A spin qubit to interface semi and superconducting technologies

A. Crippa¹, D. Jirovec¹, K. Aggarwal¹, A. Hofmann¹, A. Ballabio², P. M. Mutter³, G. Tavani², M. Botifoll⁴, J. Kukucka¹, O. Sagi¹, F. Martins¹, J. Saez-Mollejo¹, I. Prieto¹, M. Borovkov¹, J. Arbiol⁴,⁵, D. Chrastina², G. Isella², and G. Katsaros¹

¹ Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria
² L-NESS, Physics Department, Politecnico di Milano, via Anzani 42, 22100, Como, Italy
³ Department of Physics, University of Konstanz, D-78457 Konstanz, Germany
⁴ Catalan Institute of Nanoscience and Nanotechnology (ICN2), CSIC and BIST, Campus UAB, Bellaterra, Barcelona, Catalonia, Spain
⁵ ICREA, Passeig de Llús Companys 23, 08010 Barcelona, Catalonia, Spain

alessandro.crippa@ist.ac.at
The route to Universal Quantum Computing

**Goals**

- Medium-term: $10^3$ physical qubits with QEC
- Long-term: $10^6$ - $10^8$ qubits

... (also) a matter of footprint!

<table>
<thead>
<tr>
<th></th>
<th>Semiconductor Single-Spin qubit</th>
<th>Superconductor Flux qubit (DWave like)</th>
<th>Superconductor Transmon qubit (IBM like)</th>
<th>Trapped Ion qubit</th>
</tr>
</thead>
<tbody>
<tr>
<td># qubits [10^6/cm²]</td>
<td>8000</td>
<td>$8 \times 10^{-4}$</td>
<td>$10^{-5}$</td>
<td>$2 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>$25 \times 10^7$</td>
<td>$2 \times 10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>chip area [mm²]</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Spin qubits on the way

Academia $\rightarrow$ Pre-industrial facilities (IMEC, Leti) $\rightarrow$ CMOS factory (Intel)

Petta et al., Science 309, 2180 (2005)
Spin qubits on the way

Vandersypen et al., npj Q. Info. 3, 34 (2017)
A solid-state platform for QIP

First demonstration of quantum supremacy

Know-how of the CMOS industry to address the scaling challenge
Crippa et al., Nature Comm. 10, 2776 (2019)

Long range connectivity
A solid-state platform for QIP

First demonstration of quantum supremacy

Know-how of the CMOS industry to address the scaling challenge
Crippa et al., Nature Comm. 10, 2776 (2019)

Long range connectivity
Outline

Proximity-induced superconductivity on Ge

An ultra-low magnetic field spin qubit on Ge

superconductors

semiconductors

germanium (Ge)
An ultra-low magnetic field spin qubit on Ge

- semiconductors
- germanium (Ge)
Ge/SiGe structure

![Graph showing Ge/SiGe structure with labels for Fermi energy, Light hole band, Heavy hole band, and Heavy hole $|\Psi|^2$.]

L-NESS, Physics Department, Politecnico di Milano
Spin qubit device

[Image of a spin qubit device with labels G1, G2, G3, G4, G5 and a magnetic field direction indicated]
Spin qubit device
Spin qubit device

G1     G2       G3       G4     G5

Energy

Position

Double quantum dot

A. Crippa

CINECA – December 2020
Double quantum dot

Hole: ⧫

Charge ⧫, ⧫

Spin ⧫, ⧫
Qubit’s basis

Two spins ½ :

\[ \vec{B} = 0 \]

**Triplets**

- \( T_- = | \downarrow \downarrow \rangle \)
- \( T_0 = \frac{| \uparrow \downarrow \rangle + | \downarrow \uparrow \rangle}{\sqrt{2}} \)
- \( T_+ = | \uparrow \uparrow \rangle \)

**Singlet**

- \( S = \frac{| \uparrow \downarrow \rangle - | \downarrow \uparrow \rangle}{\sqrt{2}} \)

\( m_s = +1 \)
\( m_s = 0 \)
\( m_s = -1 \)

\( m_s = 0 \)

\( \Delta E = | \uparrow \downarrow \rangle - | \uparrow \uparrow \rangle \)

Energy

\( J \)
Qubit’s basis

Two spins $\frac{1}{2}$:

\[
\begin{align*}
T_- &= |\downarrow\downarrow\rangle \\
T_0 &= \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}} \\
T_+ &= |\uparrow\uparrow\rangle
\end{align*}
\]

\[
\begin{align*}
m_s &= +1 \\
m_s &= 0 \\
m_s &= -1
\end{align*}
\]

\[
H = \begin{pmatrix}
-J(\epsilon) & \frac{\Delta g \mu_B B}{2} \\
\frac{\Delta g \mu_B B}{2} & 0
\end{pmatrix}
\]

\[\Delta g: \text{ g factor difference} \]
\[\mu_B: \text{ Bohr magneton}\]
\[B: \text{ external magnetic field}\]
Why Ge?

Planar Ge:

- Low $m^*$
- Intrinsic high g factor (compared to GaAs and Si) $\to \Delta g$
- Excellent electrostatic control $\to J$

Low magnetic field operability

$$H = \begin{pmatrix}
-J(\epsilon) & \frac{\Delta g\mu_B B}{2} \\
\frac{\Delta g\mu_B B}{2} & 0
\end{pmatrix}$$

$\Delta g$: g factor difference
$\mu_B$: Bohr magneton
$B$: external magnetic field
X gate (Rabi oscillations)

$\Delta g = 2.04$

<10ns to perform a X gate
Z gate (exchange oscillations)

<10ns to perform a Z gate
Coherence (Echo)

\[ \pi/2 \quad \pi \quad \pi \quad \pi/2 \]

\( \tau_s \)

Jirovec et al., arXiv 2011.13755 (2020)

T2 > 15 \( \mu \)s with 16 refocusing pulses
Section 2

Proximity-induced superconductivity on Ge

superconductors

germanium (Ge)
«Conventional» superconducting qubit

Transmon qubit

Josephon junction

Barends et al., PRL 111, 080502 (2013)
«Super» superconducting qubit

Transmon qubit

Sycamore processor

Barends et al., PRL 111, 080502 (2013)

Towards a Ge-superconducting qubit

Aggarwal et al., arXiv 2012.00322 (2020)
Semi-super monolithic integration

quantum bus

S Ge S

transmon qubit

BOTH qubits within a single material platform: germanium

spin qubit

Ge

microwave resonator
Semi-super monolithic integration
Conclusions & Outlooks

• Singlet-triplet Ge spin qubit:
  ‣ Single-qubit gates in less than 10 ns, coherence > 15 μs
  ‣ Tools for characterizing and mitigating errors
  ‣ Low B field operability → coexistence with superconducting classical & quantum electronics

  Jirovec et al., arXiv 2011.13755 (2020)
Conclusions & Outlooks

• Singlet-triplet Ge spin qubit:
  ‣ Single-qubit gates in less than 10 ns, coherence > 15 μs
  ‣ Tools for characterizing and mitigating errors
  ‣ Low B field operability → coexistence with superconducting classical & quantum electronics

Jirovec et al., arXiv 2011.13755 (2020)

• Superconducting Ge junction:
  ‣ Towards transmon qubits → coexistence with semiconducting classical & quantum electronics

Aggarwal et al., arXiv 2012.00322 (2020)

on a CMOS-compatible substrate
Conclusions & Outlooks

- Singlet-triplet Ge spin qubit:
  - Single-qubit gates in less than 10 ns, coherence > 15 μs
  - Tools for characterizing and mitigating errors
  - Low B field operability \(\rightarrow\) coexistence with superconducting classical & quantum electronics

- Superconducting Ge junction:
  - Towards transmon qubits \(\rightarrow\) coexistence with semiconducting classical & quantum electronics

Jirovec et al., arXiv 2011.13755 (2020)
Aggarwal et al., arXiv 2012.00322 (2020)

on a CMOS-compatible substrate

Thank you!

alessandro.crippa@ist.ac.at
alessandro.crippa@nano.cnr.it
Why holes?

Contacts: favorable work functions of many metals to inject carriers (fermi pinning)

Well: deeper than for electrons

Properties: low m* (~0.1m_e) → promotes the confinement by uniform potential landscapes
→ large extent of the wavefunction
electrical spin manipulation with no detrimental effects on coherence
ease in fab (gates pitch relaxed)