CEN/CLC/JTC 22/WG 3 "Quantum Computing and Simulation"
WG Secretariat: **AFNOR**
Convenor: **Lefebvre Catherine Mrs**

CEN-CLC-JTC 22-WG 3_CryoSolidState_QuantumDevices_SpinQubits

Document type	Related content	Document date	Expected action
Meeting / Document for discussion	Meeting: VIRTUAL 22 Feb 2024	2024-02-21	

Functional description of
Quantum Devices

Date of submission:	2024-02-21
Submitted by:	Nico Hendrickx (N.W.Hendrickx@tudelft.nl) Rob F.M. van den Brink (Rob.vandenBrink@Delft-Circuits.com)
Expected action:	
Expected date:	2024, February 26th (or 22th) meeting of JTC22/WG3
WG3-Project:	Cryogenic Solid State QC

1. Abstract

The chapter on "Quantum Devices" in draft 02 of "Cryogenic Solid State Quantum Computing" includes texts on Transmons. The present contribution extend that chapter with content dedicated to Spin Qubits.
It offers a literal text proposal.

Start of literal text proposal

5. Layer 1 – Quantum Devices

The quantum devices in hardware layer 1 are modules with qubits that are operating at cryogenic temperatures and may be implemented as chip and/or on PCB (Printed Circuit Boards). Different solutions have been developed over time on how to implement these devices, including transmons, semiconductor spin qubits, flux qubits, topological qubits and artificial atoms in solids. Functional descriptions and functional requirements of these devices are described below.

5.1 Functional Description

5.1.2 Functional description of Spin Qubits

A spin qubit defines an implementation of a unit of quantum information. A multitude of connected spin qubits on a chip define a quantum processing unit (QPU). A spin qubit based QPU is typically controlled by a combination of dc, baseband, and microwave signals. The dc signals are used to bias the QPU to the right operating regime. The baseband signals can be used to perform quantum operations, as well as perform qubit initialization and readout. The microwave signals can be used to perform quantum operations, as well as reflectometry for qubit readout.

Different implementations of spin qubits in quantum dots exists, but in general the quantum information is encoded in one or more electron/hole spins confined in one or more semiconductor quantum dots. The simplest example is a single electron/hole in a quantum dot, where spin-up and spin-down states span the qubit Bloch sphere.

Typically, the spin-qubit is operated in a cryostat within the bore of a cryogenic magnet, the latter to provide a static magnetic field. This can either be a single-axis or multi-axis (vector) magnet.

A single spin qubit is typically controlled by electric signals send to the different input terminals of the qubit. Effective control signals can also consist of components on several input lines, for example to offset crosstalk within the QPU. Typical control input lines of the QPU are defined by electrostatic gates which define a very-high impedance load.

Typically control signals control different physical parameters of the spin-qubit system:

- Charge occupation within the quantum dot system. By shifting the potential levels within the quantum dot system, carriers can be moved between quantum dots.
- Coupling between the different quantum dots. By shifting the potential level of the barriers between different quantum dots in the quantum dot system, the interaction between different quantum dots can be controlled.

From a signal perspective, the control signal inputs can typically be categorized as follows:

- DC signals required to bias the spin-qubit into the correct working regime. These can be applied both to the charge occupation and coupling control parameters. Typical amplitudes of these signals are $-2<V_{dc}<2$ V.
- Baseband signals (100 Hz < f < 1 MHz), used to switch between different operation regimes, such as initialization, manipulation, and readout of the qubit. Typically, these signals consist out of extended plateaus where the same voltage is held, connected with ramped transitions. These can be applied both to the charge occupation and coupling control parameters. Typical amplitudes of these signals are 100-500 mV at the QPU.
- Baseband signals (1 MHz < 1 GHz), used to perform qubit operations. Depending on the encoding and/or operation mode of the qubit, these signals are used to either perform single or multi-qubit gate operations.
    - For some qubit encodings where single qubit operations are performed using baseband signals, these typically consist of ramped rectangular pulses on the charge occupation parameters, with durations of 1-100 ns. The selection between an X or Z rotation is done in this case through a separate control parameter controlling the coupling. Changing the voltage applied to the coupling control line, will tilt the axis around which the qubit will rotate during the baseband pulse, thus switching between e.g. X or Z rotations.
    - Two-qubit interactions can also be performed by applying a ramped rectangular pulse with typical durations of 1-100 ns to the correct control parameter.
    - In addition, these pulses can be shaped differently (e.g. Gaussian pulse) for higher performing qubit operations.
    - Typical signal amplitude might be 10-100 mV at the QPU.

- Microwave signals (100 MHz < f < 20 GHz), used to perform qubit operations. Depending on the encoding and/or operation mode of the qubit, these signals are used to either perform single or multi-qubit gate operations.
  - To perform resonant single qubit operations, these signals consist of short bursts of microwave signals, with a frequency matching the qubit frequency. The duration of the burst controls the angle of rotation, while the relative phase between different bursts controls the rotation axis. As an example, phase shifting a microwave burst by pi/2 with respect to a previous burst will produce a Y rotation, as compared to an X rotation for a burst with phase equal to 0.
  - In addition, these pulses can be shaped differently (e.g. Gaussian pulse) for higher performing qubit operations.
  - Typical amplitude of these signals might be -30 dBm at the QPU.
- Readout signals (100 MHz < 8 GHz), used to perform qubit readout through a resonant readout resonator. Depending on the implementation of the readout, such resonator can be connected to an electrostatic gate or ohmic contact. A readout tone is injected into the resonator for a time of 1-10 microseconds. The reflected signal will have a shift in frequency or amplitude, depending on the exact implementation of readout.
  - Typically, the feed signal for the readout resonator is injected through a directional coupler. The readout signals from the resonator output are amplified with a chain of dedicated low-noise amplifiers, both at cryogenic and room temperature.

Control signals in different frequency domains can sometimes be combined into a single input line, making use of bias-tees/diplexer circuits at different cryogenic stages. It is important to ensure the time-integral of the baseband signals equals zeros in this case, to prevent charging and drift of the bias tee circuitry.

5.1.3 Functional description <other Qubit flavors>

Other experts are invited to contribute dedicated text for a functional description of other type of Qubits.

5.2 Functional Requirements

5.2.2 Functional requirements of Spin Qubits

The operation of spin qubits can easily be deteriorated by external disturbances from inside or outside the device. Examples are disturbing quantities like temperature, magnetic fields, electric fields, vibrations. But there may be more issues of relevance that are to be specified, which may be less obvious. Their relevance is explained below.

5.2.2.1 Thermal requirements

Quantum dot spin qubits operate at cryogenic temperatures, typically between 20 and 1000 mK. This is necessary to reduce thermal broadening of the electron states to improving the performance of commonly used readout techniques. Furthermore, low operation temperatures can aid in minimizing charge noise originating from defects in the QPU material stack that can negatively impact qubit coherence. The low temperatures are achieved using a cryogenic cooling system, which typically consists of a dilution refrigerator with a pulse-tube cryocooler. The cooling system cools the qubits and their local control interconnections to very low temperatures (phonon temperature of <50 mK), while also providing some level of electromagnetic and mechanical isolation. To also achieve equally low electron temperatures, proper thermalization of all components and filtering of relevant lines should be carefully managed.

5.2.2.2 Magnetic field requirements

Magnetic field fluctuations and/or distortions can be a source or decoherence or operation errors with the QPU. It is therefore important to minimize the levels of magnetic interference in the cryostat. As an example, careful placement of the cryostat in relation to sources of magnetic noise, such as transformers or large-current carrying wires can help to minimize magnetic interference. To minimize the distortion of applied magnetic fields, care should be taken to avoid the use of magnetic materials in the vicinity of the QPU, avoiding magnetization because of the applied magnetic fields.

5.2.2.3 Electric field requirements

Electric field fluctuations can be a source of decoherence or operation errors within the QPU. In particular, for spin-qubit implementations where a coupling between electric and magnetic fields is implemented for rapid qubit control, e.g. through spin-orbit interaction or the presence of micromagnetic structures. In such case, fluctuations of the applied control voltages can directly impact the qubit energy splitting and lead to decoherence. As a result, the qubit coherence can be impacted by noise with a wide range of frequencies, including slow (near dc) fluctuations. Therefore, it is important to minimize the levels of electric interference and noise on the control lines. One approach to reduce electric noise is by filtering and/or attenuating the control lines going into the cryostat. Exact filter bandwidths and attenuation values depend on the requirements of each specific line and should be tailored to the application. Another approach is to use control electronics that have a low output noise, in particular within the required output bandwidth, as this is particularly difficult to filter.

5.2.2.4 EM field requirements

Electromagnetic interference can also be a significant source of noise and can cause decoherence in the QPU. Therefore, it is important to minimize the levels of electromagnetic interference (EMI) in the cryostat. One approach to reducing EMI is to use shielding materials to block external electromagnetic fields from entering the cryostat. This can be achieved by using materials such as conductive foils to create a Faraday cage around the cryostat. Additionally, careful placement of the cryostat and other equipment can help to minimize the amount of EMI that enters the cryostat. Finally, when the bandwidth requirements of certain control lines permit, using twisted pair wiring can aid in reducing EMI pickup in the control highway.

5.2.2.5 Vibration requirements

Cryostat vibration can be a significant source of noise and can cause decoherence in the QPU. While the qubits themselves are not affected by the vibrations, noise can couple into the system through the generation of effective electric of magnetic fields. Vibrations in the cables have been shown to induce triboelectric noise. Vibrations of the qubit with respect to the cryogenic magnet can lead to effective magnetic noise. Therefore, it is important to minimize the vibration levels in the cryostat. One approach to reducing vibration is to use a mechanical support system that isolates the QPU from external vibrations. This can be achieved by using a combination of passive and active vibration isolation techniques. Passive isolation techniques include using rubber pads or springs to decouple the QPU from the cryostat, while active isolation techniques use sensors and actuators to cancel out vibrations in real-time. Another approach is to use a cryocooler that operates at a higher frequency than the natural frequency of the cryostat, which can help to reduce vibration levels. Additionally, careful placement of the cryocooler and other equipment in the cryostat can help to minimize vibration.

5.2.2.6 Signal integrity requirements

Depending on the specific implementation, the accuracy of the quantum operations can be sensitive to the exact pulse shape arriving at the QPU. The usage of various components with different bandwidths and (effective) filter characteristics in the control highway will lead to a deformation (in the time domain) of the input signal at room temperature. One approach to reduce these effects is by measuring the deformation and predistortion of applied signals to correct for the imperfections in the control highway. Another approach is to design the control highway in such a way that within the relevant bandwidth, minimal signal distortion is present.

Secondly, cross talk between different control lines can lead to unwanted quantum operations and/or decoherence. One approach to overcome this is by minimizing crosstalk between different control lines, through careful design and implementation of proper shielding/grounding of the control highway. Another approach to overcome this is by applying correctional operations to the QPU, to undo effects caused by the crosstalk of previous operations. To ensure that levels of crosstalk are within the required limits, it is important to measure and monitor crosstalk between various control lines. This can help to identify any sources of crosstalk and enable corrective measurements to be taken.

5.2.3 Functional requirements <other Qubit flavors>

Other experts are invited to contribute dedicated text for a functional requirements of other type of Qubits.

End of literal text proposal