Study of the effective mass dependent charge qubit performance in voltage-tunable double quantum dot channel nanowire FETs

2nd International Conference on Low-Energy Digital Devices and Computing (ICLED 2024)

LT 301, NTU Alumni @One North, 11 Slim Barracks Rise, Singapore 138664
1 – 4 August, 2024

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Outline

- Introduction.
- Semiconductor qubits.
- Advantages and challenges of quantum dots.
- DQD generation in nanowire FET.
- Mathematical modelling.
- Results.
- Conclusions.
- Acknowledgements.
- References.

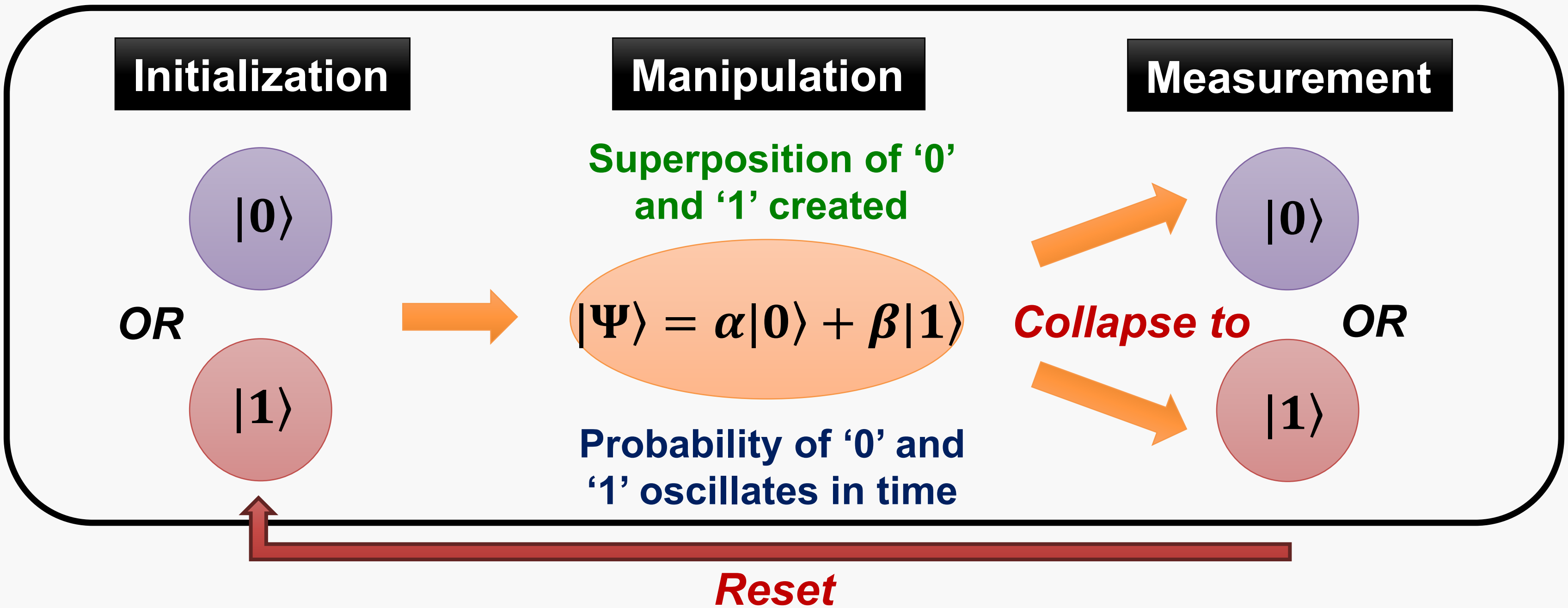
Introduction: Qubits

- Quantum analogue to the classical bit.
- Two-level system with basis states $|0\rangle$ and $|1\rangle$.
- Information is represented by a state $|\Psi\rangle$ where,

$$|\Psi\rangle = \alpha|0\rangle + \underbrace{\beta|1\rangle}_{}$$

Superposition

Typical qubit operation:

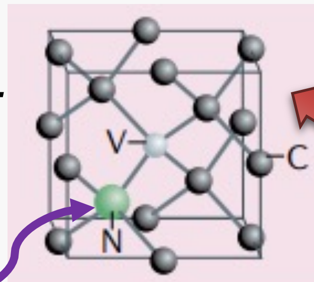


Semiconductor qubits

Semiconductor qubits

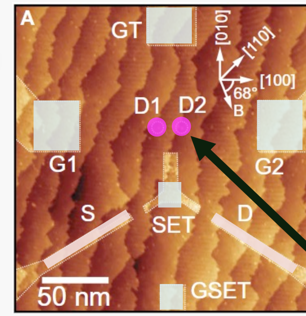
Color centres

Neumann et. al., *Nat. Phys. 6*, pp. 249 – 253 (2010)



Color centres arising due to incorporation of N and Si defects into high bandgap materials, host the quantum state.

Dopant based

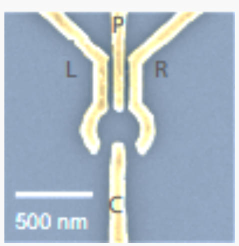


Watson et. al., *Sci. Adv. 3*, e1602811 (2017)

^{31}P dopants in Si, with gate controlled quantum state.

Quantum dots

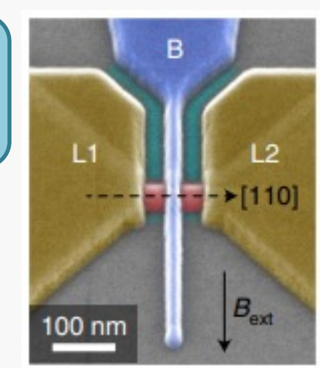
Gate-defined quantum dots



Kulesh et. al., *Phys. Rev. App. 13*, 041003 (2020)

Gate voltages create quantum dots by depleting 2D electron gas.

Quantum dots in FET architecture



Camenzind et. al., *Nat. Electron. 5*, pp. 178-183 (2021)

Gate voltage creates quantum dots in the channel.

QDs: Advantages & Challenges

Challenges:

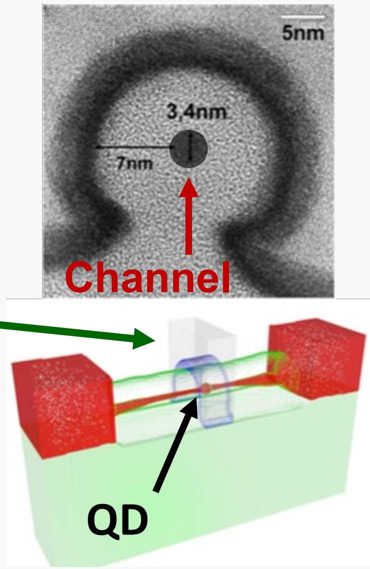
- QD sizes are limited by lithography processes, which lead to ~meV energy level spacing.
- Extremely susceptible to environmental noise.
- Operation limited to ~mK temperatures.

Advantages:

- Established technology for qubit generation.
- Fabrication process compatible with existing semiconductor processing technologies.
- Reduced complexity in operation.

Motivation for qubit generation in FET devices:

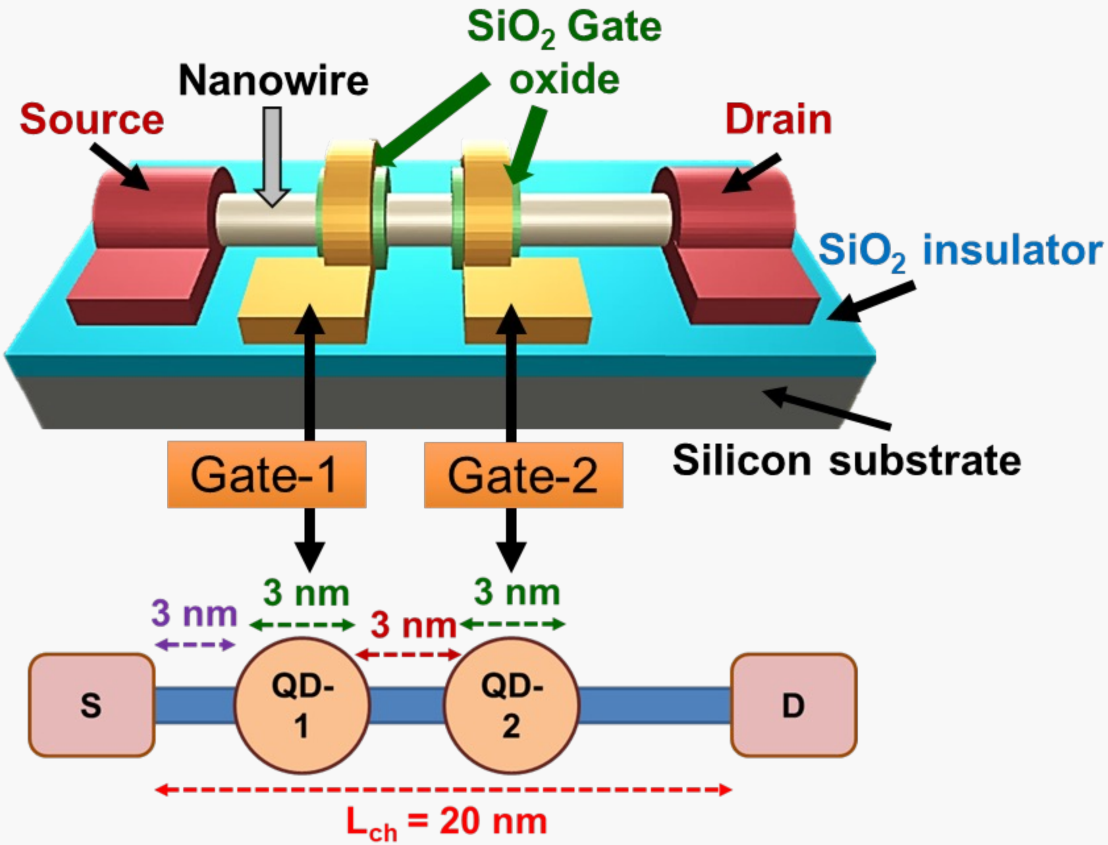
- ➢ Channel dimensions are already at quantum length scale.
- ➢ Localized gates on the channel of nanowire FETs can create quantum dots.
- ➢ Gate lengths and channel dimensions can be tuned for high temperature operation.
- ➢ CMOS compatible technology.



Lavieville et. al., *Nanoletters 15(5)*, 2015

DQD generation in NWFET

- Use localized gates to create QDs in channel of a nanowire FET.
- Gate voltages control electron population inside the QDs.
- Gate voltages also modulate inter-dot tunneling.
- Gate length and nanowire diameter control the overall QD eigenstates.



Schematic of charge qubit device in state-of-the-art nanowire FET architecture.

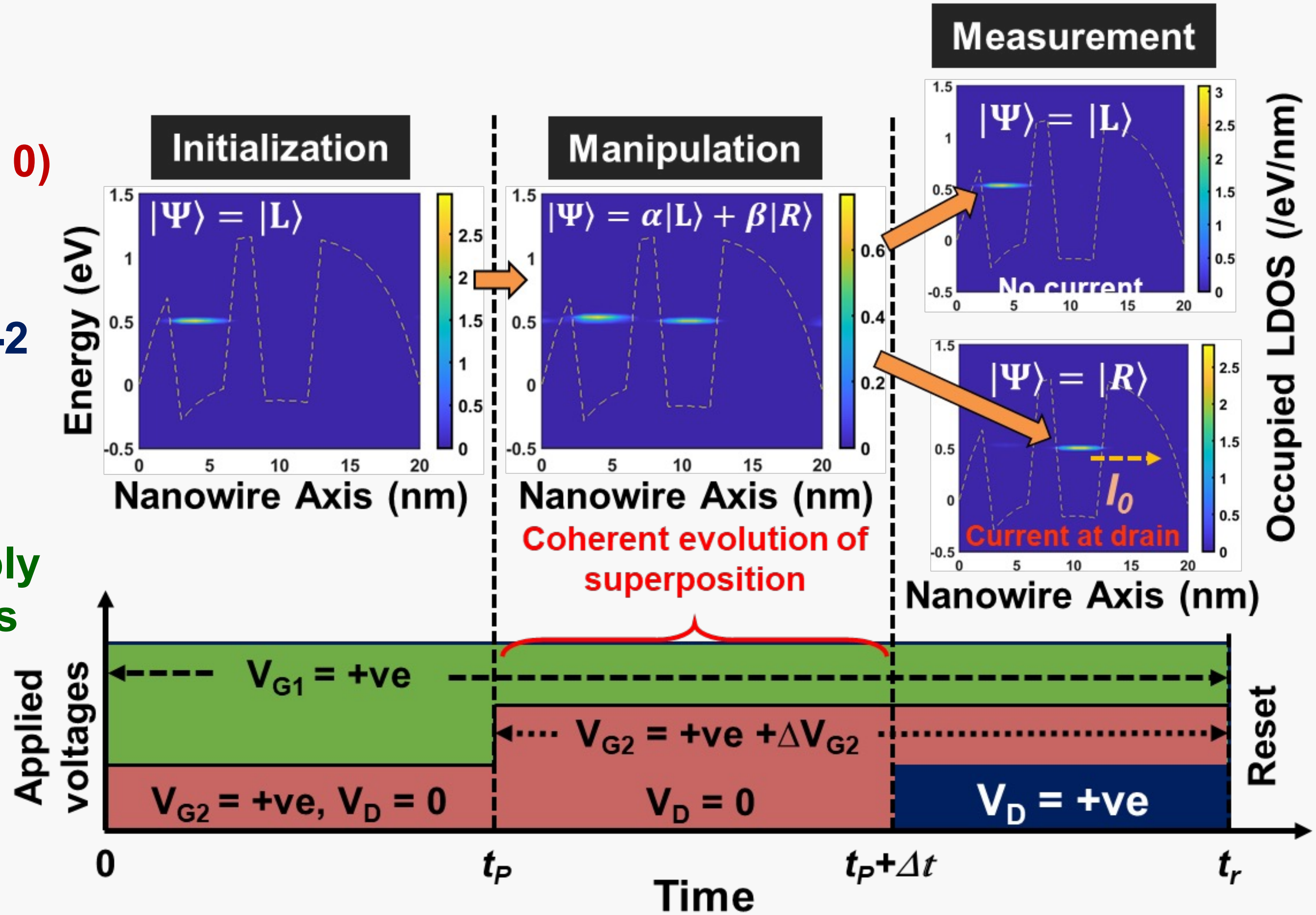
Scheme of charge qubit operation

Apply V_{G1} at gate-1 ($V_D = 0$)

Apply V_{G2} pulse at gate-2 ($V_D = 0$)

After some time, Δt, apply positive V_D (V_{G2} pulse is <u>still</u> applied)

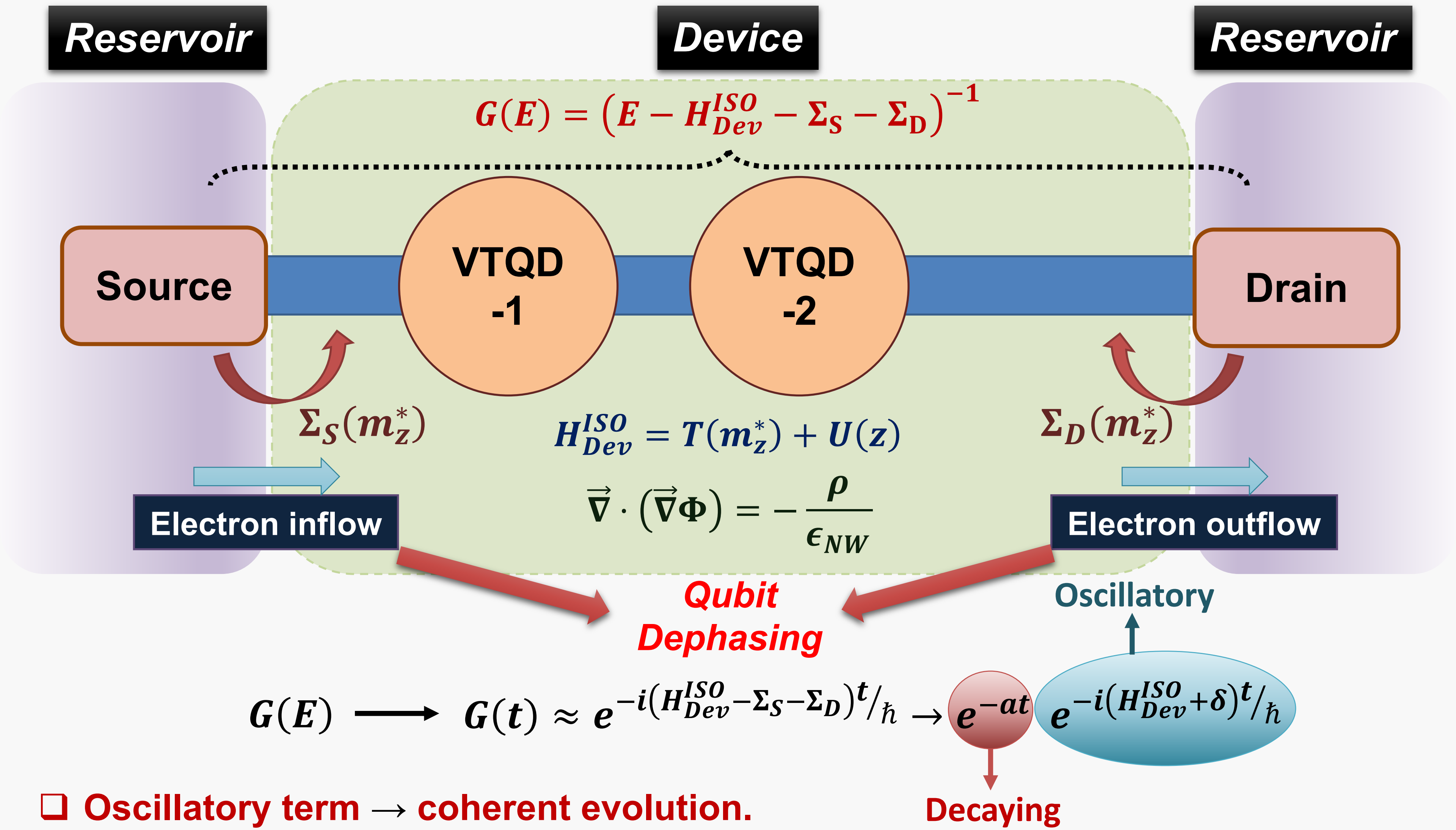
Reset all voltages



Operation scheme is similar to Gorman et. al., PRL 2005. (*10.1103/PhysRevLett.95.090502*)

****Positional basis: $|L\rangle$ and $|R\rangle$ are the logical qubit states!***
Physics remains same, the representation changes.

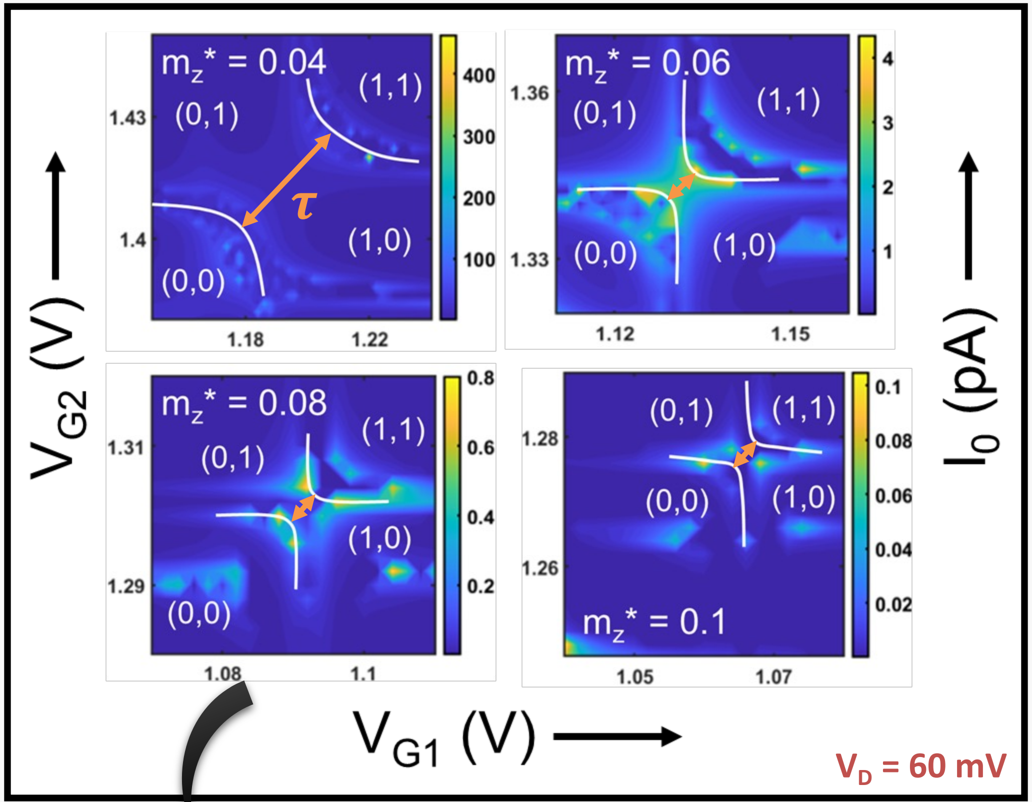
Mathematical Modeling: NEGF

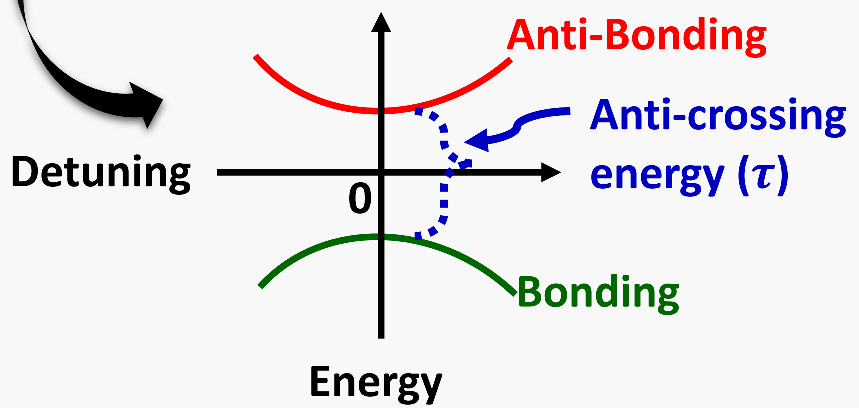


- Oscillatory term → coherent evolution.
- Decaying term → dephasing.
- Drain bias increases ‘a’ → quicker dephasing.

Results: Charge stability

- **Performance predominantly depends on transport effective mass.**
- **Charge stability diagram denotes the charge states of the DQD.**
- **Anti-crossing energy is the measure of inter-dot coupling strength.**
- **Lower voltages are required to obtain charge stability at higher m_z^*.**
- **The stability diagram sharpens from hyperbolic to straight line like nature with the increase in m_z^*.**





High effective mass → low tunneling probability → low anti-crossing energy.

Results: Bloch sphere coverage

- Bloch sphere coverage indicates the achievable superpositions of $|L\rangle$ and $|R\rangle$.
- Higher coverage → better (more) information encoding ability.
- Coverage varies with m_z^* dependent inter-dot tunneling probability.

Superposed state:

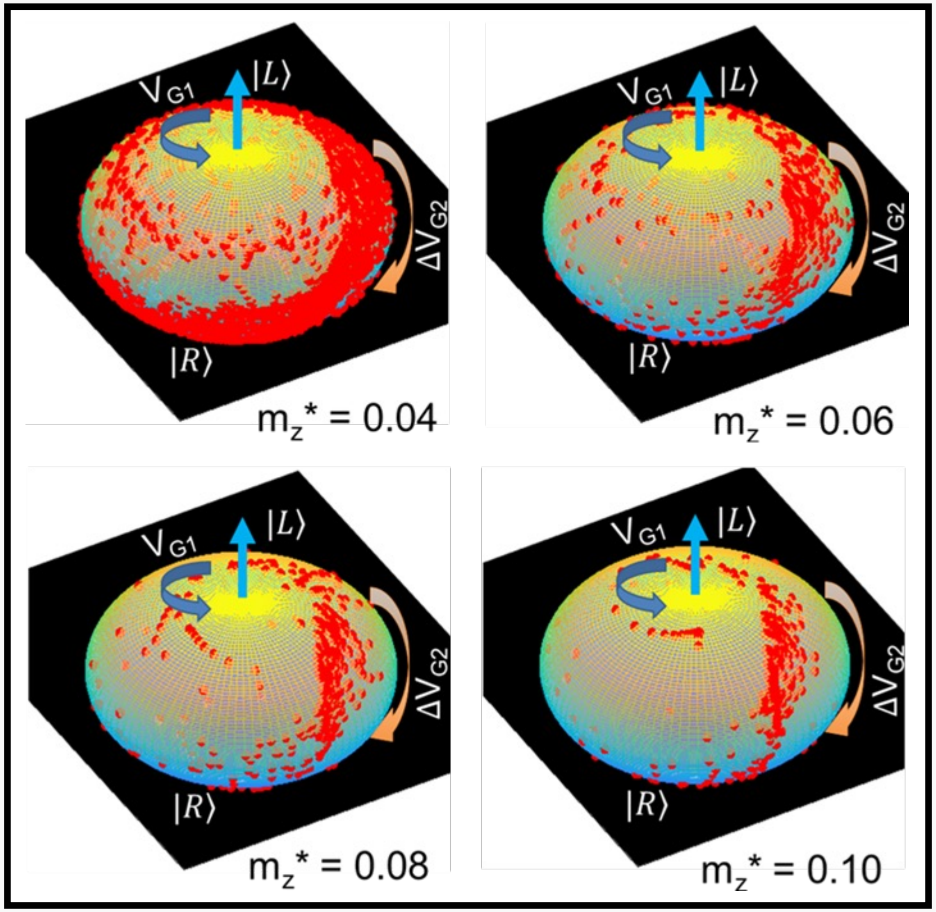
$$|\Psi\rangle = \sin(\theta/2)\,|L\rangle + \cos(\theta/2)e^{i\phi}\,|R\rangle$$

ΔV_{G2} modulates θ

V_{G1} modulates ϕ

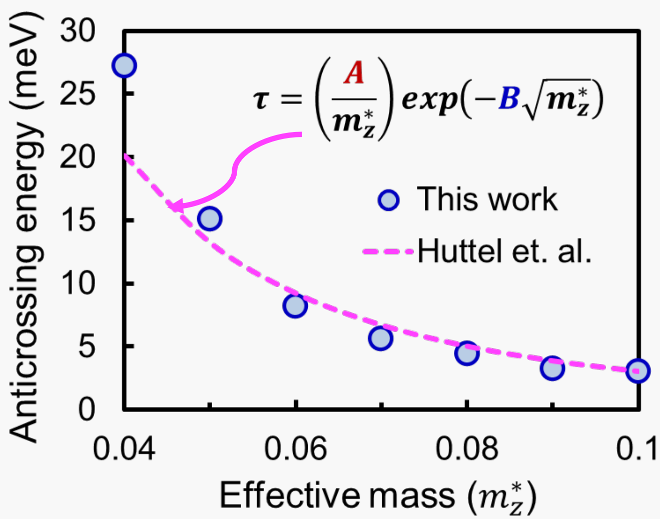
➢ <u>Higher</u> m_z^* degrades tunneling probability ⇒ superposition not possible at every gate voltage combination.

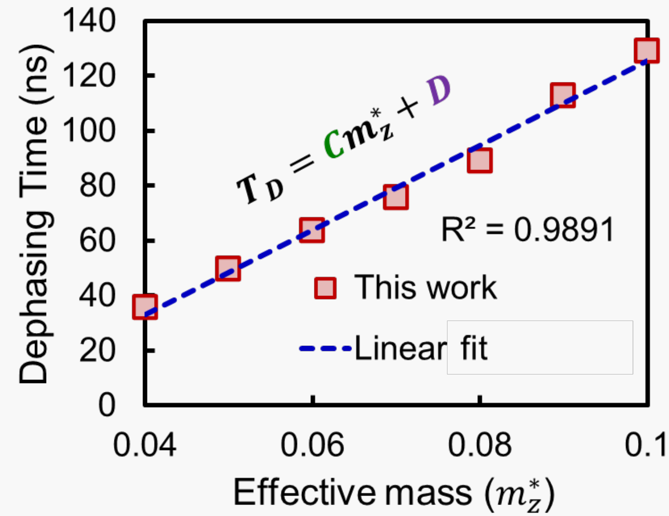
➢ ϕ coverage significantly reduced!



Mathematically, θ is obtained from LDOS and ϕ is obtained from local phase of the Green's function

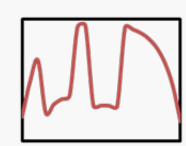
Results: Anti-crossing & Dephasing





- **Anti-crossing energy rapidly decreases with increase in m_z^*.**
- **The expression for anti-crossing energy can be derived using WKB approach for a double quantum well/dot problem. Huttel et. al. experimentally verified it.**
- **This work shows agreement at high m_z^*. Difference at low m_z^* due to level broadening and band bending along channel.**
- **Dephasing time (T_D) boosted by increased effective mass as tunneling probability to drain is reduced.**

*****Increased dephasing times obtained at the cost of reduced inter-dot coupling, i.e., reduced Bloch sphere coverage***



Huttel et. al. (2005, PRB)
DOI: 10.1103/PhysRevB.72.081310

Dephasing in details…

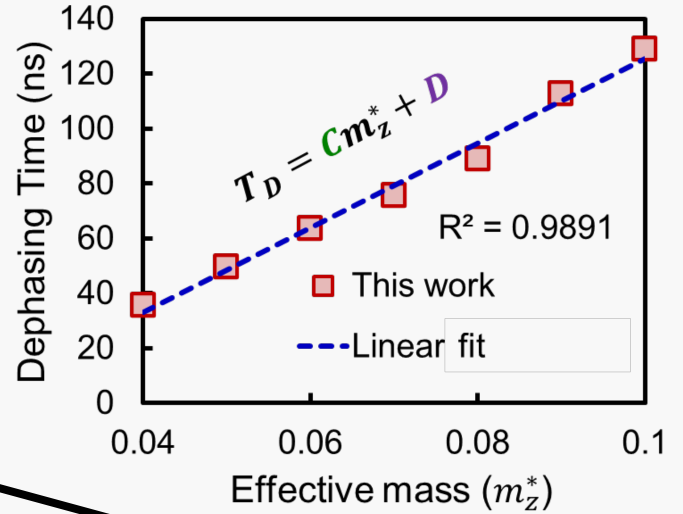
- Recall the time domain Green's function…

$$G(t) = G_0 e^{-i\left(H_{Dev}^{ISO} - \Sigma_S - \Sigma_D\right)t/\hbar}$$

Σ_S, Σ_D are complex. So,

$$e^{-at}$$

$$G(t) \approx \left(e^{-i\left(H_{Dev}^{ISO} - Re(\Sigma_S) - Re(\Sigma_D)\right)t/\hbar}\right) e^{-Im(\Sigma_S + \Sigma_D)t/\hbar}$$



Imaginary part of the self-energies are responsible for dephasing!

See: *Nag Chowdhury et. al., Adv. Quantum Technol., 2023 [10.1002/qute.202200072]*

**In tight binding form, $\Sigma_D = \frac{\hbar^2}{2m_z^*}(\dots) \Longrightarrow a \propto \frac{1}{m_z^*}$

- Thus, $T_D = \frac{1}{a} \propto m_z^*$

- The linear fit "$Cm_z^* + D$" suggests that dephasing time will approach zero for some critical m_z^* value!

** *For more details about Σ_D, see:*
Nag Chowdhury et. al., J. App. Phys., 2014 [10.1063/1.4869495]
Venugopal et. al., J. App. Phys., 2002 [10.1063/1.1503165]

Conclusions

- Inter-dot coupling and source/drain coupling significantly dependent on transport effective mass.
- High effective mass reduces inter-dot coupling and Bloch sphere coverage, while sharpening the charge stability diagram.
- High effective mass reduces coupling of DQD with source/drain reservoirs so as to boost dephasing time.
- However, longer dephasing times obtained at the cost of reduced inter-dot coupling and degraded Bloch sphere coverage.
- Dephasing time varies linearly with effective mass.
- Physics driven approach to anti-crossing and dephasing ensures validity of predicted results across different qubit platforms.

References

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Acknowledgements

- Department of Electronic Science, C.U.
- Centre for research in nanoscience and nanotechnology (CRNN).
- Centre of Excellence (CoE) in Systems Biology and Bio-Medical Engineering, TEQIP Phase-III.
- University Grants Commission.

THANK YOU.