

An Interactive Tool of Spin Qubit for Quantum Science and Engineering Education

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Abstract—Silicon-based spin qubits represent a promising technology for scalable quantum computing. However, the complex nature of this field, which requires a deep understanding of quantum mechanics, materials science, and nanoelectronics, poses a significant challenge in making it accessible to future engineers and scientists. Spin Quantum Gate Lab, a spin qubit simulation tool, is proposed in this paper to address this obstacle. This tool is designed to introduce key concepts of spin qubit to undergraduate students, enabling the simulation of single-qubit rotational gates and two-qubit controlled-phase gates. By providing hands-on experience with quantum gate operations, it effectively links theoretical quantum concepts to practical experience, fostering a deeper understanding of silicon-based quantum computing.

Index Terms—Spin qubit, Quantum Computing, Education, Quantum Gate

I. INTRODUCTION

Quantum computing represents a revolutionary approach to computation, leveraging the principles of quantum mechanics to solve problems that are currently intractable for classical computers [1]. Among various quantum computing technologies, silicon-based spin qubits stand out due to their scalability and compatibility with existing semiconductor fabrication techniques [2]. These qubits leverage the spin of electrons in silicon quantum dots, making them a promising candidate for large-scale quantum computing systems.

Silicon-based qubits offer several advantages. They can operate in two-dimensional arrays, which is crucial for implementing quantum error correction—a necessary component for reliable quantum computing. Additionally, silicon’s well-established fabrication processes and its ability to integrate with classical CMOS technology further enhance its potential for scalable quantum computing. Despite these advantages, the field of spin qubit technology is complex and requires a deep understanding of both quantum mechanics and semiconductor physics, posing a significant challenge for students and early-career researchers.

To address this educational challenge, online simulation tools play a crucial role. They serve as effective educational tools for illustrating abstract quantum concepts, allowing students to explore and manipulate quantum systems in a controlled, virtual environment. Such tools are particularly

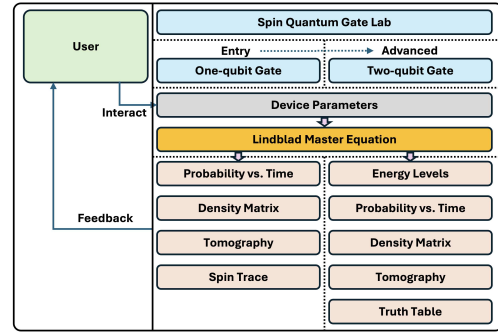


Fig. 1: The framework of the Spin Quantum Gate Lab, offering interactive parameters and various display modes for simulation results.

valuable in quantum computing education, where access to actual quantum hardware is limited and expensive.

The Spin Quantum Gate Lab [3] has been developed to meet this educational need, providing a hands-on, interactive environment for learning about spin qubit operations. It simulates single-qubit rotational gates and two-qubit controlled-phase gates, allowing students to visualize and experiment with quantum gate operations. This tool makes complex knowledge of theoretical quantum mechanics accessible by connecting it with practical quantum computing, offering valuable insights into the behavior of spin qubits. By enabling students to manipulate parameters and observe outcomes in real-time, it fosters a deeper understanding of quantum phenomena and their applications in computing.

II. OVERVIEW OF THE SPIN QUANTUM GATE TOOL

The Spin Quantum Gate Lab provides a comprehensive platform for simulating spin qubit operations. As illustrated in Fig. 1, the framework includes simulations of both one-qubit and two-qubit gates. These two kinds of gates form a universal gate set for quantum computing and make a complete educational platform.

One-qubit gates serve as a basic and foundational model for beginners. Fig. 2a shows a part of a silicon-based quantum processor. When a voltage is applied to the plunger gate (the golden part in the figure), it forms electric potentials that trap electrons. These electron spins can be manipulated through an

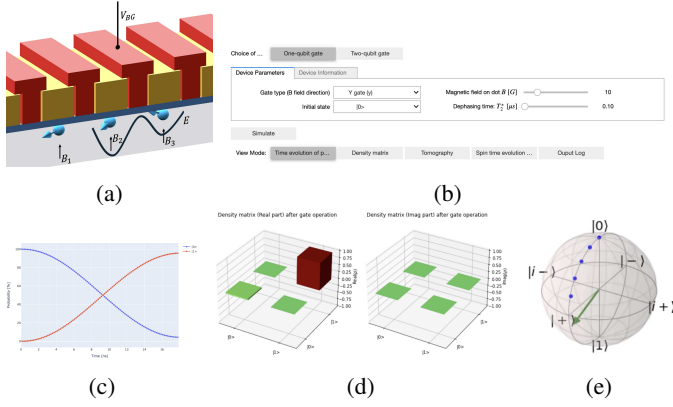


Fig. 2: (a) Schematic structure of a part of spin qubit array. Single-qubit rotational gate and two-qubit gate form a universal gate set for quantum computing. A magnetic field rotates a spin, resulting in a single-qubit rotational gate. A voltage applied to the barrier gate between two spins results in a two-qubit entangling gate. (b) The control panel offers settings for different initial states, magnetic field values, dephasing times, and etc. (c) The time evolution of probability view shows the probability of each state, demonstrating how pure states decohere over time. (d) The density matrix provides a comprehensive view of the quantum state, including mixed states and decoherence effects. (e) The spin rotation sequence demonstrates spin rotation under an applied magnetic field, providing insights into the physical dynamics.

external magnetic field and thus form single-qubit rotational gates. Users can control various parameters through the control panel (Fig. 2b), offering flexibility in model interaction.

The simulation process is based on the Lindblad Master Equation (LME) [4], [5]:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H, \rho] + \sum_i \gamma_i \left(L_i \rho L_i^\dagger - \frac{1}{2} L_i^\dagger L_i \rho - \frac{1}{2} \rho L_i^\dagger L_i \right),$$

where ρ is the density matrix, H is the effective Hamiltonian of the system, L_i are the Lindblad operators representing different quantum processes, and γ_i are the decay rates, which is $1/T_2^*$.

The simulation results are presented through various visualization modes. Time evolution of probability, as shown in Fig. 2c, illustrates how state probabilities change over time, including the effects of decoherence. The Density Matrix (Fig. 2d) provides a comprehensive view of the quantum state, covering mixed states. The Spin Rotation Sequence (Fig. 2e) demonstrates how the spin rotates when a magnetic field is applied, offering straightforward insights into the physical dynamics of spin rotation. Other views, such as Tomography and numerical results in the output log, are also included to give learners a comprehensive and vivid picture of the spin qubit world.

The two-qubit gate, involving two electrons confined by the potential created by plunger gates, is realized by applying a detuning gate voltage on the barrier gate to couple them, as shown on the right in Fig. 2a. The two-qubit gate model in Spin Quantum Gate Lab introduces a more advanced scenario

than the single-qubit model, simulating a controlled-phase (CPhase) gate [6]. The CPhase gate is particularly useful for understanding quantum entanglement, as the state of the second qubit depends on the state of the first qubit.

By engaging with these hands-on simulations and various demonstrations of the results, this tool allows users to explore the fundamental operations and principles of quantum gates, enhancing their grasp of quantum computing concepts.

III. INCORPORATION OF THE TOOL INTO EDUCATION ACTIVITY



Fig. 3: Education activity powered by Spin Quantum Gate Lab during Code-a-thon day.

The Spin Quantum Gate Lab has been successfully integrated into undergraduate quantum computing courses, supporting over 200 users with 1,453 simulation runs to date. It has provided students with hands-on experience (Fig. 3) in quantum gate operations, enhancing their understanding of complex quantum concepts. These activities have effectively bridged the gap between theoretical quantum concepts and practical experience across various educational levels, from K-12 to undergraduate studies.

IV. CONCLUSIONS

The Spin Quantum Gate Lab has made a notable contribution to quantum computing education. By offering an interactive and accessible platform, it enhances the undergraduate curriculum, seamlessly linking theory with practical application. The lab tool's inclusion of multiple visualization modes equips students with a deeper understanding of quantum phenomena. This tool significantly enriches the quantum computing education ecosystem, equipping students to navigate the complexities and seize the opportunities in this rapidly advancing field.

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