INDIAN INSTITUTE OF SCIENCE

IISC QUANTUM TECHNOLOGY INITIATIVE

QT204 - INTRODUCTION TO MATERIALS FOR QUANTUM TECHNOLOGIES

Project Report

Spin Qubits in Graphene Quantum Dots

Chaitali Shah
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Contents

1 Introduction

In 1997, a novel approach for the implementation of qubits was proposed by Daniel Loss and David DiVincenzo. They proposed the idea of spin qubits that met the DiVincenzo criteria for quantum computing as elaborated hereafter.

1. Identification of well-defined qubits: They proposed that quantum dots could act as a host for qubits, where the two level system of the qubit is realized as the spin of the electron residing on the dot.

2. Reliable state preparation/initialisation: A simple state of all spins up is achieved if the system is cooled sufficiently in a uniform applied magnetic field. A specific arrangement of up and down spins can be created by a applying the reverse of the spin-valve measurement apparatus.

3. Low decoherence: The spins in quantum dots should generically have longer decoherence times than their charge since spins are almost insensitive to any environmental fluctuations of the electric potential whereas charge qubits are rather strongly coupled to the environment.

4. Accurate quantum gate operations: Two qubit gate operations could be performed using a purely electrical gating of the tunneling barrier between neighboring quantum dots. Such gating had already been achieved by a split-gate technique - tunneling was forbidden for a high barrier potential and for a low barrier potential, the spins would be subject to a transient Heisenberg coupling. According to the Hubbard model, this coupling is given by $H(t) = J(t)\boldsymbol{S_1}.\boldsymbol{S_2}$ where $J(t) = \frac{4t_0(t)}{u}$ is the time-dependent exchange constant, $t_0(t)$ is the tunneling matrix element, u is the charging energy and $\boldsymbol{S}$ is the spin-$\frac{1}{2}$ operator of the dot.

   For a duration τ_s such that $J_0\tau_s = \pi$, the time evolution operator $U(t)$ becomes the SWAP operator U_{swap}. The quantum XOR gate is obtained as
   $U_{XOR} = e^{i\frac{\pi}{2}S_z^1}e^{-i\frac{\pi}{2}S_z^2}\sqrt{U_{swap}}e^{i\frac{\pi}{2}S_z^1}\sqrt{U_{swap}}$,
   where $e^{i\frac{\pi}{2}S_z^1}$ etc. are single qubit operations. The rotations for single qubit operations can be performed by a magnetic field $\boldsymbol{H_i}$ pulsed exclusively onto spin i. The XOR gate along with the single qubit operations forms the universal set for quantum computations.

5. Strong quantum measurements: A 75% reliable POVM measurement scheme suggested is by switchable tunneling into a super-cooled para-magnetic dot. Another scheme which would result in an almost 100% reliable measurement requires a spin-dependent, switchable “spin valve” tunnel barrier.

2 Graphene Spin Qubits

Spin qubits were have been implemented in semiconductor materials such a gallium arsenide, silicon and germanium. Many advances and experimental breakthroughs have been achieved especially in GaAs technology. In such devices, the spin–orbit interaction, coupling the spin to lattice vibrations and the hyperfine interaction of the electron spin with the surrounding nuclear spins are the major causes of decoherence. Therefore, it is advisable to explore other materials for implementation of spin qubit that can overcome the shortcomings of the semiconductor quantum dots.

2.1 Advantages of Graphene Spin Qubits

Carbon-based materials like nanotubes and graphene offer themselves to be good choices. Ideally, a qubit should be easy to manipulate and should have minimal coupling with its environment. Graphene is advantageous on both these accounts as elaborated below.

1. The atomic number of carbon is 6 and it has a relatively low atomic weight. Therefore, the spin-orbit interaction is weaker when compared to heavier elements. Nanotubes exhibit significant spin-orbit interactions due to curvature of the tube but coupling in graphene quantum dots is rather weak.

2. Carbon has two stable isotopes: ^{12}C and ^{13}C. Their nuclear spins are 0 and $\frac{1}{2}$ respectively. The composition of natural carbon is 99% ^{12}C and 1% ^{13}C. Since hyperfine interactions with nuclear spins are absent in the predominant ^{12}C isotope, there is lower decoherence.

3. Single qubit gate operations or rotations are implemented using electron spin resonance(ESR) or by electric-dipole-induced spin (EDSR).The Rabi frequency of a qubit rotation in ESR experiment depends on the electron spin g-factor, which is different for different materials. In GaAs, its magnitude is found to be less than 0.43, whereas it is close to 2 in the case of graphene. This indicates that spin rotations in a graphene dot are about five times faster than that of a GaAs dot in an ESR experiment for the same same field strength of the external oscillating magnetic field. Graphene exhibits faster operations are important to progress towards fault-tolerant computing.

4. In small band gap semiconductors like graphene nano-ribbons, qubit manipulations can be done either through tunneling via conduction band states (i.e. normal tunneling) or through tunneling via valence band states (i.e. Klein tunneling). By means of Klein tunneling, two distant non-neighbour qubits can be strongly coupled without disturbing the state of intermediate qubits. Spins qubits in graphene can coupled over long distances via Klein tunneling, unlike in other semiconductor materials where coupling is only between nearest neighbours. Non-local interactions raise the error threshold for fault-tolerant quantum computation and are important for error-correction.

Hence, graphene quantum dots are an excellent candidate for implementation of spin qubits.

2.2 Challenges in Graphene Spin Qubits

There are two fundamental challenges that need to be addressed in the case of graphene spin qubits.

1. A unit cell of graphene has two atoms with the same potential, which leads to a lack of band gap. In such a case, it is difficult to create a tunable quantum dot in graphene. The phenomenon of Klein tunnelling makes it hard to achieve controllable confinement of particles.

2. The conduction band and valence band of graphene meet at the Dirac points. The six Dirac point of graphene are divided into two non-equivalent sets - K and K'. Owing to this valley degeneracy that exists due to these sets, it is non-trivial to form two-qubit gates. The breaking of the valley degeneracy is a pre-requisite for two-qubit gates using Heisenberg exchange coupling for spins in tunnel-coupled dots.

2.3 Developments in Graphene Spin Qubits

Many setups have been proposed to overcome the challenges faced in graphene spin qubits and are presented here.

2.3.1 Graphene nanoribbons with armchair-terminated boundaries

Quantum confinement by suitable transverse states leads of opening of a band gap in ribbons. In particular, semiconducting armchair boundary conditions are imposed on two opposite edges of the sample. These boundary conditions couple the two valleys and thus, the valley degeneracy is lifted in such a device.

The structure is shown in Fig. 1 is based on a ribbon of graphene (grey) with semiconducting armchair edges (white). The voltage applied to the barrier gates (blue) is used to confine the particles to appropriate states. Additional gates (red) allow one to shift the energy levels of the dots.

Virtual hopping of electrons through barrier 2 gives rise to a tunable exchange coupling J between two electron spins localized in the left and the right dots. The exchange coupling is then used to generate universal two-qubit gates. For more than two dots in a line, any two of them can be coupled with the others being decoupled by detuning.

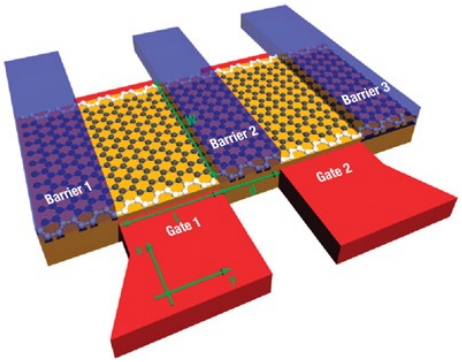

Figure 1: Graphene Quantum Dot in nanoribbon with armchair boundary conditions
Reprinted from *Spin qubits in graphene quantum dots, Trauzette et al.*

2.3.2 Discs in single-layer graphene

Electric fields can also be used to confine electrons in single layer and bilayer graphene even without specific boundary conditions. In gapped graphene, the valley degeneracy of graphene can be broken at finite magnetic field. These quantum dots suffer less from edge roughness (deviation from ideal edge features) as compared to nanoribbons. In single layer graphene, graphene quantum dots (QDs) have been mostly realized by top-down lithography and etching and many of the basic quantum transport properties such as Coulomb blockade, charge detection, and electronic phase coherence have been experimentally demonstrated.

2.3.3 Discs in bilayer graphene

The band-structure of bilayer graphene develops a gap in the presence of a perpendicularly applied electric field. Bilayer graphene is potentially superior to single-layer graphene due to the creation of a tunable bandgap by electric fields which allows for an all electrical control of graphene quantum dots. Until recently, all devices were limited by leakage currents due to shortcomings in opening a homogeneous gap through the whole device. The development of a dry-stacking methods for sandwiching graphene and other two-dimensional materials between two layers of insulating hexagonal boron nitride (hBN) allowed for devices of extremely high electronic quality. Another development was the idea of using few-layer of graphite placed under the devices as a back gate. This improves substantially the electrostatic coupling to the active layer and helps screening the residual disorder due to the substrate.

3 Recent Experimental Advances in Bilayer Graphene Quantum Dots

Quantum Point Contact: In 2018, a quantum point contact was realised in bilayer graphene, with leakage resistances below depletion gates as high as R $\approx$ 10 $G\Omega$. The experiment was performed on two ultra-clean bilayer graphene samples encapsulated in hexagonal boron nitride (hBN) with a homogeneous top gate stripe crossing the current path in combination with a global graphite back gate. as shown in Fig. 2 Two split gate devices were realized to create an electronic channel on the scale of the Fermi-wavelength. Realizing one-dimensional nanostructures in bilayer graphene by electrostatic gating paved the way towards controllable quantum dots in bilayer graphene.

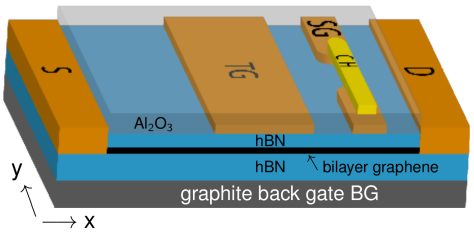

Figure 2: Layout for quantum point contact
Reprinted from *Electrostatically induced quantum point contact in bilayer graphene, Ensslin et al.*

Gate-defined quantum dots: The same group that realised the quantum point contact, also studied the spin and valley states in bilayer graphene quantum dots, demonstrating the first gate-defined quantum dots in bilayer graphene. Their experiment demonstrated charging of a bilayer graphene quantum dot with single holes when coupling it to n-type source and drain leads through p-n tunnel barriers. Charging energies were observed to be more than 10 meV. On application of perpendicular magnetic field in their second experiment, shell filling and orbital degeneracy were observed. It was shown that the lifting of valley degeneracy was in agreement with theoretical predictions. In the final experiment of that study, the quantum dot were subjected to an in-plane magnetic field to find Zeeman splitting which had a spin g-factor that agreed with the expected value.

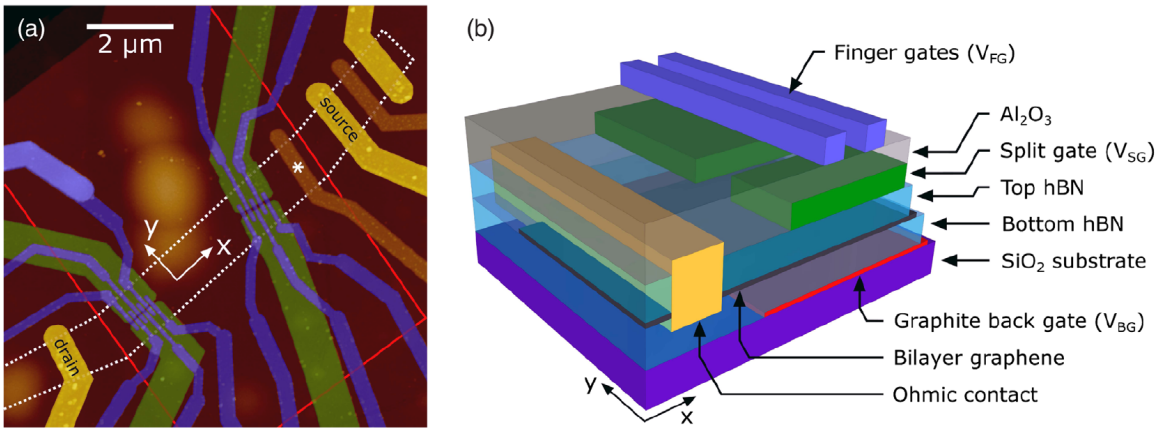

Figure 3: Bilayer graphene quantum dot : (a) False color scanning force micrograph of the device. (b) 3D sketch of part of the device
Reprinted from *Spin and Valley States in Gate-Defined Bilayer Graphene Quantum Dots, Ensslin et al.*

Charge Detection: In 2019, the detection of single charge carriers in bilayer graphene quantum dots was achieved in an electrostatically define device. These devices use bilayer graphene encapsulation in hexagonal boron nitride (hBN), edge contacts and a graphite back gate, that screens charge impurities trapped in the silicon oxide substrate. The charge detector was based on a quantum dot separated from the first dot by depletion underneath a 150 nm wide gate. Coulomb resonances in the sensing dot are sensitive to individual charging events on the nearby quantum dot, and step changes in current are detected due to change in potential. The charge detection using coulomb diamonds can be seen in Fig. 4.

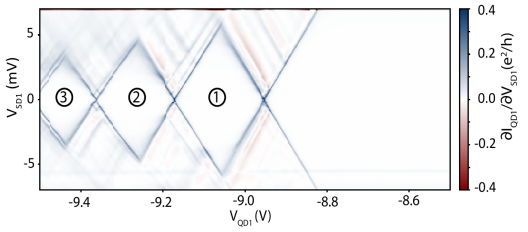

Figure 4: Measurement of Coulomb blockade diamonds of quantum dot, when the first three holes are charged into the dot.
Reprinted from *Charge Detection in Gate-Defined Bilayer Graphene Quantum Dots, Ensslin et al.*

Double Quantum Dots: A study of bilayer graphene double quantum dot device in the few-electron regime was presented soon-after. Finger gates were used to modulate the band profile along a channel defined by metallic split gates as shown in Fig 5. High uniformity was observed by finite bias spectroscopy data. A double quantum dot can be created two gates and the charges on the quantum dots can be controlled. The paper also suggested a third gate layer to implement inter-digitated finger gates to obtain control over the electrochemical potentials and the tunnel barriers as possible direction for progress.

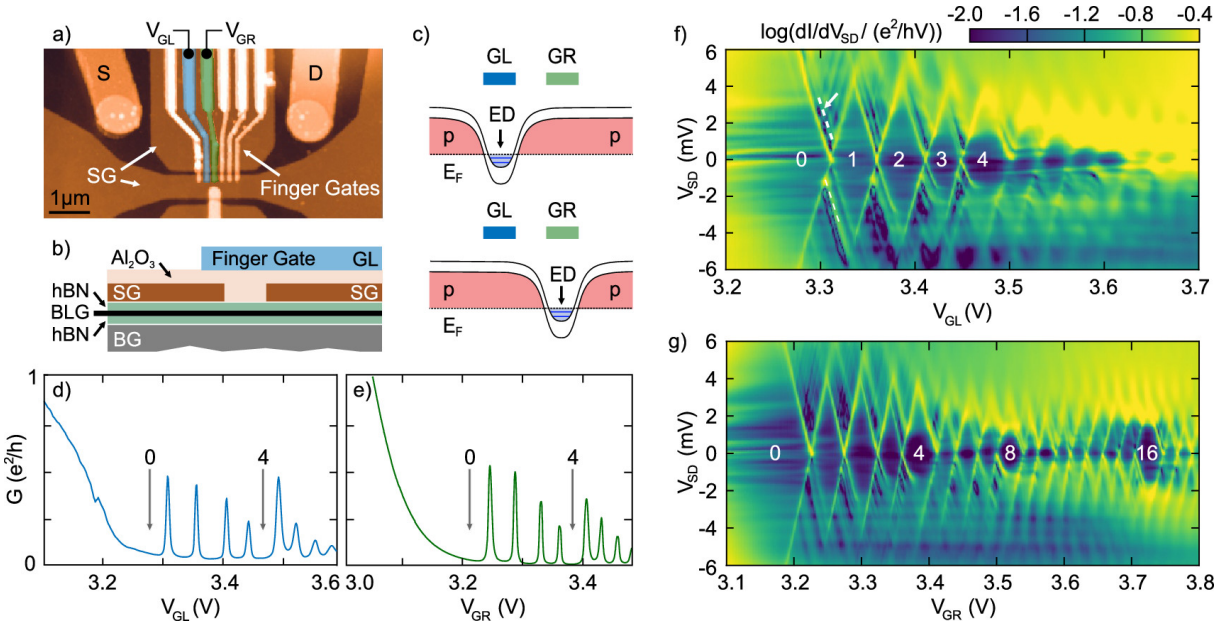

Figure 5: (a) Gate layout of the device. (b) Schematic cross section of the device. (c) Schematics of the band profile along the one-dimensional channel illustrating the formation of QDs. (d,e) Conductance through a QD formed under GL and GR as a function of the gate voltage V_GL and $V_SD = 1$ mV. (f,g) Finite bias spectroscopy measurements for both QDs.
Reprinted from *Single-electron double quantum dots in bilayer graphene, Ensslin et al.*

Pulsed-gate spectroscopy: Recently, it was shown that pulse-gate experiments may be performed on gate-defined bilayer graphene QDs on graphitic gates. The spin relaxation time of a single electron in such edge-free nanostructures was found to be in the right order of magnitude, which exhibition of any unexpected relaxation processes.

4 Conclusion

Graphene is a promising candidate to host spin qubits in quantum dots due to long coherence times. Bilayer graphene especially has many redeeming qualities that present it as a viable option for quantum computing. There are abundant studies in progress that will improve our understanding of the characteristics and performance of these devices.

5 References

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