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

Nilayan Paul[1], **Basudev Nag Chowdhury**[1], **Sanatan Chattopadhyay**[1,2,*]

[1]*Department of Electronic Science, University of Calcutta, 92 A.P.C. Road, Kolkata 700009, India*

[2]*CRNN, University of Calcutta, JD block, Sector III, Salt Lake City, Kolkata 700098, India*

*Corresponding author: scelc@caluniv.ac.in

Semiconductor based double quantum dot (DQD) devices **[1]** have drawn significant attention over the past two decades for potential implementation as charge qubits that offer extensive control over the manipulation of their quantum states. Such devices operate on the principle of localization of an excess electron partially in both the QDs, which is usually manipulated by varying inter-dot tunnel coupling using several gates and measured at drain as current or conductance **[2-3]** or by QPC **[4]**. However, such qubit operations are still limited to the requirement of extremely low temperatures (~100 mK) and offer very short dephasing times (~1-10 ns) **[3]**. Further, such qubit device architectures are fundamentally different from the CMOS based state-of-the-art classical bits. Therefore, it is essential to explore novel device schemes for possible qubit operation at room temperature with little modification of the present mainstream CMOS technology **[5-6]**. In this context, a device scheme based on GaAs nanowire field-effect transistor (NWFET), with two separated localized gates, has recently been proposed for room temperature charge qubit operation **[7]**. Such devices can be geometrically engineered for improvement of the qubit performance parameters **[8]**. Further, material engineering of the device may lead to obtain superior performance in terms of qubit operations. Therefore, current work investigates the impact of nanowire material composition on room-temperature charge qubit operation in a dual-gate $Al_xGa_{1-x}As$ NWFET, by varying the value of 'x' from 0 to 1, which leads to the variation of electron effective mass from 0.06 to 0.15, bandgap from 1.42 eV to 2.16 eV, and dielectric constant from 12.9 to 10. In such a device (see Fig. 1(a) and (b)), the application of appropriate gate voltages (V_{G1} and V_{G2}) leads to the formation of voltage-tunable quantum dots (VTQDs) in the nanowire channel beneath the gates. The electron occupation of such VTQDs can further be controlled by small incremental variation of the applied gate voltages for 'Initialization' and 'Manipulation' operations of the qubit, while the application of a small bias (V_D) at drain enables the 'Measurement' of qubit state. The 'Manipulation' of qubit state over the Bloch sphere is performed by suitably varying the absolute and relative values of the two gate voltages, which is shown in the current work through NEGF formalism. The NEGF approach further allows consistent incorporation of the effects of leads (source/drain), including level broadening due to coupling and the effect of temperature dependent broadening in the device, which is manifested as current/conductance mapping in the charge-stability diagrams **[9-10]**. In the modeling, the device Green's function given by **[7-8]**, $G=\left(E-H_{ISO}-\Sigma_S-\Sigma_D\right)^{-1}$, incorporates such phenomena through the self-energies ($\Sigma_{S/D}$) of source/drain along with their respective F-D distribution functions, while the DQD formation and coherent manipulation of superposed states is performed through gate voltages in H_{ISO}. The self-energies being non-Hermitian in nature also allow the theoretical modeling of non-Unitary evolutions of the quantum state, including the qubit 'Initialization' (through Σ_S) and 'Measurement' (through Σ_D) operations. Subsequently, the effects of such material composition in terms of Bloch sphere coverage and charge-stability diagrams are shown in Fig. 2(a) and (b), respectively. It is apparent from the Bloch spheres that $Al_xGa_{1-x}As$ nanowires with higher values of 'x' show reduced ϕ coverage, indicating lesser but selective information encoding probability in the qubit, which is attributed to weakened resonance tunneling between the VTQDs. This also manifests in the charge stability diagrams (see Fig. 2(b)) as sharpened but reduced anti-crossing, while leading to an increase in dephasing times of the proposed device; from ~70 ns for 'x=0' to ~100 ns for 'x=1'. Such weakening of inter-dot resonance arises from increased electron effective mass along with the enhancement of inter-dot and source/drain barriers in devices having larger band gaps for higher values of 'x'. Therefore, tuning the composition of $Al_xGa_{1-x}As$ in dual-gate nanowire FETs may lead to optimized performance of qubit in terms of improved dephasing times, relevant charge stability diagrams and desired Bloch sphere coverage.

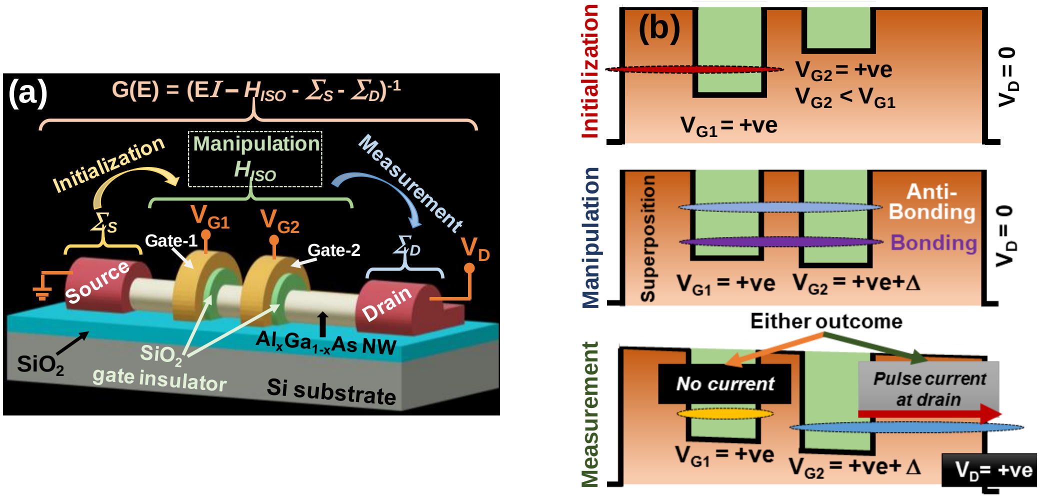

Figure 1 (a): Schematic of the $Al_xGa_{1-x}As$ dual-gate nanowire FET considered in the current work; (b): Schematic of charge qubit operation in the considered device, showing initialization, manipulation, and measurement operations.

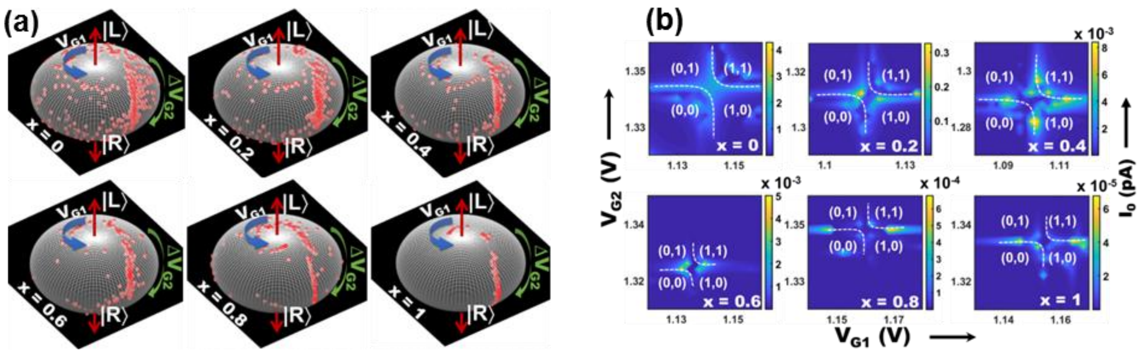

Figure 2 (a): Bloch spheres and (b): Charge-stability diagrams for x = 0.2, 0.4, 0.6, 0.8, 1, in the dual-gate $Al_xGa_{1-x}As$ nanowire FET.

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