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Analysis and 3D TCAD simulations of EDSR in an industrially-compatible FD-SOI device

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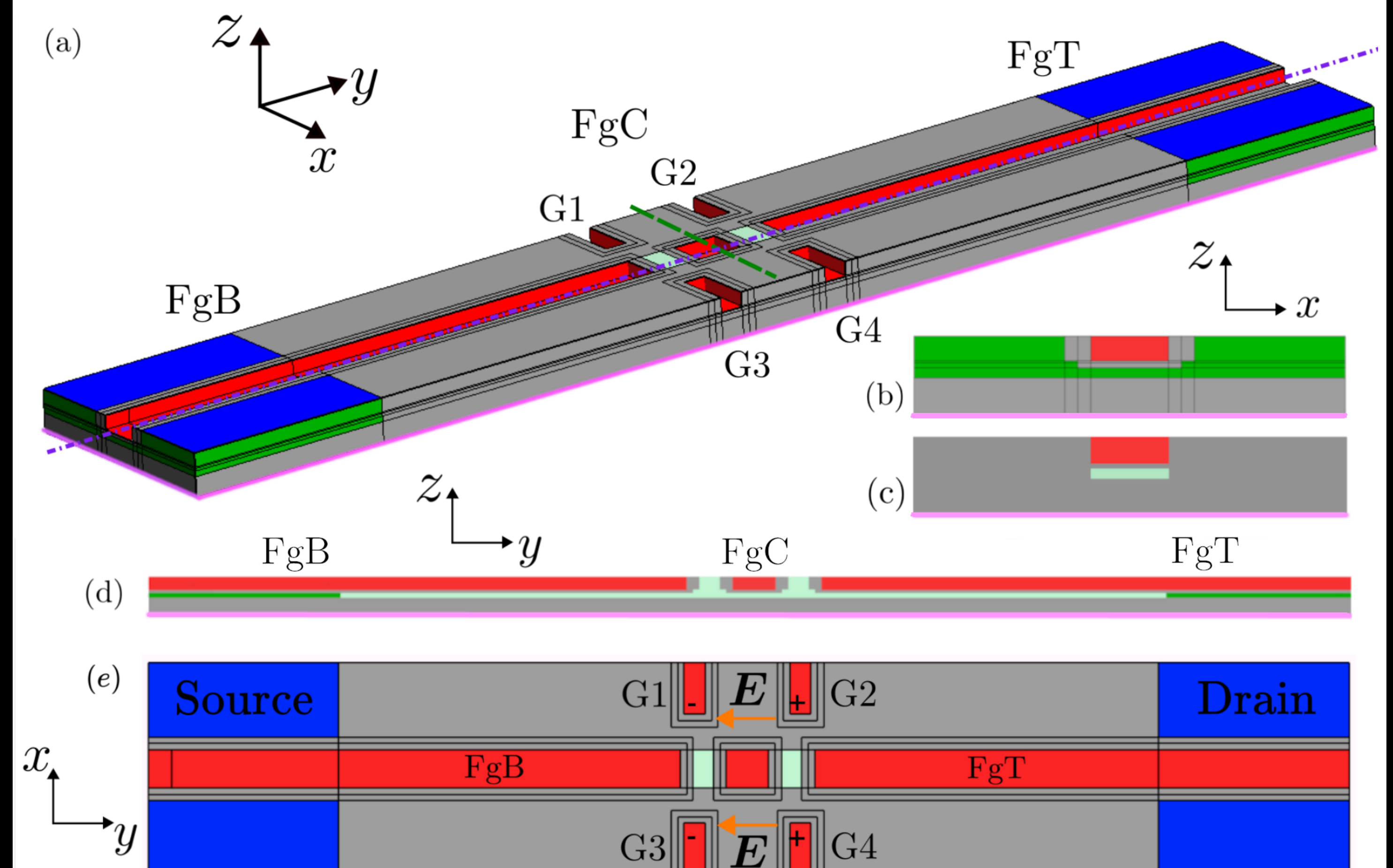
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Introduction

- An essential component of a microelectronics engineering toolbox is technology computer-aided design (TCAD) software.
- In May 2022, Nanoacademic released **QTCAD**[®], a TCAD software package for spin qubits in semiconductors.
- Here, we present TCAD simulations of electric-dipole spin resonance (EDSR) in the presence of a micromagnet.¹
- We consider a simplified 3D model of a 28 nm Fully Depleted Silicon on Insulator (FD-SOI) device, akin to foundry-compatible structures recently investigated with STMicroelectronics, Université Grenoble-Alpes, and Institut quantique.^{1,2,3}
- These simulations can give insight into the viability of EDSR in this device before considerable effort and resources are deployed to engineer a device with an integrated micromagnet.
- We find Rabi frequencies on the order of MHz by driving the system using the side gates. We also compute the associated leakage out of the qubit subspace.

FD-SOI device model



Hamiltonian and Eigenstates

System Hamiltonian

$$H(t) = H_0 + U(t)$$

$$H_0 = \frac{-\hbar^2}{2} \nabla \cdot [M_e^{-1} \cdot \nabla] + V(\vec{r}) + H_Z$$

$U(t)$: EDSR drive

$V(\vec{r})$: Confinement potential

H_Z : Zeeman Hamiltonian

Non-Linear Poisson Equation

$$-\nabla \cdot (\epsilon \nabla \phi) = \rho[\phi]$$

$$V = -e(\phi - \phi_F) - \chi$$

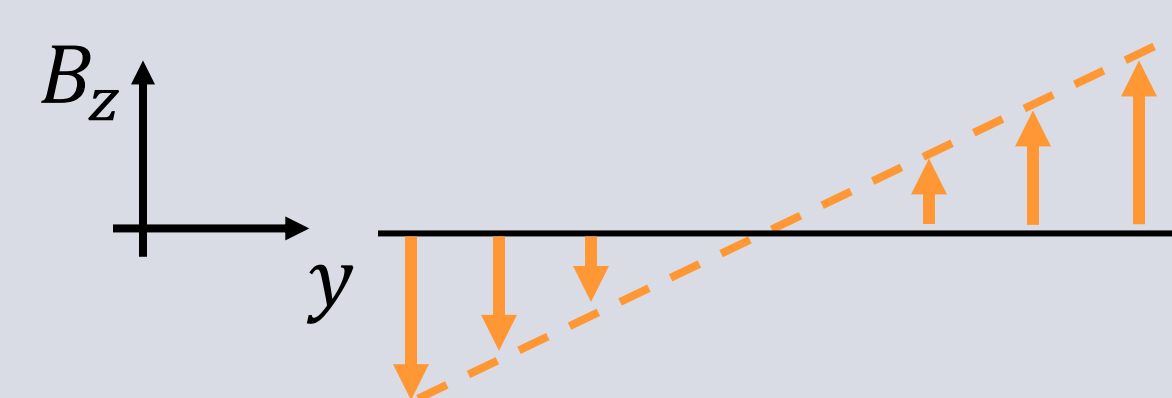
ϕ_F : Reference potential

χ : Electron affinity

$T = 1.4$ K: Convergence at cryogenic temperatures achieved using adaptive meshing⁴

Zeeman Hamiltonian

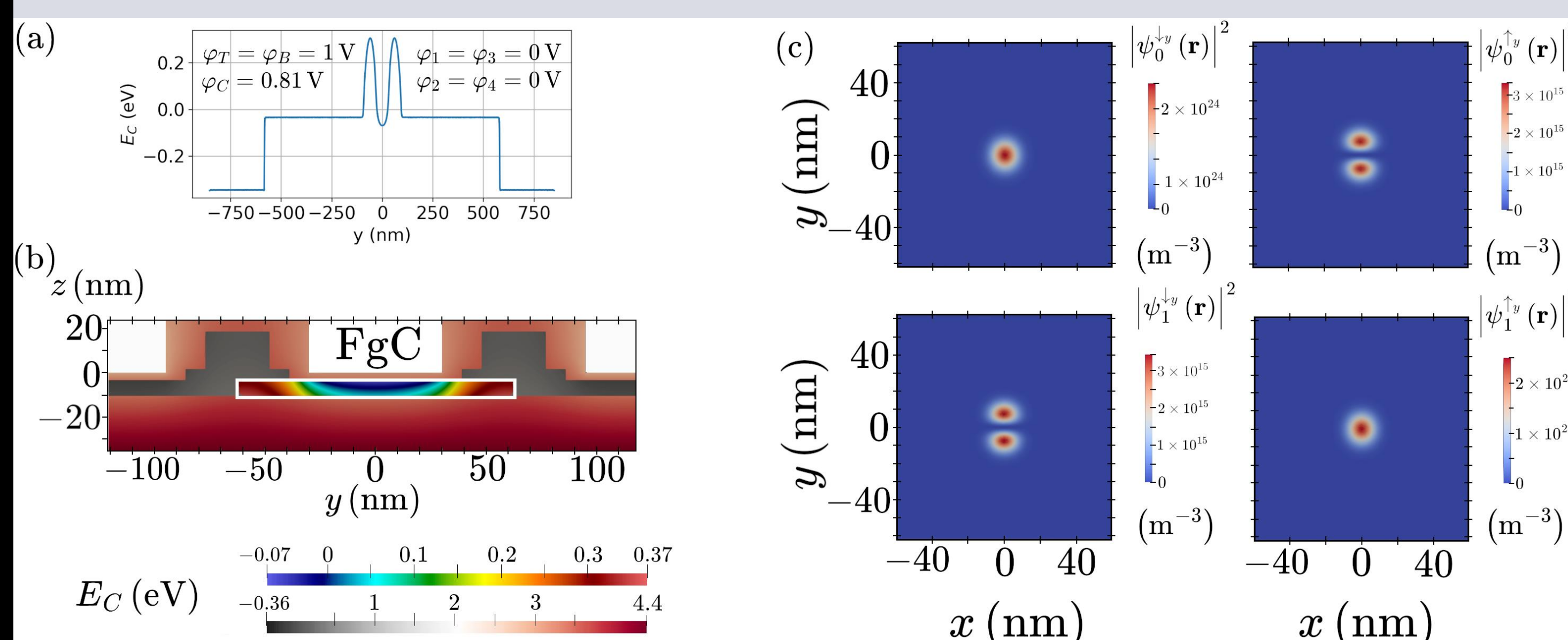
$$\vec{B} = (0, B_y, b_y)$$



b is the slope

$$H_Z = -\vec{\mu} \cdot \vec{B} = \frac{\mu_B g^*}{\hbar} \vec{S} \cdot \vec{B}$$

$g^* = 2$: Effective g-factor



EDSR Dynamics

Electric-dipole Hamiltonian

$$U(t) = e\vec{r} \cdot \vec{E}(t) = eE_y \cos(\omega t) y$$

Solve the Poisson equation for a given side-gate voltage configuration

$$\phi_1 = -\phi_2 = \phi_3 = -\phi_4 = \Phi$$

to obtain the confinement potential, $\tilde{V}(\vec{r}, \Phi)$

$$U(t) = \Delta V(\vec{r}, \Phi(t)) = \tilde{V}(\vec{r}, \Phi(t)) - V(\vec{r})$$

Matrix elements of the EDSR drive

ν labels the eigenstates of H_0

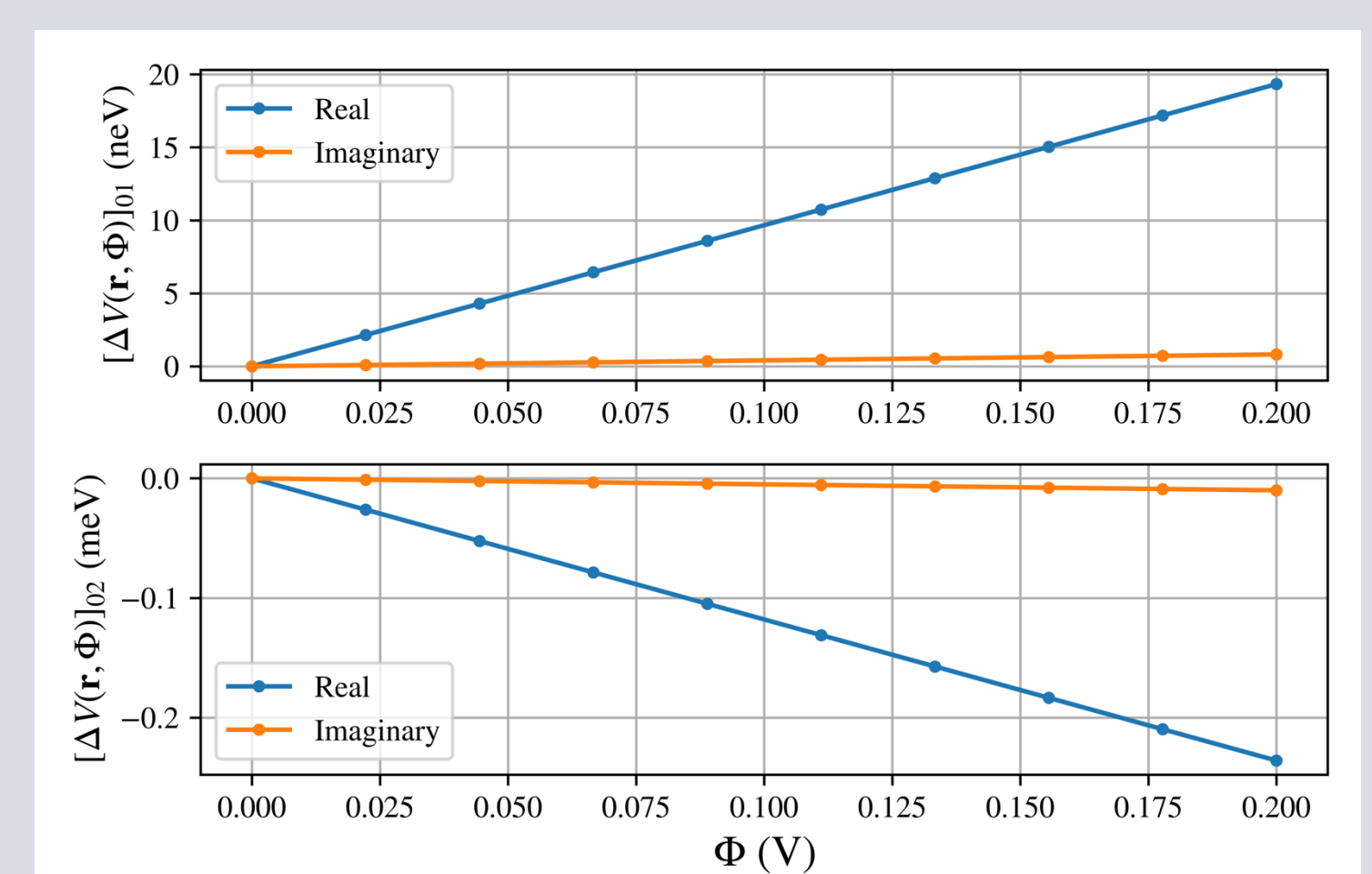
Matrix elements depend linearly on the applied bias:

$$[\Delta V(\vec{r}, t)]_{\nu\nu'} = \alpha_{\nu\nu'} \Phi$$

$$[\Delta V(\vec{r}, \varphi_0 \cos(\omega t))]_{\nu\nu'}$$

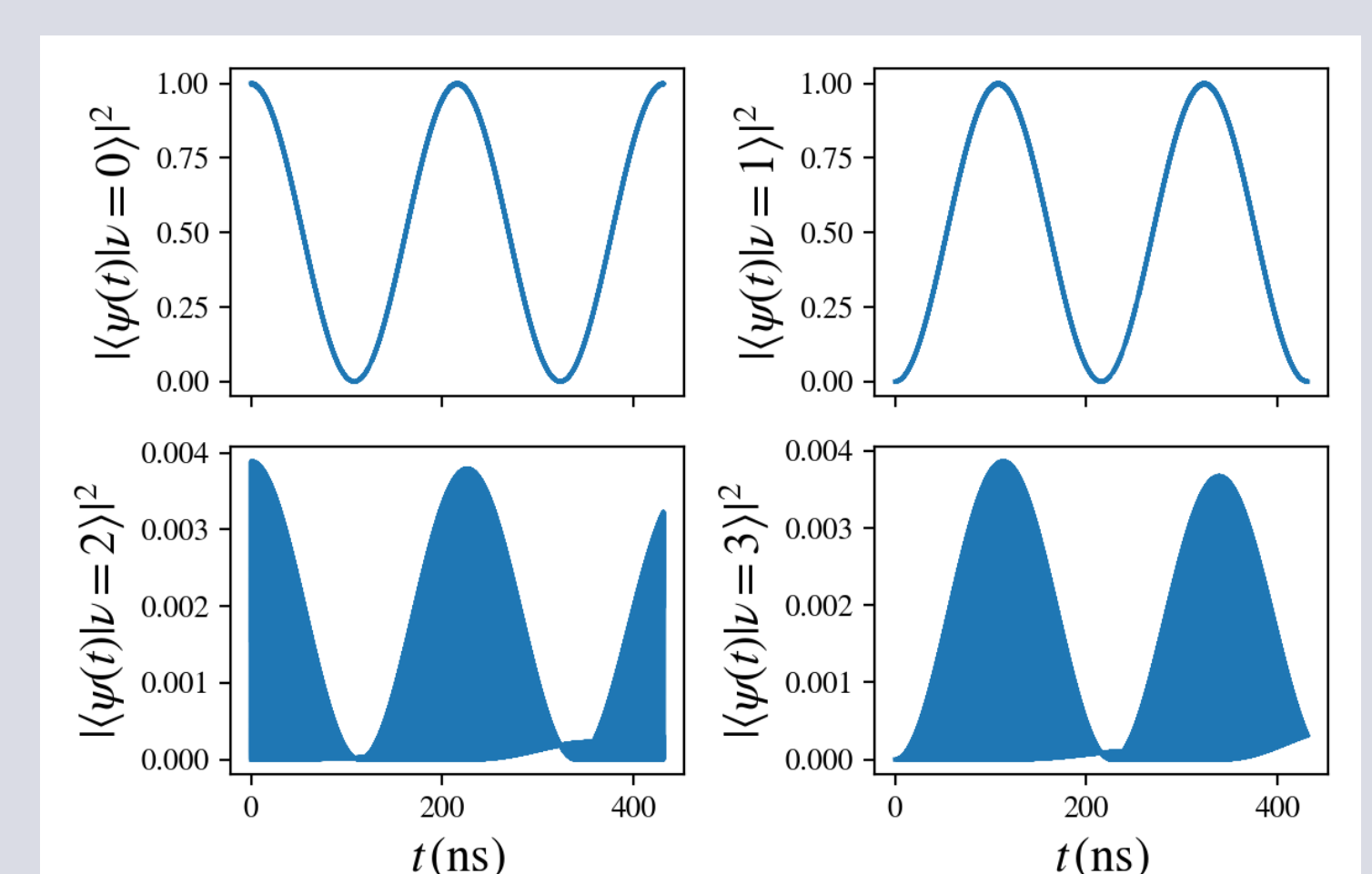
$$= \alpha_{\nu\nu'} \varphi_0 \cos(\omega t)$$

$$= [\Delta V(\vec{r}, \varphi_0)]_{\nu\nu'} \cos(\omega t)$$



Dynamics Simulations⁵

- EDSR transitions between the qubit states ($\nu = 0, \nu = 1$).
- Rabi frequency of $f_R = 4.7$ MHz for $\varphi_0 = 0.2$ V.
- Leakage to higher states (e.g. $\nu = 2, \nu = 3$) is $\lesssim 0.004$.



Conclusions

- We simulated the EDSR signal for a spin qubit located in a STMicroelectronics 28 nm ultra thin body and buried oxide (UTBB) Fully Depleted Silicon on Insulator (FD-SOI) device.
- The simulations were performed starting only from the device geometry and before the device was fabricated.
- We find Rabi frequencies on the order of MHz using a drive applied to the side gates of amplitude 0.2 V.
- The leakage out of the qubit subspace does not prevent single-qubit gate fidelities from achieving the (surface-code) fault-tolerant threshold.
- In future work, we will investigate how charge impurities can affect the presented Rabi oscillations.

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