Quantum Measurement & Control Chip Program

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PROGRAM DESCRIPTION

The QMCC Program (UNSW) focuses on coherent control and readout of single-P-atom electron spin qubits in silicon. The Program makes extensive use of the facilities of the National Magnet Laboratory at UNSW, develops fast and sensitive techniques for the measurement of electronic nanostructures, and works closely with the Integrated Quantum Computer Devices (UNSW) and Ion Beam (UM) Programs on device design and production.

In 2009, our new donor spin qubit architecture [1] has been investigated in depth, achieving one of the most important milestones in solid-state spin qubits research - the single-shot readout of an electron spin.

Tunnel rates in qubit structures

In our qubit architecture, the spin readout time is essentially determined by the tunnel time between the implanted P donors and the island of a silicon Single-Electron Transistor (SET). We have developed a method for measuring the electron tunnel time without requiring high-bandwidth detection of the SET current [2]. The method is based on the dc measurement of the SET current while pulsing the donor control gate. The frequency dependence of the non-equilibrium currents can be analysed with rate equations to extract the donor – SET tunnel time (Figure 1)

Single-shot spin readout

By applying appropriate pulse sequences to the control gates (Figure 2), and measuring the SET current with a high-bandwidth (up to 200 kHz) preamplifier, we have demonstrated the time-resolved, single-shot readout of the electron spin of an implanted P donor in silicon [3].

A single-shot spin readout sequence consists of a 3-level pulse that shifts the electrochemical potential of the donor electron with respect to the SET island (Figure 3). In the “load” phase, an electron with random spin is loaded onto the donor. In the “read” phase, the spin-up and spin-down states are tuned above and below the electrochemical potential of the SET island, respectively.

Therefore, when a spin-up electron is present, it first tunnels out of the donor, unblocking the SET current, until a spin-down electron tunnels on again. This results in a characteristic “blip” of current that can be easily resolved. Finally, the “empty” pulse flushes the electron away from the donor, to make sure that a new electron with random spin can be loaded in the next cycle.

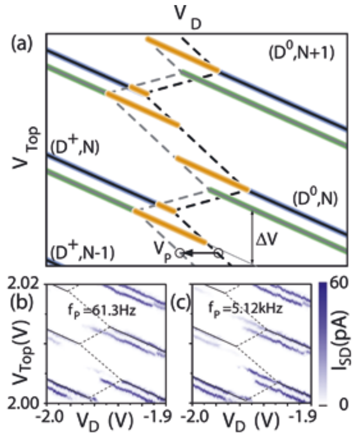

FIGURE 1

Sketch (a) and measurement (b,c) of the SET current while pulsing the donor gate in a qubit structure. The frequency dependence of the non-equilibrium currents (orange lines in (a)) allows the extraction of the electron tunnel rate between donor and SET island.

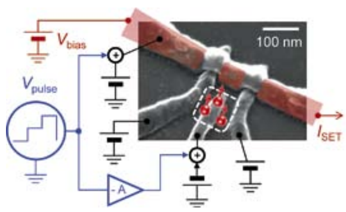

FIGURE 2

Circuit diagram and SEM image of the qubit device employed for single-shot spin readout.

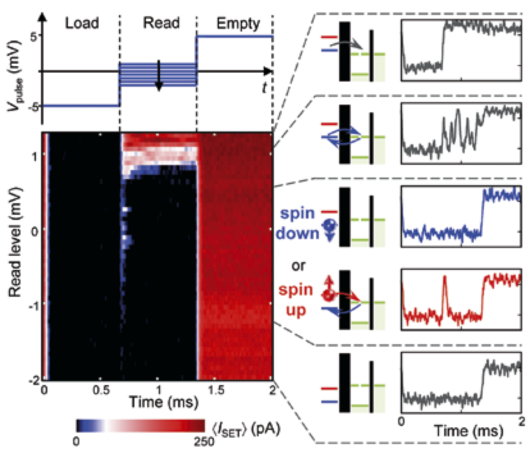

FIGURE 3

Three-level pulse sequence for single-shot spin readout. The main panel shows averaged SET current as a function of the “read” pulse voltage. The time-resolved single-shot traces highlight the correct tuning region where projective readout of spin-down (blue) or spin-up (red) electrons is obtained.

Figure 3 shows the method to determine the correct read level for spin readout. The SET current as a function of the "read" pulse voltage goes from high, to showing random telegraph noise, through the correct value where either no blip (spin-down) or one single blip (spin-up) is observed.

By varying the time τ the electron spends on the donor during the "load" pulse, we have measured the spin relaxation rate $1/T_1$ (Figure 4). The results are in qualitative and quantitative agreement with theoretical predictions and bulk spin-resonance experiments of P donors in silicon. The magnetic field dependence is described by $1/T_1(B) = K_0 + K_5 B^5$, where the term $\propto B^5$ is characteristic of relaxation via spin-orbit coupling, while the constant term could be due to dipolar flip-flops with nearby donors. The longest relaxation time we observed is $T_1 \approx 0.9$ s at $B = 1.75$ T.

Thanks to the high charge transfer signal, i.e. the large change in SET current when an electron tunnels on or off the donor, we achieve a very high readout visibility, $> 90\%$ (Figure 5) with a detection bandwidth ~100 kHz, corresponding to a readout time < 10 µs.

Fast Electrically Detected Magnetic Resonance (EDMR) of P donors

After adapting the EDMR technique to high-bandwidth ($>$1 MHz) signal detection, by connecting the device to a radiofrequency resonant tank circuit (rf-EDMR) [4], we demonstrated the ability to observe the hyperfine-split resonance lines of P donors in a bulk-doped MOSFET (Figure 6) [5]. This paves the way to the time-resolved observation of P donors magnetic resonance in semiconductor nanostructures.

Devices for local electron spin resonance

To demonstrate the coherent quantum control of a single P donor spin, integrated with the single-shot readout capability, we have designed and optimized a new generation of devices that combine implanted P donors, a readout SET, and a new type of local electron spin resonance (ESR) line. The new transmission line is optimized for maximum magnetic field and vanishing electric field. It consists of a coplanar waveguide (ground-signal-ground), transformed into a coplanar stripline (signal-ground) by an on-chip balun (Figure 7).

Low-temperature integrated circuits for qubit readout

The use of classical CMOS electronics at temperatures below 4K can be advantageous in architectures for the control and readout of silicon qubits. Fully depleted silicon on insulator CMOS is a primary candidate for such electronics. However, a hitherto unexplored maxim of integrated circuit design is the use of matched components at low temperatures. We have investigated the effect of low temperature operation on the matching in CMOS current mirrors [6,7]. By comparing measurements of the low frequency accuracy in a silicon on sapphire mirror at 300K and 4K, we found that, while matching is reduced at low temperatures, circuit structures relying on matching components can still be employed at low temperatures albeit at reduced performance.

Using the knowledge gained from our matching study, we have further designed a low-temperature amplifier that can read out the state of the single electron transistors fabricated in the Centre.

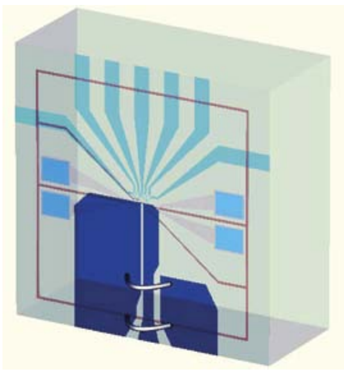

FIGURE 7

Three-dimensional model of the qubit device for coherent single-spin control incorporating a novel ESR line, with on-chip balun.

KEY PUBLICATIONS

[1] A. Morello et al., *Phys. Rev. B* **80**, 081307(R) (2009)

[2] H. Huebl et al., *arXiv:0912.2431, submitted to Phys. Rev. B*

[3] A. Morello et al., *in preparation for submission to Nature*

[4] H. Huebl et al., *Rev. Sci. Instrum*. **80**, 114705 (2009).

[5] L.H. Willems van Beveren et al., *in preparation for submission to Phys. Rev. B*

[6] S.R. Ekanayake et al., *to appear in IEEE Trans. Electron Devices (2010)*.

[7] K. Das and T. Lehmann, *accepted for IEEE International Symposium on Circuits and Systems 2010*

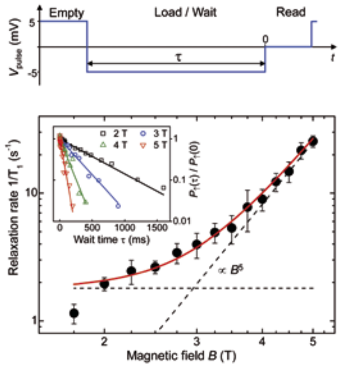

FIGURE 4

Field dependence of the spin-lattice relaxation rate, obtained by varying the wait time τ in the 3-level pulse sequence. Inset: exponential decays of the spin-up fraction P_1 at different magnetic fields.

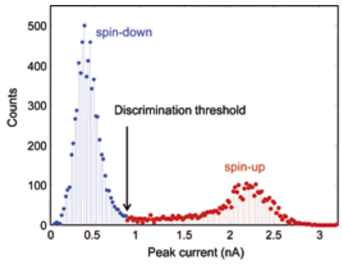

FIGURE 5

Histogram of the peak currents at the beginning of the readout pulse. Appropriate choice of the discrimination threshold between spin-down and spin-up allows a readout visibility $> 90\%$.

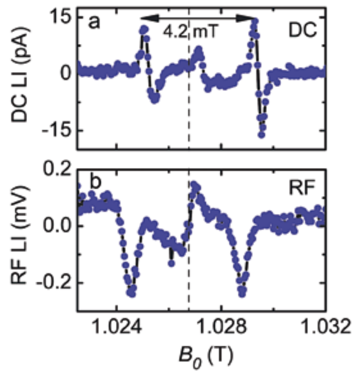

FIGURE 6

Electrically detected magnetic resonance of P donors, obtained both by reading out the changes in DC current though the MOSFET (top), or by measuring the changes in reflected power from a resonant tank circuit (bottom).