Engineering Solid-State Qubits Structures for High-Temperature Silicon Quantum Computing Through Multi-Scale Simulations

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Abstract
Quantum computing is today considered one of the key future technologies that will lead the next revolution of electronics. Among the different possible physical platforms, semiconductor-based qubits provide several advantages, not least their integration with electron/hole spin control/readout circuitry on the same die, though nowadays they require extremely low temperatures (e.g. 100 mK) to be reliably operated. Nevertheless, the scaling of CMOS technology is expected to reach 5 nm gate length and less than 2 nm channel cross-section by the year 2030. This will enable tunneling-based coupled quantum-dot (QD) devices to be operated at much higher temperatures, expecting to reach coupling energies on the order of 0.25-1 meV corresponding to control frequencies in the 60-240 GHz range, suitable for operation at 3-12 K. Since huge efforts are required to identify and engineer optimal structures, such as device geometry and employed materials, physics-based simulations are critical to this purpose.

We use Ginestra™ – a commercial multi-scale device simulation software developed by Applied Materials – as a test-bed for material characterization, simulation of electrical properties and device optimization, which makes it a unique simulating tool. As an industrial partner of the European FET Open Project 1Qubits, we will support the development of future silicon-based technology for the realization of Si, SiGe and III-Nitride QDs, their scalability to nanometric scale and the projection towards room-temperature quantum computing.

Key innovations
Integration of qubits and electronics on the same die based on commercial 22nm FDSOI CMOS foundry technology
• demonstration of qubit and qubit 3a with operation above 3 K scalability of the qubits to 10mK dimensions. Prove the suitability 3b operation through atomistic simulations at that 2c
• Silicon-based qubits: realization of a three-stacked n- and p-MOSFET with multiple gates, where QDQDs in the thin undoped semiconductor film below each top gate
• III-N electron and hole spin qubits: better prospect than Si and SiGe qubits with larger coupling energy and mode energy splitting.
• 60 240GHz spin control and readout circuits: short, 10-20ps spin control pulses, resulting in large ratios between the gating and the decoherence times
• Thermal noise filtering: connecting many identical qubits in parallel to minimize readout errors

GINESTRA™ CAPABILITIES
MATERIALS
Co, Ti, Cu, Ta, Si, Hf, TiO₂

DEVICES
PCRAM, MRAM, FinFET, RRAM, 3D-NAND

TESTS & SIMULATIONS
• Characterization
  ▶ defect spectroscopy
  ▶ Reliability
  ▶ Reliability
  ▶ stress-induced LDD
  ▶ stress-induced LDD
  ▶ breakdown and TDDB

APPLICATIONS
Cryo & Quantum

In-Silico Design
Global/Foundry
Custom mode tape-out in the
120nm FDSOI technology

University of Toronto (UT)
• Unique results showing quantum effects in production 20nm FDSOI transistors
• Unique access to 13nm FDSOI in development (through GF)
• nano-scale device and circuit design, tape-out and testing expertise (beyond 110 nm)
• Atomic simulations expertise
• Computing capabilities

Aarhus University (AU)
• nano-scale device and circuit design, modelling and testing expertise (up to 110 nm)

IMT Bucheon
• Advanced nanofabrication and nanolithography facilities
• Cryogenic and non-cryogenic on-wafer measurement capabilities

International nano devices
Manufacturing laboratory (NANO)
FORTH Crete
• Ion trap expertise
• Advanced nanofabrication facilities
• Advanced cryogenic magnetophysics and DC characterization

Consideration
Compact model for qubit operations and circuit simulations
Simulation of QD qubits
Device modelling and simulation of QD qubits
Compact models for QD qubit circuits

Silicon Quantum Computing Through Multi-Scale Simulations

I-V characteristics

n-MOSFET
p-MOSFET

Electron-spin qubit
Hole-spin qubit

Manipulation of the qubits: maximization (left) and minimization (right)

Single-shot read-out of an individual electron spin in a quantum dot

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