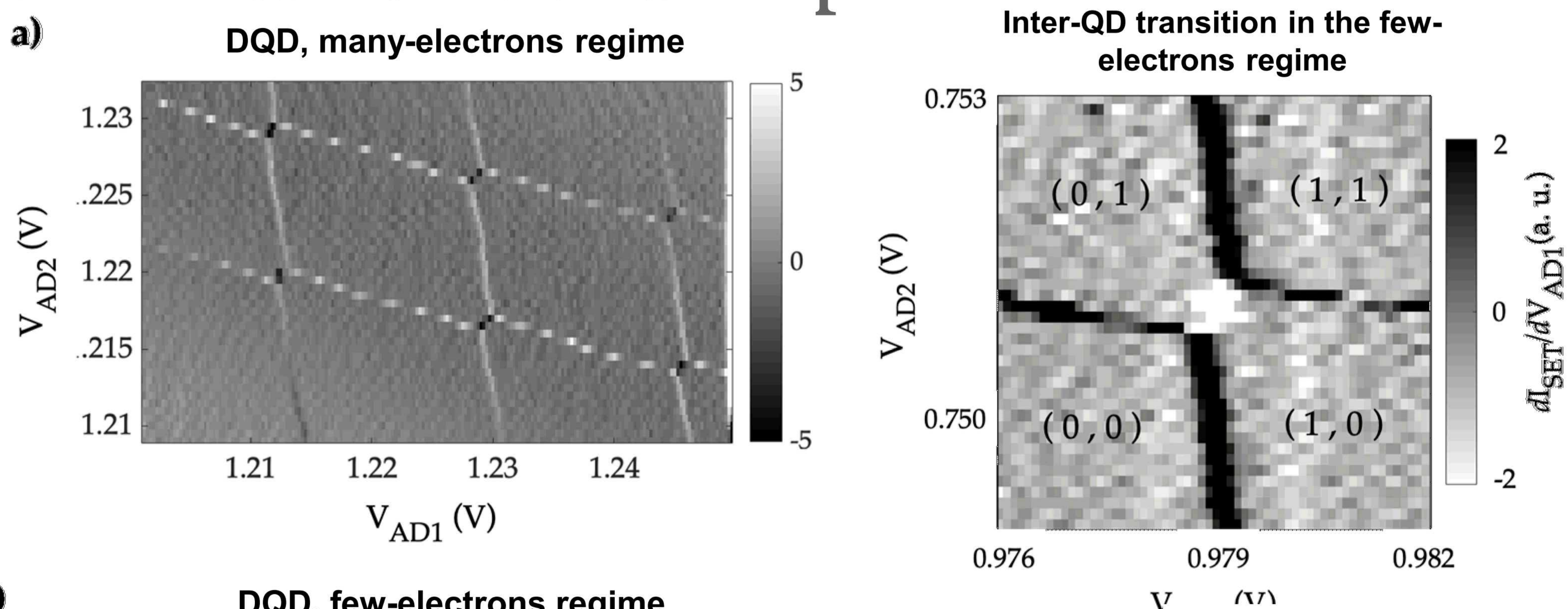
Falling back on the empirical model:

$$C_{AR\to SET} = \frac{1}{\frac{1}{C_{AR\to SET_0}} + \frac{1}{e}\frac{C_{AR\to R}C_{R\to SET}}{C_{Rtot}C_{AR\to SET_0}} V_{AR}} = \frac{1}{\frac{1}{C_{AR\to SET_0}} + \frac{\Theta}{e} V_{AR}}$$

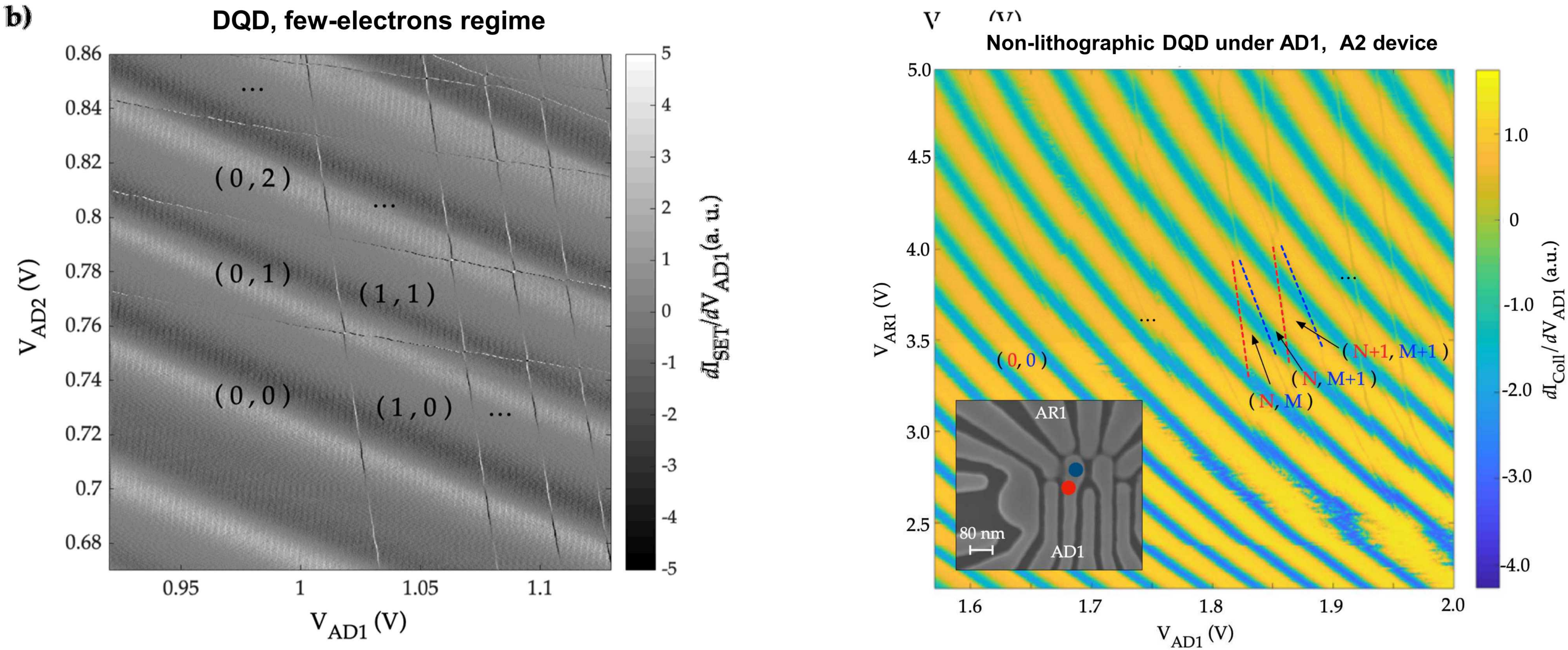
Scale-up of the split accumulation gate structure

Scaling-up: double quantum dot

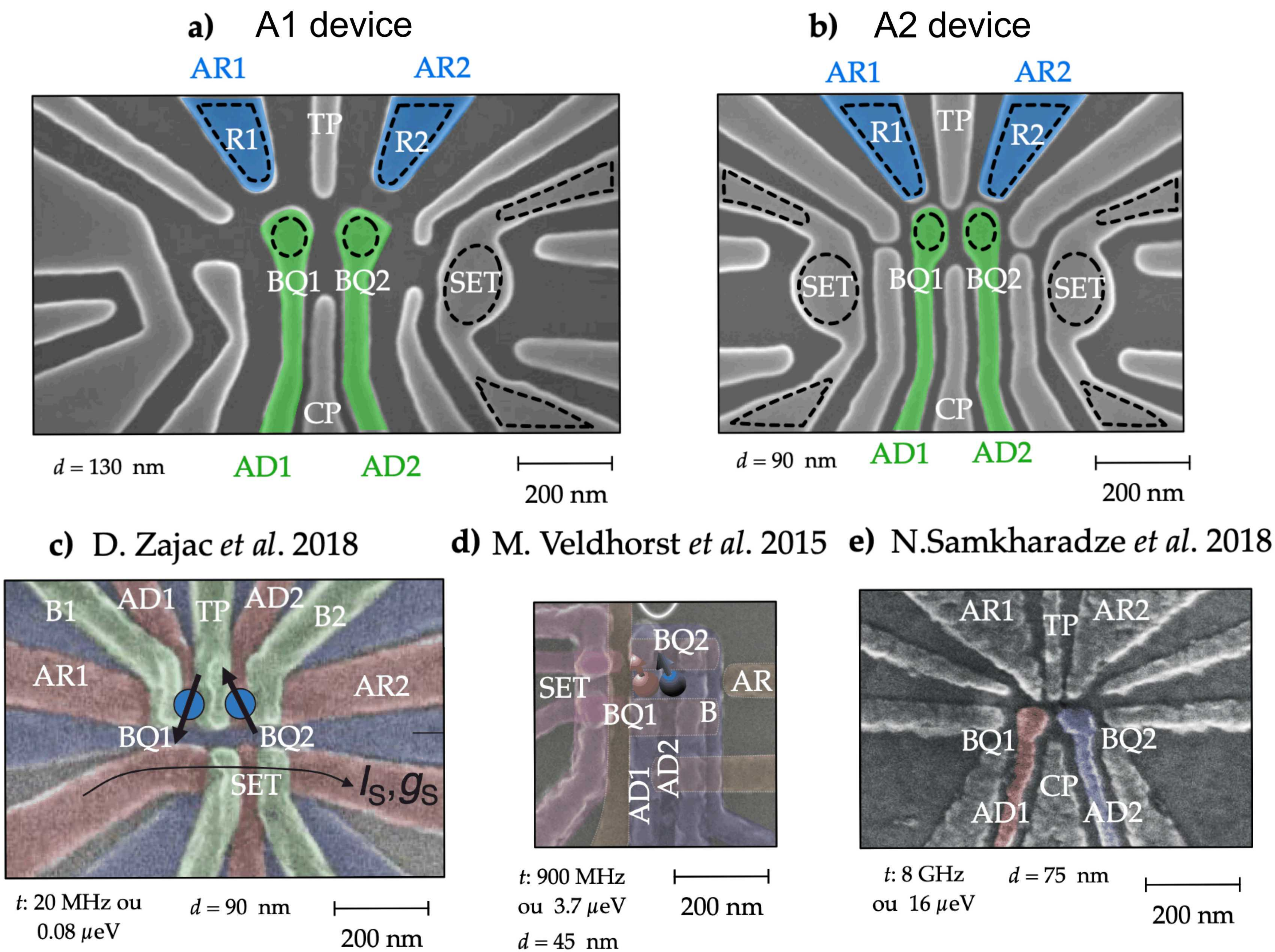
a)



b)



Dimensions vs inter-QD coupling: comparison



Conclusion

Main results of the thesis

Favorable comparison of those 3 criterias with litterature results

1. Single-electron regime reached
2. Valley splitting control
3. Tunnel rate control
    1. Demonstration of an alternative control method with the reservoir accumulation gate
    2. Definition of a performance criterion allowing comparison between different geometries-> Control orthogonality
    3. Development of a tunnel rate extraction method using sinle-frequency pulse spectroscopy
4. Development of a model for the charge transition curvature
5. Presentation of a preliminary study on commercial devices based on the split accumulation gate structure

Main impact of the thesis

1. Demonstration of the possibility of realization of performant quantum dots with a single gate layer
2. Description of a parameter for performance comparison between different architectures
3. Description of an alternative tunnel rate control method with the reservoir accumulation gate
4. Modelization of the charge transition curvature phenomenon, useful for simulations and machine learning algorithm training for automatic quantum dot initialization
5. Demonstration of the split accumulation gate structure potential for industrial realization of quantum dot processors

Thank you

Project supervision

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