Towards Monolithic Quantum Processors in Production

FDSOI CMOS Technology

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Outline

- Introduction
- Quantum Processor SoCs
- Cryogenic characterization of 22nm FDSOI CMOS Technology
- Conclusions
Two-level quantum system

Natural systems:  
- Natural spins $|\downarrow\rangle$, $|\uparrow\rangle$
- Orthogonally polarized light $|\uparrow\rangle$, $|\uparrow\rangle$

Effective systems:  
- Isolate two levels from a manifold structure
  - Mechanisms: Energy separation, selection rules, ...
- Requires nonlinearity!

\[ i\hbar \frac{d}{dt} \Psi(t) = \hat{H}(t) \Psi(t) = E(t) \Psi(t) \]

Control of two-level system

- Qubit is pseudo spin
  - Independent of qubit realization
  - Methods from nuclear magnetic resonance

- Basic idea
  - **Coherently** rotate spins by static or oscillating magnetic fields
  - Static fields parallel to quantization axis => free precession, changes $\phi$ on Bloch sphere
  - Oscillating fields perpendicular to quantization axis => change population, changes $\theta$ on Bloch sphere
Spin ½ hamiltonian in a rotating magnetic field

\[ \hat{H}_S = \frac{g \mu_B}{2} \hat{\sigma} \cdot \vec{B} = \frac{g \mu_B}{2} \begin{bmatrix} B_z & B_x - i B_y \\ B_x + i B_y & -B_z \end{bmatrix} \]

\[ i \hbar \frac{d}{dt} X(t) = \frac{g}{2} \mu_B \begin{bmatrix} B_z & B_x - i B_y \\ B_x + i B_y & -B_z \end{bmatrix} X(t) \]

\[ \vec{B}(t) = B_{dc} + B_1(t) = (B_1 \cos \omega t, B_1 \sin \omega t, B_0) \]

\[ \omega_0 = \omega_L = \frac{g \mu_B}{2 \hbar} B_{dc} \]

\[ \omega_R = \frac{g \mu_B}{2 \hbar} B_1 \ll \omega_0 \]

\[ \omega_0 = \text{qubit (Larmor) frequency}, \quad \omega_R = \text{Rabi frequency} \]

\[ \hat{H} = \frac{g \mu_B}{2} \begin{bmatrix} B_0 & B_1 e^{-j \omega t} \\ B_1 e^{j \omega t} & -B_0 \end{bmatrix} = \hbar \begin{bmatrix} \omega_0 & \omega_R e^{-j \omega t} \\ \omega_R e^{j \omega t} & -\omega_0 \end{bmatrix} \]

\[ U = e^{-i \hat{H}t} \text{ describes spin evolution in time} \]

\[ |\Psi(t)\rangle = \cos \frac{\theta}{2} e^{-i(\psi + \omega_0 t)/2} |\uparrow\rangle + \sin \frac{\theta}{2} e^{i(\psi + \omega_0 t)/2} |\downarrow\rangle \]


\[ \theta(t) = \theta = \text{constant in time}. \quad \phi(t) = \phi + \omega_0 t \]
Superconducting qubits: most common today

Superconducting Qubit:
- Nonlinear L-C Resonator with $Q > 1$ Million
- Josephson Junction is nonlinear inductor

Superconducting Microwave Resonators:
- read-out of qubit states
- multi-qubit quantum bus
- noise filter

$E_{01} \sim 5 \text{ GHz} \sim 240 \text{ mK}$
Google’s Josephson junction transmon qubit

J. Bardin et al., JSSC, Nov. 2019
Google’s 54-qubit superconducting processor: 10 mK

F. Arute et al., Nature 574, 505 (2019)
Semiconductor quantum dot qubits

- Qubits formed in QDs where electrons/holes are confined by an energy potential well created in the conduction/valence band of a semiconductor structure: Si, Si/SiGe MOSFET, FDSOI, FinFET
- QDs placed in close proximity to enable coupling which is a function of barrier height/thickness
- Two adjacent (usually lowest) energy levels in QD used to create basis states |0> and |1>

[W. Huang, Nature 2019]  
[D.M. Zajec, Science 2018]  
[L. Hutin, VLSI 2016]  
[Intel, IEDM 2018]
Our approach and goals

- **Foundry FDSOI** CMOS-based QD qubits
  - SiGe p-MOSFET with channel/S-D heterojunction for hole spin qubit
- Investigate same and new spin control and readout techniques as SC qubits
- *mm-wave AMS circuits* for spin manipulation and readout *on the same die with the qubits*
- **2-4 K** operation now, *(maybe) 77 K* in 15 years
The SiGe p-MOSFET is the SiGe hole-spin qubit

- $L=18 \text{ nm}; \ W = 50 \text{ nm}$
- source/drain-to-channel heterojunction: $\Delta E_V = 35-40 \text{ meV}$
- $t_{oxe} = 1 \text{ nm} =>$ larger $f_R$ than thick oxide/semiconductor qubits

Si$_{0.7}$Ge$_{0.3}$/Si$_{0.75}$Ge$_{0.25}$

[S. Bonen et al. EDL 2018]
Electron- and hole-spin DQD concept in FDSOI

- Double quantum-dot (DQD) qubit = 2-gate MOSFET cascode
- Quantum dot (QD) under each top gate
- Individual gate control of each QD
- Potential barrier between dots
- Back gate for entanglement control (needs special mask)
- mm-wave E-field applied on gate and z-axis dc magnetic field
Charge qubit concept in FDSOI

- Similar to charge coupled devices
- Gates control barriers (tunnel coupling, $t$) between QDs
- Degree of freedom is position of electron in DQD
- Voltage applied between dots creates detuning: $E_{P1} \neq E_{P2}$
- Rabi frequency from probability oscillation

$$f_R = \frac{2t}{2\pi\hbar}$$

$$\hat{H} = \begin{bmatrix} E_{P1} & t \\ t & E_{P2} \end{bmatrix}$$

$$|\psi(t)\rangle = a(t)|10\rangle + b(t)|01\rangle$$

[Image showing double-well potential with oscillatory occupancy of wells and probability amplitudes $a(t)$ and $b(t)$]
Equivalent circuit of Double Quantum Dot

- Tunnel barriers described by $R_t, C_t$
- Gate-to-dot (channel) capacitance $C_g = 20 \text{ aF} \ldots 30 \text{ aF}$
- Use charge conservation analysis: $\Delta Q = C \times \Delta V_g$ as in switched capacitor circuits
  where $Q_{1,2} = N_{1,2} \times q$
- $q = 1.6 \times 10^{-19} \text{ C} \Rightarrow \Delta V_g = 3-5 \text{ mV per electron/hole}$

[D.K. Ferry, et al. Ch.6, Nanostructures, 2005]
Comparison to other qubit families

- >20x $f_L$, $f_R$ compared to SC qubits:
  - > 20$^2$x smaller readout resonators, > 20x higher operation temp.

- Larger $g$, $f_R$ than vertically stacked SiGe/Si/SiGe FinFET qubit

- Backgate control for circuit $V_T$ adjustment at low temperature

- Potential selective fast backgate for CNOT gate

- All spin control/readout schemes from SC qubits can be used
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Classical controller

- **Three functions**
  - Initialization
  - Manipulation
  - Read-out

- **Phenomena employed**
  - Coulomb blockade
  - Pauli spin blockade
  - Quantum capacitance reflectometry

[L. Hutin, IMS 2019]
Nondemolition, dispersive (non-resonant)
• mm-wave reflection meas. (phase, amp)
  • narrow band
  • needs inductors (large area)
  • needs precision ADC

• Charge, current or voltage amplifier
  • SET/capacitive coupling needed
  • Broadband
  • Noisy, 1/f noise sensitive
Hole-spin monolithic quantum processor

- **Qubit array**
  - 0.5 pW (10pA/50mV) per qubit
  - $10^{10}$ qubits = 5 mW

- **Spin manipulation**
  - Low phase noise (OFDM) signal at $f_L$
  - 60-100 GHz for 3-5 K operation
  - 140-240 GHz for 8-12 K operation
  - n-MOSFET switch + phase pulse modulators

$$P_{dc} = 0; \quad P = \frac{f^2 R}{2 C} V_{DD}^2$$

- **SRAM** stores digital pulse sequences (gate operations)

**Control/readout circuits** dominate consumption. Integration limited by **cryostat lift**
Equal1.lab 22nm FDSOI QPU for 4 K Operation

Fully-integrated SoC
- Quantum
- Analog
- Mixed-signal
- Digital
Equal1.lab 22nm FDSOI Quantum Core

Quantum structure & tightly integrated control & interface

2D structure allows Topological quantum computer

Patented quantum structures in customized GlobalFoundries FDX process

[D. Leipold, et al. 2019]
Photon-enhanced interaction/entanglement

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Monolithic QPs in FDSOI

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- **Cryogenic characterization of 22nm FDSOI CMOS Technology**
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Measurement set-up at 2 K
Die QPU testing limited by padframe, cryostat lift

Monolithic QPs in FDSOI
Quantum behavior at low $V_{DS}$ and 2 K

$V_{DS} = +/- 1 \text{ mV}$

$V_{BG} = +/- 0.5 \text{ V}$

$I_{SD'}, I_{DS}$, $I_{SD}$

[M. Gong et al. RFIC 2019]
Energy level spacing tuneable from backgate

$\Delta V_{GS}$ increases (doubles) at +/-2V back gate voltage as $C_{gs}$ decreases

[S.Bonen et al. EDL 2018]
18nmx70nm p-MOSFET: $I_{DS}$ vs $V_{GS}$ and $V_{DS}$

- **Sign of $I_{DS}$ follows $V_{DS}$**
- **Operates like a single hole transistor (single electron transistor)**
- **Regions of no current indicate bias regimes with integer number of trapped holes in the QD**
- **“Diamonds” with large $\Delta V_{DS}$ indicate large $E_2 - E_1$. Estimate ~15 meV for this device**
- **$E_2 - E_1$ limited by $W = 70$ nm**

$V_{BG} = \text{FLT}$

**6.2 K**

$\Delta V_{DS}$

$\Delta V_{GS}$
Resonant tunnelling current peaks widen over $V_{\text{GS}}$ and decrease in $|I_{\text{DS}}|$ height as temperature increases.

More thermionic emission over both barriers of the QD as temperature increases.
Qubit operation temperature scaling

- $f_L$, $T$ increase $\sim L^{-2}$, $W^{-2}$ (very favourable scaling law)
- $f_L$, $T$ increase linearly with dc magnetic field $B_{dc}$
  - $B_{dc} = 2.9T \Rightarrow \Delta E_m = 0.33\text{meV}, f_L = 80.4\text{ GHz}, T = 4\text{ K}, 22\text{-nm FDSOI}$
  - $B_{dc} = 8.6T \Rightarrow \Delta E_m = 1\text{meV}, f_L = 241.2\text{ GHz}, T = 12\text{ K}, 12\text{-nm feature?}$
  - $B_{dc} = 17.3T \Rightarrow \Delta E_m = 2\text{meV}, f_L = 582.4\text{ GHz}, T = 24\text{ K}, \text{SiGe BiCMOS?}$
- Magnetic field and double-dot coupling energy limit $T$, $f_L$
  - Higher gyromagnetic factor helps $\Rightarrow$ hole spin in SiGe channel
“Classical” MOSFET behaviour in saturation

Floating Back Gates

$V_{GS} = 0.4 - 0.8\text{V}$

$I_{DS}\text{ (mA)}$

$V_{DS}\text{ (V)}$

$300\text{ K}$

$3\text{ K}$

40x20nx590nm MOSFETs

40x20nx590nm SG, 1x

$\text{f}_T\text{ 300K}$

$\text{f}_{MAX}\text{ 300K}$

$\text{f}_T\text{ 3K}$

$\text{f}_{MAX}\text{ 3K}$
Peak $f_T$, $f_{\text{MAX}}$ current densities invariant with temp.
$R_{\text{poly}}$ does not change over temperature

[3.3 K, 100 $\Omega$ polyres. vs. 200 $\Omega$ polyres.]

[300 K, 100 $\Omega$ polyres. vs. 200 $\Omega$ polyres.]

[M. Gong et al. RFIC 2019]
Parameter extraction at 2-3 K

- Need on-die calibration in 2 K mm-wave probe station (with magnetic field)
- Source/drain resistance confirms different barriers for p- and n-MOSFET

[M.J. Mecca et al. RFIC 2019]
Thick and Thin-Oxide Varactors: Q degrades

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Monolithic QPs in FDSOI
MoM Cap does not change but Q improves at 3 K

[M. Gong et al. RFIC 2019]
Monolithic integration of qubits and readout TIA

Challenges:
- Large gain, low power
- Bandwidth, noise
- Drive 50 Ω off chip with minimum size 1x18nmx70nm MOSFET
- Design kit models valid at 2-4 K

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TIA and n-qubit+readout circuit vs. temperature

[S. Bonen et al. EDL 2018]
Specification and optimal TIA design for readout

- Amplify 1pA...1nA to 10 mV
  => $Z_{21} > 110 \, \text{dB} \Omega$
- Lowest possible noise
- $\text{BW} > f_L / 20$ ($f_L = 60-160$ GHz)
- $Z_{out} = 50 \, \Omega$
- $P_{DC} < 5 \, \text{mW}$

![Electron Spin Qubit Diagram]
Output spectrum measured with variable-amplitude sinusoidal signals applied to the gate of the DQD.

At -110dBm output power, the 4GHz sinusoidal signal is clearly visible above the noise floor. Based on the 251 kΩ TIA gain, this corresponds to $3pA_{rms}$ current at the input of the TIA.
Challenges

- Qubit fidelity $<<$ transistor fidelity $\Rightarrow$ **Tradeoff: T vs. fidelity**
- Spin readout, qubit-to-qubit isolation
- Gyromagnetic-factor engineering for high-temp scaling
- $W_f \leq 50$ nm (limits operation temperature today)
- CNOT Gate (or other 2 qubit logic gate)
  - (Minor) process/mask changes still needed
- Entanglement across multiple qubits
Conclusions

- **Monolithic integration** of CMOS spin control/readout circuits and qubits
- **SiGe hole-spin qubit** in p-MOSFET channel
- > 60GHz spin-manipulation/readout low-noise, AMS circuits needed
- At 2-4 K, minimum-size 22nm FDSOI MOSFET can be used as qubit in the subthreshold and as “classical” transistor in saturation
- 100-qubit processor < 2 W, probable now at 2-4 K in 22-nm FDSOI
- Future scaling to 10nm qubit gate length and 15nm width => 77 K operation?
In a nut shell: The Trinity
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- CMC and Jaro Pristupa for CAD tools and support
Multi site measurements

- **IMT Bucharest: November 2017 to present**
  - Custom-built cryostat DC-67 GHz, 6 K – 300 K
  - DC and non-calibrated GSG 2-port S-params w/o B-field: TIA, transistors, quantum dots, passives

- **University of Waterloo, Ontario, Canada: March 2018**
  - Lakeshore CPX 3.3 K commercial system
  - DC and calibrated GSG 2-port S-params: Transistors, passives

- **Lake Shore Cryotronics, Westerville, Ohio, USA: June 2018**
  - Lakeshore CPX 2K commercial system
  - DC and calibrated GSG 2-port S-params: Single and double QDs, TIA
Semiconductor qubits

Information encoded in particle **spin** or **charge location**

Satisfies

\[ i\hbar \frac{d|\psi(t)\rangle}{dt} = \hat{H}(t)|\psi(t)\rangle = E(t)|\psi(t)\rangle \]

Basis states

\[ |\uparrow\rangle = |0\rangle; \quad |\downarrow\rangle = |1\rangle \]

Superposition states

\[ |\Psi\rangle = a|\uparrow\rangle + b|\downarrow\rangle \]

- \( a \) and \( b \) are **complex** numbers
  - \( a = \cos(\theta/2), \quad b = e^{i\varphi}\sin(\theta/2) \)
  - \( |a|^2 + |b|^2 = 1 \)
  - Only **two deterministic real** variables: \( \varphi, \theta \) \( \Rightarrow \) coherent phase modulation

\[
\tan \theta \overset{\text{def}}{=} \sqrt{\frac{\Delta^2 + \tilde{\Delta}^2}{\epsilon}} \quad \text{with} \quad 0 \leq \theta \leq \pi
\]

\[
\tan \varphi \overset{\text{def}}{=} \frac{\tilde{\Delta}}{\Delta} \quad \text{with} \quad 0 \leq \varphi \leq 2\pi
\]
10 coupled double QD qubits with TIA readout

Improved gain and bandwidth

[M. Gong et al. RFIC 2019]
SiGe HBT performance improves at 6-80 K

0.1x4.5µm CBEBC

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Monolithic QPs in 22nm FDSOI