Optimisation of electron spin qubits in electrically driven multi-donor quantum dots

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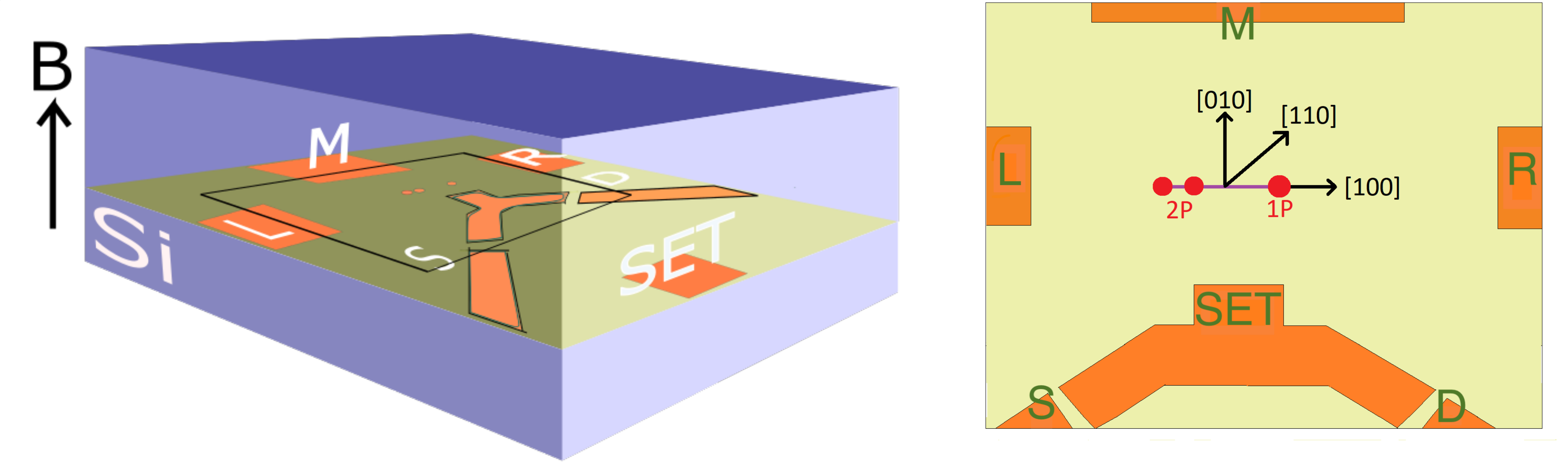


Fig.1: a) STM imaging of the qubit, b) in-plane gate control

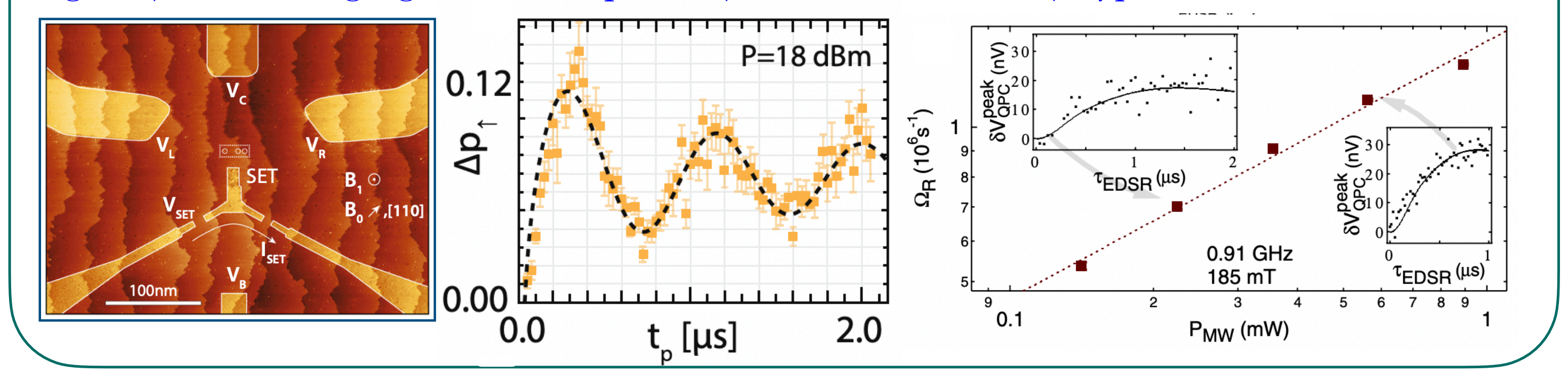
Proposal

- 2P (phosphorus double donor):1P (single donor) spin qubit
- Describe the theory of the multi donor quantum dot: wave function, electrical operation, noise
- Electron dipole spin resonance (EDSR)
- Minimal computational expense: effective theory.

Motivation

- 2P:1P qubit with Rabi freq. 1.2 MHz, $T_2^* = 295\,ns$, 0.8 ns two-qubit gate[1]
- Donors offer atomic-scale precision placement, orientation specified properties (e.g. [110] qubit axis sees suppression of exchange oscillation)
- Scalable semiconductor multi-qubit chips possible.[2]
- Hyperfine interaction between the qubit electron spin and P-donor nucleus provides strong spin-orbit coupling (advantage over micromagnet engineering): $H_{hf} = \mathscr{A}_0 \sum_i \delta(\mathbf{r} - \mathbf{R}_i)\vec{I_i} \cdot \vec{S}$[3]

Fig.2: a) STM imaging of 2P-1P qubit, b) Rabi oscillation, c) hyperfine mediated EDSR



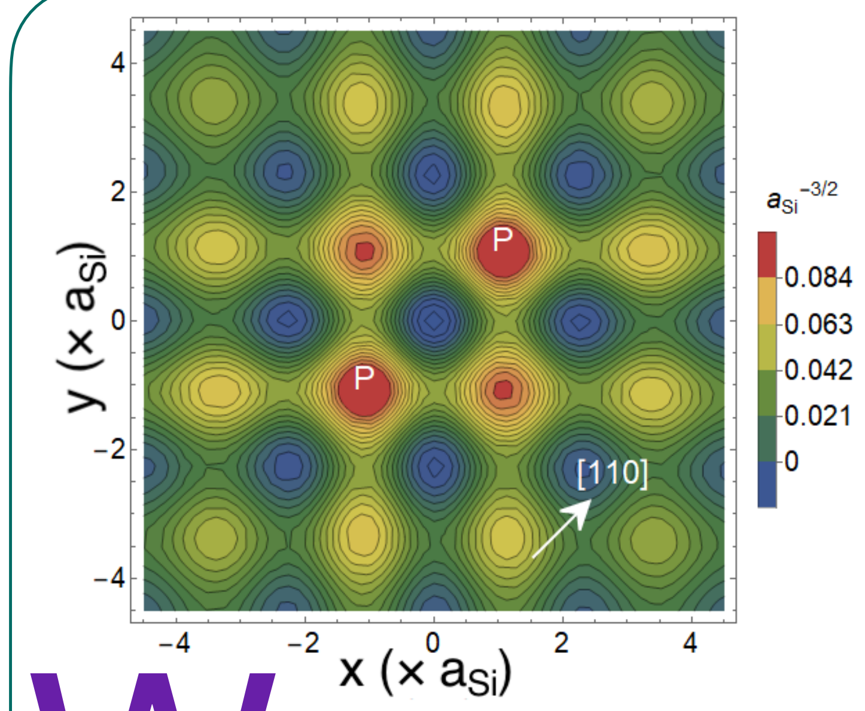


Fig.3: Theoretical result for the 2P wave function from the EMA approach

Wavefunction

- 2P: effective mass theory, *Slater*'s formalism[4]
- Indirect bandgap in Si leads to multi valley physics, LCAO method gives ground-state wave function for double donor QD, consisting symmetric combination of valleys from the two donors. $\Psi_{2D}(\mathbf{r}) = \frac{1}{\sqrt{\sum_\xi w_\xi^2}} \sum_\xi w_\xi S_\xi u_\xi(\mathbf{r})$

EDSR

- 2P-1P overlap introduces tunneling of e^- between QDs.
- The 2P:1P GS is obtained using Hund-Mulliken approach.
- A global magnetic field resolves the spin-states into ⇑ and ⇓ states.
- Hyperfine interaction : (1,0) ⇑ ↔ (0,1) ⇓
- Rabi ratio: $T_1/T_\pi \sim 10^6$, million operations in one relaxation time.
- When an ac $\tilde{E}(t)$ is applied, spin-flip takes place owing to time-dependent modulation of difference in hyperfine between left and right dots. (EDSR)

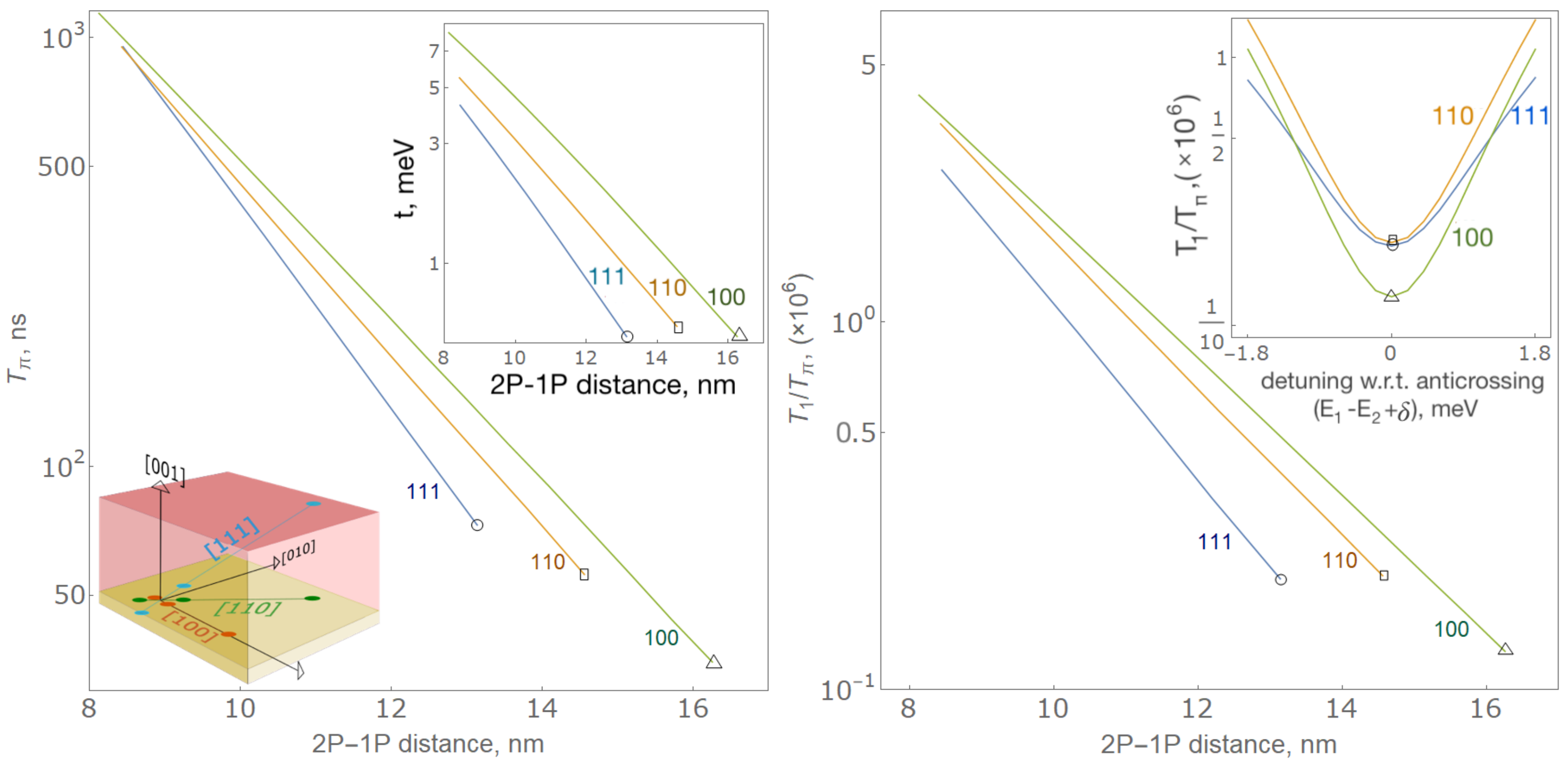


Fig.4: a) EDSR Rabi time vs 2P-1P distance for different qubit geometry, b) Rabi ratio vs 2P-1P distance

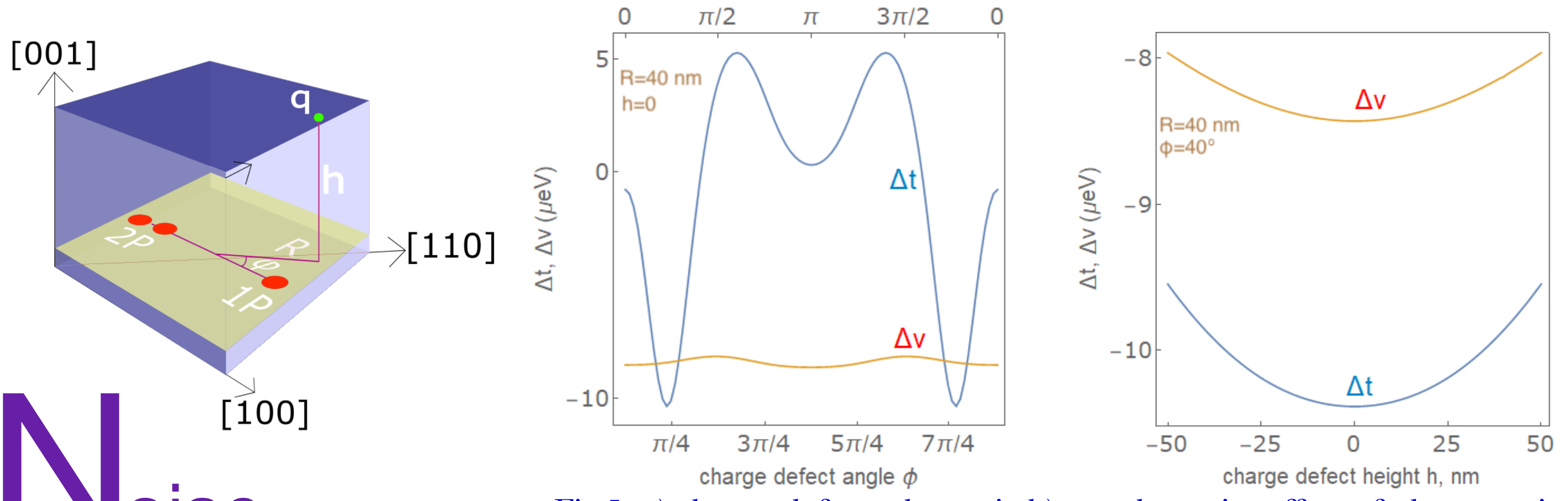


Fig.5: a) charge defect schematic b) angular noise effect of charge noise c) noise effect vs. height of charge defect.

Noise

- Charge defect in the vicinity of the physical qubit can modify the tunneling between the 2P and 1P dots as well as the self-energies of the QDs.
- Such charge noise lead to decoherence of the qubit state ⇑ → ⇓ .
- Time of decoherence (T_2^*) from charge noise can be modelled as Random Telegraph noise: $\boxed{\left.\frac{1}{T_2^*}\right|_{RTN} = \frac{32\zeta^2\tau k_{ge}^4}{\hbar^2\delta\varepsilon^4}\left(\frac{4t\Delta t}{\delta\varepsilon^2} + \frac{\epsilon\Delta v}{\delta\varepsilon^2}\right)^2,}$
- Noise is the most detrimental at particular angular orientation, and is minimal at the qubit plane, supporting the in-plane gated control.

Perorations

- 2P ground state energy of -121 meV, well-benchmarked against tight binding (TB), NEMO numerical models.[5-7]
- 2P ground state valley weights explained by competing effects: effective mass anisotropy (EMA) and valley-orbit coupling (VOC).
- Complete in-plane gate control is possible, under a global out-of-plane magnetic field $\vec{B_z}$ an in-plane ac electric field $\tilde{E}(t)$ induces qubit spin-flip.
- The spin-flip EDSR mechanism relies on contact hyperfine coming from the donor nuclear spins.
- $T_\pi \sim 50\,ns$, fast qubit rotation; $T_1/T_\pi \sim 10^6$, excellent Rabi ratio.
- Qubit geometry determines the best EDSR for when qubit axis ∥ [111] and best Rabi ratio for when qubit axis ∥ [100].
- Noise simulation produces the detrimental defect position to be $\theta = 40^0$, h=0, R=30 nm.
- Charge noise leads to EDSR single qubit gate error of 2%
- Efficient two qubit exchange gate of 3 GHz.

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