Understanding the composition dependent charge qubit operations in a dual-gate $Al_xGa_{1-x}As$ nanowire FET using NEGF approach

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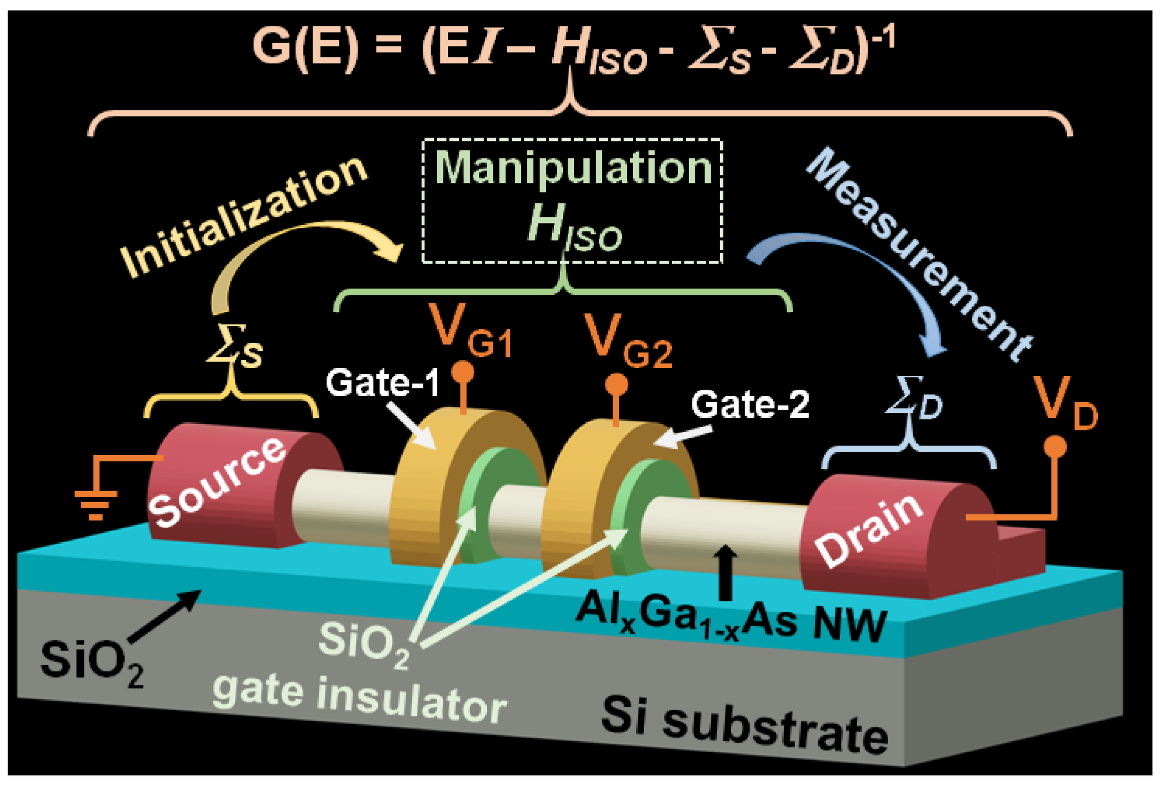
INTRODUCTION

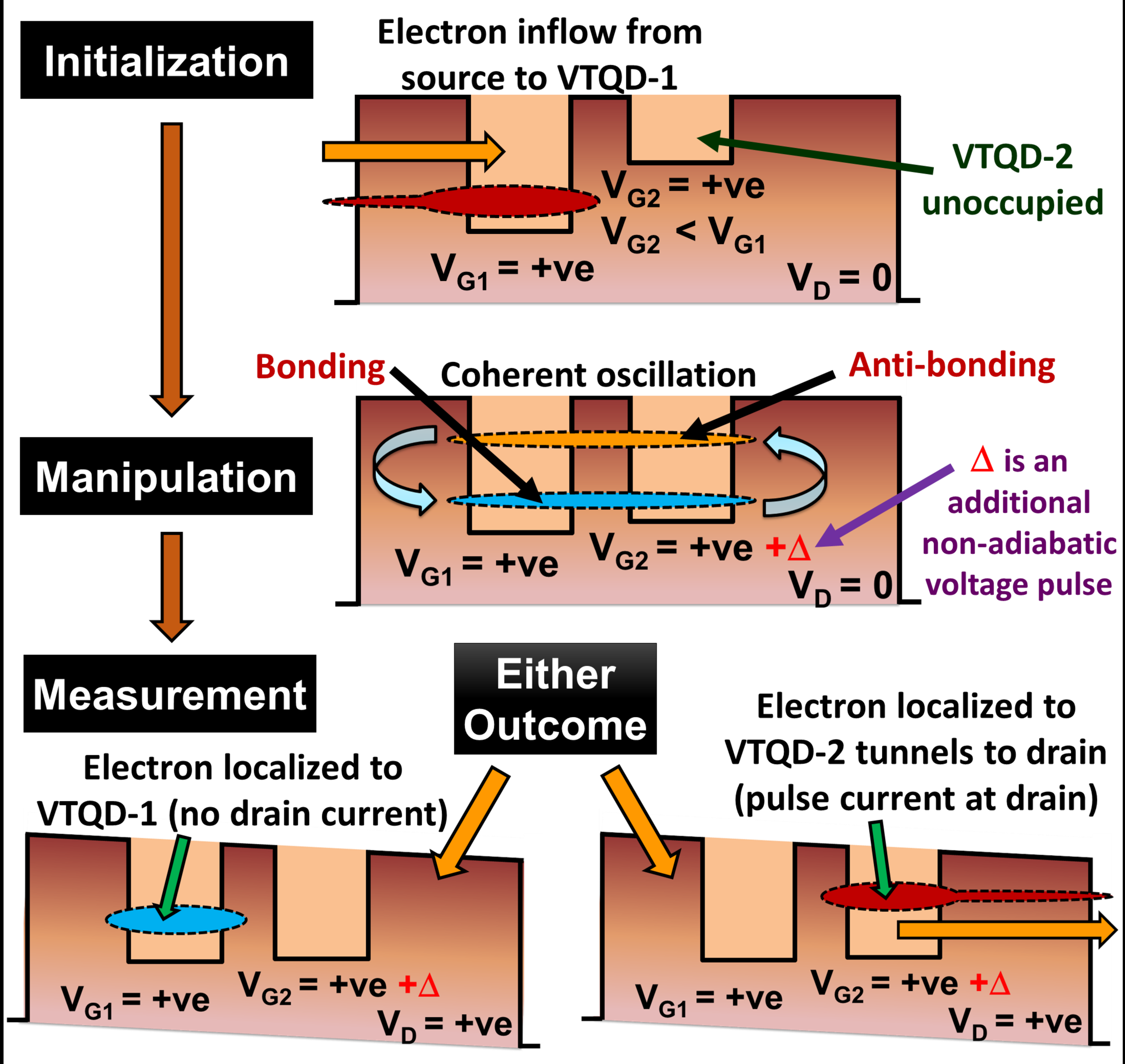
- ❑ Double quantum dot (DQD) devices for scalable quantum computers: control over quantum state manipulation; compatibility with already existing state-of-the-art fabrication processes.
- ❑ Challenges: very short dephasing time (~1-10 ns) and operational at ultra-low temperature operation (~mK-µK) [3-5].
- ❑ Voltage-tunable quantum dots (VTQDs) potentially free from the above limitations.
- ❑ Present work: Al composition dependent charge qubit operation and performance of a dual-gate $Al_xGa_{1-x}As$ nanowire FET with voltage-tunable DQDs.

SCHEME OF THE CHARGE QUBIT DEVICE



- ❑ Nanowire diameter: 5 nm; Gate length: 3 nm (each); Gate separation: 3 nm; Channel length (source to drain): 20 nm.
- ❑ Single electron occupancy of VTQDs ⇒ reduced charge noise.
- ❑ Energy gap between VTQD states >> phonon energy @ RT ⇒ negligible phonon scattering.

SCHEME OF THE CHARGE QUBIT OPERATION



Non-adiabatic voltage pulses eliminate the need for microwave driven state manipulation!

MATHEMATICAL MODELING

- ❑ Retarded Green's function, $G(E)$, to model the charge qubit operation [1] is:

$$G(E) = [E - H_{ISO} - \Sigma_S - \Sigma_D]^{-1}$$

H_{ISO}: Isolated nanowire Hamiltonian with two gates; $\Sigma_{S/D}$: source/drain self-energies which incorporate non-unitary evolutions of the quantum state [2].

- ❑ $\Sigma_S \rightarrow$ 'Initialization'; $\Sigma_D \rightarrow$ 'Measurement'.
- ❑ Gate voltages $V_{G1(2)}$ are non-decohering!
- ❑ $G(E) \rightarrow$ LDOS: $D(E) \rightarrow n(z) = \int D(E)dE$
- ❑ 'Measurement' → Pulse current at drain; to obtain employ Landauer formula:

$$I_0 = \frac{2e}{h}\int dE\,T(E)\big(f_S(E) - f_D(E - V_D)\big)$$

- ❑ Dephasing time → decay of pulse current in time domain for continuous ΔV_{G2} pulses at gate-2.

$$I(t) = I_0\, F.T._{E\rightarrow t}\,[G_{ISO}(E)\Sigma_D(E)G(E)]$$

- ❑ $F.T._{E\rightarrow t}$ ⇒ Fourier transform from energy to time domain.
- ❑ Positional basis: |L>/|R> → logical qubit states where superposed state expressed as,

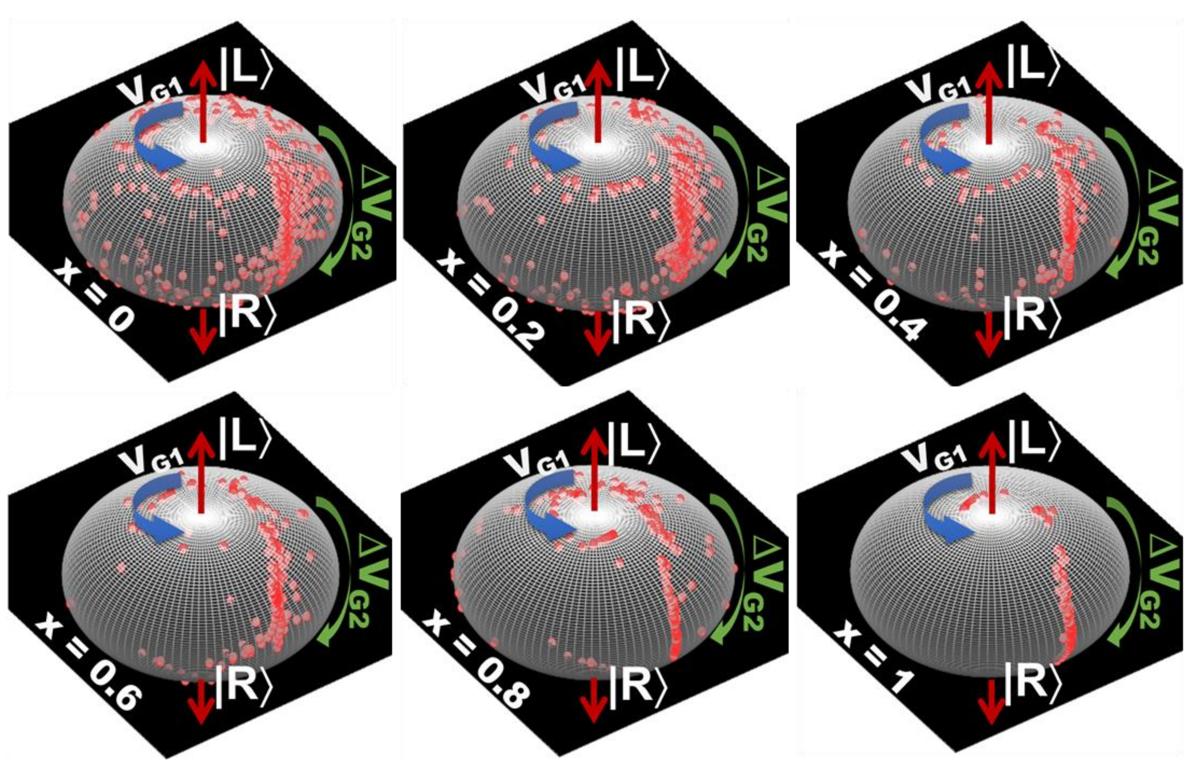
$$|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|L\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|R\rangle$$

- ❑ $n(z) \rightarrow \theta$; manipulated by non-adiabatic ΔV_{G2} pulses at gate-2.
- ❑ Local phase of $G(E) \rightarrow \phi$; manipulated by varying V_{G1} keeping V_{G2} fixed.

RESULTS AND DISCUSSIONS

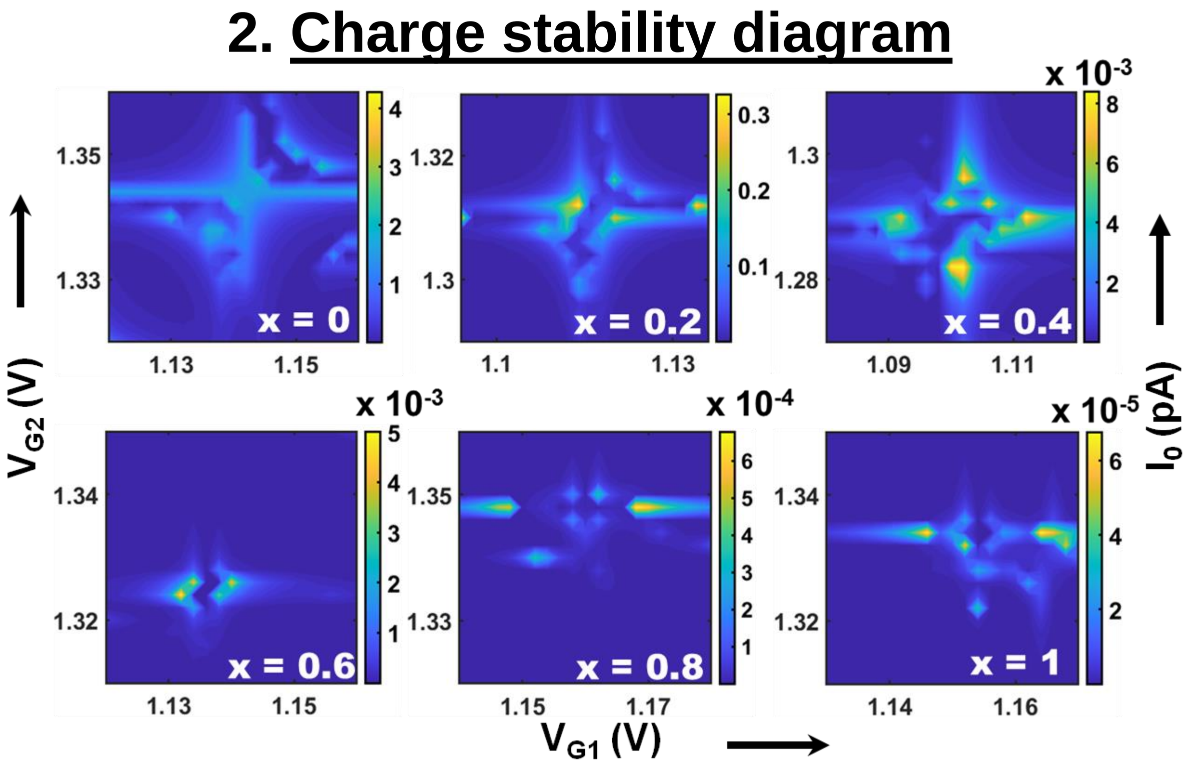
- ❑ High Al composition leads to high effective mass (m*); high bandgap; low permittivity.
- ❑ High m* → reduced tunneling probability.
- ❑ High bandgap/low permittivity observed to enhance tunnel barriers.

1. Bloch sphere coverage



- ❑ High m* → reduced tunneling probability and degraded inter-dot coupling ⇒ reduced Bloch sphere coverage, less information can be encoded!

2. Charge stability diagram

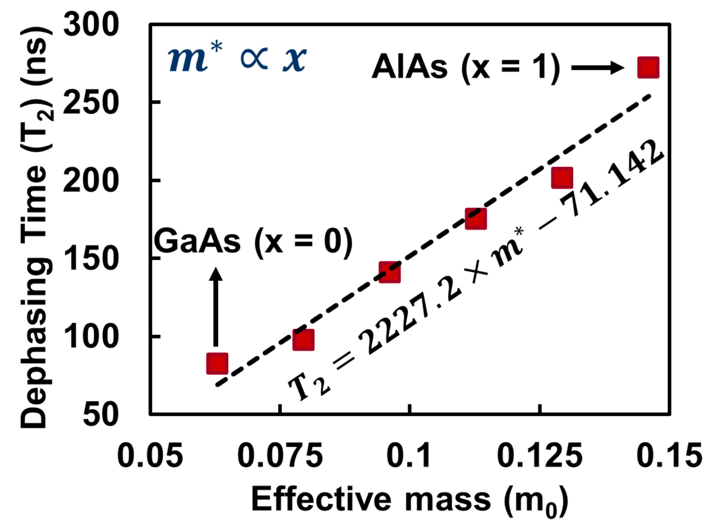


- ❑ High Al composition → weak inter-dot coupling (high m*, high tunnel barriers) ⇒ reduced anti-crossing energy.
- ❑ Qubit current also significantly reduced!

3. Dephasing time

Al composition (x)	Dephasing Time (T_2) (ns)
x = 0: GaAs	82. 4
x = 0.2: $Al_{0.2}Ga_{0.8}As$	97.5
x = 0.4: $Al_{0.4}Ga_{0.6}As$	141.0
x = 0.6: $Al_{0.6}Ga_{0.4}As$	175.3
x = 0.8: $Al_{0.8}Ga_{0.2}As$	201.3
x = 1: AlAs	272.1

Reduced DQD/ reservoir coupling, high tunnel barriers ⇒ high T_2.



CONCLUSION

- ❑ Higher Al content ⇒reduced Bloch sphere coverage.
- ❑ Lower Al content ⇒ improved inter-dot tunneling, enhanced anti-crossing energy.
- ❑ Al composition dependent dephasing time: ~10x – 20x higher than previously reported values (~10 ns) for GaAs based DQDs at 100 mK [3-5].
- ❑ High dephasing times at the cost of reduced anti-crossing, qubit current and degraded Bloch sphere coverage.
- ❑ Dimension dependent strong quantization reduces the charge noise and phonon scattering phenomena.

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