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# Qubit read-out in Semiconductor quantum processors: challenges and perspectives

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**Abstract**— We report the efforts, challenges and perspectives dedicated towards building a reliable spin read-out for Si spin qubit systems. We review several strategies that are pursued in the semiconductor quantum circuit community. We discuss their pros and cons with respect to their performance (speed and fidelity), their integration potential and their footprint. We then address the envisioned architecture to read-out spin qubits at large scale.

## I. INTRODUCTION

With one- and two-qubit gates, qubit read-out is one of the three fundamental quantum operations that needs to be implemented on individual qubits in a quantum computer. It is essential to obtain the results of the quantum computation with reasonable fidelities. It is also crucial for fault tolerant quantum computation and quantum error correction (QEC) protocols since it allows to witness and trace back the errors occurring during the calculation flow [1]. In the context of semiconductor quantum circuits, qubit read-out with fidelities above 99% with speed below one microsecond per shot are requested to guaranty QEC efficiency and ensure competitive computation run time. Moreover, repeated [2] or quantum non-demolition measurements [3] are desirable in order to adjust the performance of the measurement while running the algorithms [4]. Key figures of merit for spin read-out operation are fidelity (or detection efficiency), speed (that must be faster than the relaxation time  $T_1$ ) and the number of elementary components needed to be able to perform the read-out (reservoir, quantum dots,...). Measuring directly the magnetic field produced by a single electron spin trapped in a quantum dot is a very challenging task that has been demonstrated in a “tour de force” experiment in the early 2000 [5]. In addition to its complexity, it turned out to be rather slow (ms) which is incompatible with quantum computation. In the semiconductor, spin read-out is performed by converting the spin into a charge information and probe the charge properties of the electron on timescales approaching the  $\mu\text{s}$ .

## II. BASICS AND CONCEPTS AROUND CHARGE READ-OUT

Two main physical concepts are used to perform single shot charge read-out: direct charge read out thanks to an electrometer (figure 2) of capacitive measurements (figure 1 & 3). In both case a double dot system is defined where individual electrons are trapped, one in each dot. Coupling to an electron reservoir on the side permit to load electron in the dot. To measure the spin state of a single electron trapped in a quantum dot under a non-zero magnetic field, an important prerequisite is the ability for the electron to tunnel to another dot or to the electron reservoir, dependent on its spin state (see section III). Once the system is defined, measuring the charge configuration of the quantum dot system with an electrometer defined on the side or performing

capacitance measurement are the two possible strategies to observe in real-time the tunneling process.

### A. Charge read-out

An electrometer is capacitively coupled to the dot system and is sensitive to the absolute charge in each dot configuration (figure 2). Change in the charge configuration induced by a tunneling process within the dot system will result in a change of the electrometer conductance. Charge sensitivity down to  $1 \times 10^{-6} \text{ e}/\sqrt{\text{Hz}}$  has been demonstrated, enabling the discrimination of the movement of a single electron in between two dots below  $1 \mu\text{s}$  [6].

### B. Capacitance measurement

Embedding one gate of the device within a tank circuit (resonator) made of an inductor and the parasitic capacitance of the circuit, it is possible to probe the change of the capacitance of the gate due to the motion of the electron with the dot system. The ability to tunnel from one dot to another results in an extra capacitance of the gate called “quantum capacitance” [7, 8]. The strength of the extra capacitance is inversely proportional to the tunneling rate and proportional to the gate lever arm  $\alpha$ . In this case, the detection method is only sensitive to the tunneling process, irrespective of the absolute number of charge within the dot systems. This method allows to distinguish charge or spin states characterized by zero or full quantum capacitance in  $10 \mu\text{s}$  [9,10]. It is worth noting that capacitance measurement can also be combined with an electrometer as illustrated by the set-up presented in figure 3.

## III. SPIN-TO-CHARGE READ-OUT

Once tunneling process can be probed in real-time at the single electron level, engineering a spin-dependent tunneling process enables to convert the spin to charge information and to read-out the spin states. The first demonstrated spin read-out in semiconductor circuits used a large magnetic field to open a large energy gap between spin up and spin down and tunnel process is in this case only possible for the excited spin up state [11]. Such a strategy has some limitations since it mainly works at high magnetic field and leads to rather low fidelity, below 90% was reported so far. In this article, we will focus on the spin-to-charge conversion occurring in a double dot with two electrons and based on the Pauli exclusion principle. The first dot contains the electron spin qubit to be measured. The second dot is used as an ancilla and is initialized in the spin down state. Two spin states are then involved in the read-out process : spin up spin down or spin down spin down. Only the first one is connected through quantum tunneling to the singlet state when the two electrons are in the same dot. Spin down spin down state is connected to the triplet state. The difference of energy between singlet and triplet in a single dot permits then to read-out the electron spin qubit states and we will

describe in the following three strategies that differs only in the way that the spin-to-charge conversion is completed.

#### A. Tunnel rate read-out

In this strategy the two electrons are brought in the ancilla dot with a tunneling process and therefore we need to distinguish singlet and triplet state in a single dot. Due to the differences in orbital configuration for singlet and triplet states in a single dot (two electrons in the ground state orbital for singlet, one in the ground and one in the first excited orbital state for triplet), different tunnel rates are observed for singlet and triplet and they can be distinguished in detecting precisely when the tunneling process occurs (see Fig4). The component requirements are the following: a charge detector, two dots and a reservoir. Fidelity up to 96% and speed approaching 10  $\mu$ s has been demonstrated and is limited by the difference of tunnel-rates [12].

#### B. Pauli spin-blockade

This strategy is taking advantage of the energy difference between singlet and triplet state in a single dot. As a consequence, a working point exists where only the electrons in the singlet state (1,1) experience tunneling to (0,2) charge state, the other states remain in the (1,1) configuration. Using a close-by electrometer,  $\mu$ s-charge detection between (1,1) and (0,2) charge configuration with up to 98% was demonstrated. Using RF gate reflectometry, only the singlet state in the double dot is characterized by an extra quantum capacitance and large signal separation for the two spin states are obtained for both electron and hole qubits [13,14,15]. For hole spin qubits, demonstration with Rabi oscillations were observed as presented in Fig 7. Single shot detection up to 98% at 5- $\mu$ s has been demonstrated recently [9]. It is worth noting that this strategy does not require any electron reservoir and in the case of gate reflectometry represent the lowest number of required elements.

#### C. Latched spin blockade

The later Pauli spin blockade mechanism induces only a change in the electric dipole moment of the double quantum dot while the total amount of charge stays constant in the system. In order to enhance the charge difference induced by the spin blockade, the system can be prepared in a configuration where (0,2), (1,1) and (1,2) charge states are degenerated. In this case, following the Pauli spin blockade spin read-out procedure, a triplet will lead to a final (1,1) charge state, and a singlet will lead to (0,2) charge state. At this point, the difference in tunnel rates from the reservoir to the first and the second dot will preserve, at short time scales the (1,1) configuration, while (0,2) and (1,2) can oscillate. Therefore, this difference of total charge number between singlet and triplet gives rise to a much larger signal.

This method can be implemented using a standard SET as a charge detector [16] or a gate-based charge sensing protocols [17]. In figure 5 and 6, typical histogram for spin separation and dependence on the fidelity with integration time are respectively shown.

## IV. PERSPECTIVES

### A. Fidelity and speed

The faster the qubit is measured, the higher the noise, the lower is the fidelity. So there are two ways to improve the fidelity at a given integration time. The first possibility is to increase the capacitive coupling between the dot and the sensor, therefore increase the signal. Effort to design quantum circuits to reach  $\alpha$  factor close to 1 are conducted. The second option consists in reducing the noise of the amplifying chain. Cryogenic environment allows accessing sub 4K noise temperature with superconducting amplifiers. Parametric amplification based on Josephson junctions has been widely used to amplify signal close to the quantum limit. Once integrated in spin qubit measurement chain, it is expected to reach a noise temperature below 100mK, which will allow a reduction of the integration time by almost two orders of magnitude. Therefore, using such amplifiers, one can expect to reach a 99.9% readout fidelity within 1 $\mu$ s integration time.

### B. Footprint

The typical size of the tank circuit (inductance, capacitance) used in the circuit read-out is at the lowest equal to 100 $\mu$ m $\times$ 100 $\mu$ m. Therefore, with the current technology, it is difficult to maintain a small footprint for the spin qubit taking into account the whole system requested to perform read out. For scaling, we will need to reduce the size of the RF components, especially there is a need for small size inductor. One approach to fabricated small footprint inductors consists in exploiting the very large inductance of superconductor thin film which are compatible with CMOS processing. For instance, TiN, which is widely used in gate stacks, allows reaching few tens of nH in a few micron squares.

### C. Strategies for scaling

Both strategies (electrometer, capacitance measurement) are compatible with RF embedding. As a consequence, multiplexing with assigning a frequency to each qubit becomes an obvious way to measure simultaneously a large number of spin qubit at the same time [18]. Such a strategy has the advantage of low overhead in term of amplifier, since the multiplexed read-out will only require a single amplifier chain. In figure 9 and 10, we present an architecture to embed spin read-out at large scale. A second strategy is to engineer for each qubit a complete nanometer amplification chain. Challenges in interconnect, footprint and heat dissipation are foreseen at large scales.

## V. CONCLUSION

Qubit read-out for electron and hole spin semiconductor quantum circuits has been the subject of an intense research effort over the last ten years. It is routinely performed at fidelity approaching 99% with timescale below 1 ms. One open question remains to address the question of the repeatability of the read-out and quantify the potential source of excitation of the qubit system occurring during the read-out. The next challenge is to be able to engineer individual qubit read-out in large scale quantum devices, with a number of technological strategies.

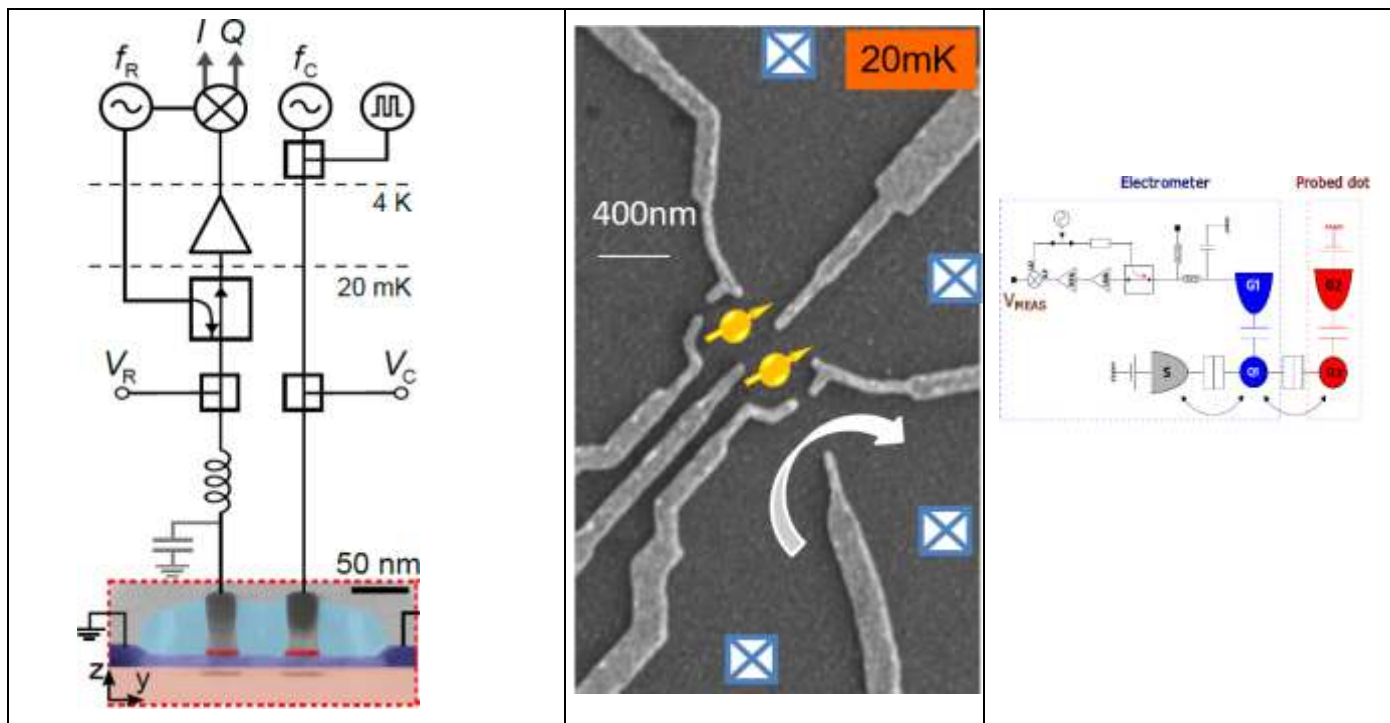


Fig. 1: Si Double quantum dot system with radio frequency gate reflectometry set-up defined on the left hand side dots.

Fig. 2: Double quantum dot system with a close-by electrometer (represented by the white arrow) defined in AlGaAs quantum dots.

Fig. 3: Single quantum dot (probed dot) coupled to a close-by electrometer made out of a single dot and reservoir.

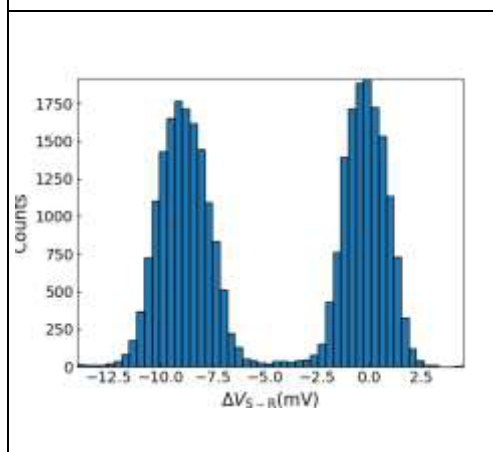


Fig. 4: Histogram of the charge detection for electrometer associated to singlet and triplet in a single dot defined in AlGaAs quantum dot (in system as defined by figure 2) and with spin-to-charge conversion obtained with tunnel-rate read-out. Integration time was 1 ms.

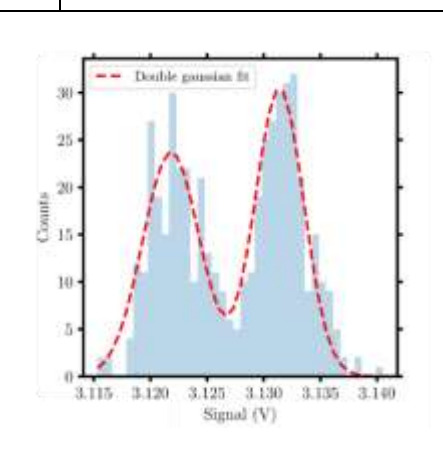


Fig. 5: Histogram of the charge detection gate reflectometry associated to singlet and triplet defined in a Si double quantum dots (see Fig. 1). Spin-to-charge conversion was obtained by latched spin-blockade mechanism. Integration time was 100 $\mu$ s.

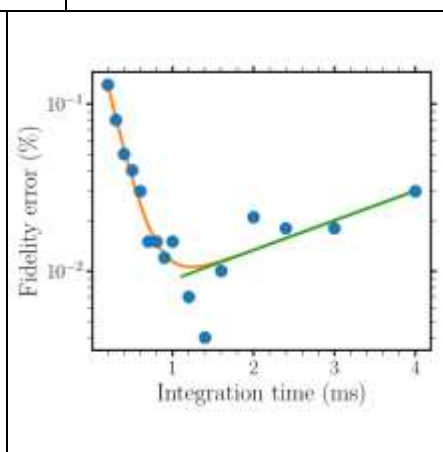


Fig. 6: Fidelity vs speed obtained with the typical curves presented in Fig. 5 with spin-to-charge conversion was obtained by latched spin-blockade mechanism.



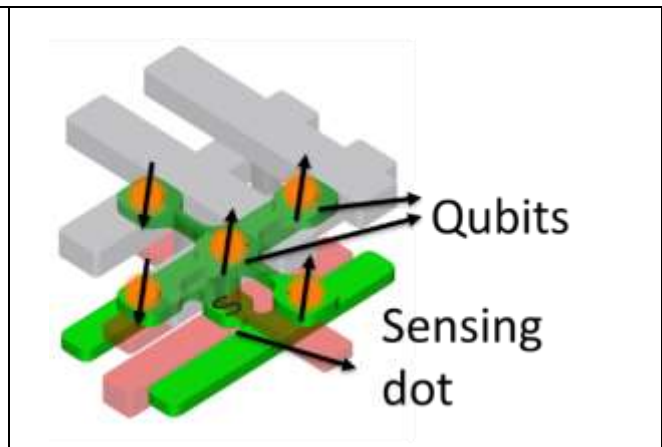
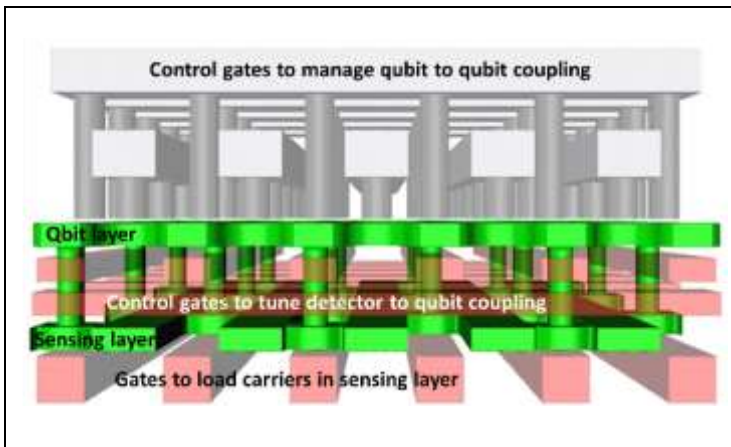
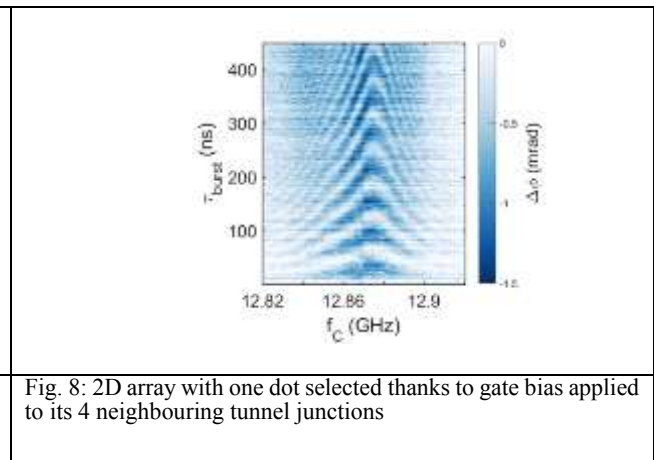
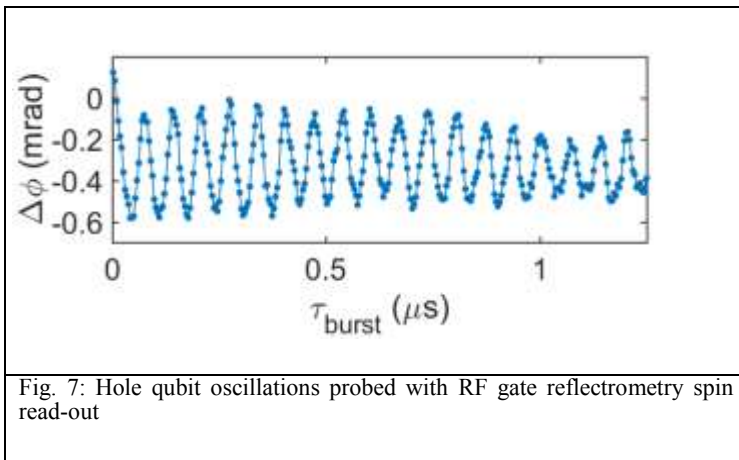


Fig. 9: The qubit contains the quantum hardware with spin qubits stored in an array of tunnel-coupled quantum dots. To control the quantum dots, a grid of long gates is designed and allows individual electrostatic and coherent control of the electron spin qubits. The lower layer is dedicated to the engineering of local reservoirs of electrons and local electrometers for the qubit layer. The two layers are coupled by a controllable tunnel barrier to allow electron transfer between them. This tunable tunnel coupling will be used to perform the read-out and the initialization of the quantum hardware.

Fig. 10: 3D unit cell of the architecture presented in Fig. 9.

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