Low temperature plasma processing of qubit materials
Malcolm Carroll and David Graves
June 8th, 2021
1. Qubits & their fab

2. Qubit metrics (coherence)

3. Defects limit coherence

4. Plasma-surface challenge & opportunity in QIS


Nersisyan et al. arXiv:1901.08042

Lisenfeld et al. npj Quant. Inf. 5 (2019)
Motivations for quantum bit (qubit) applications

- Quantum computing promises speed up in critical areas
  
  ... simulation of nature, better make it quantum mechanical...

- Quantum sensing offers the potential to outperform 'classical' limits
- Quantum communication introduces new forms of security and efficiency

https://qzabre.com
Motivations for quantum computing

- “While it may be years ... to pay off, ... quantum computing ... is at best a missed opportunity, at worst an existential mistake”

From: ”Where will quantum computers create value and when”, BCG report 05/19

<table>
<thead>
<tr>
<th>EXHIBIT 2</th>
<th>The Expected Phases of Quantum Computing Maturity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NISQ era</td>
</tr>
<tr>
<td>Rough # of qubits:</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>3–5 years</td>
</tr>
<tr>
<td>Technical achievement</td>
<td>Error mitigation</td>
</tr>
<tr>
<td>Example of business impact</td>
<td>Material simulations that reduce expensive and time-consuming trial-and-error lab testing</td>
</tr>
<tr>
<td>Estimated impact (operating income)</td>
<td>$2 billion–$5 billion</td>
</tr>
</tbody>
</table>

Source: BCG analysis.
# IBM hardware roadmap

## Scaling IBM Quantum technology

<table>
<thead>
<tr>
<th>Released</th>
<th>In development</th>
<th>Next family of IBM Quantum systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>2019</td>
<td>September 1, 2020</td>
<td>2023</td>
</tr>
<tr>
<td>27 qubits</td>
<td>65 qubits</td>
<td>1,121 qubits</td>
</tr>
<tr>
<td>Falcon</td>
<td>Hummingbird</td>
<td>Condor</td>
</tr>
<tr>
<td></td>
<td>127 qubits</td>
<td>Path to 1 million qubits</td>
</tr>
<tr>
<td>2021</td>
<td>2022</td>
<td>and beyond</td>
</tr>
<tr>
<td></td>
<td>433 qubits</td>
<td>Large scale systems</td>
</tr>
</tbody>
</table>

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A quantum bit (qubit) are the transistor of quantum computers

- Qubits are defined by two stationary states labeled 0 and 1
- Any quantum mechanical two level system can be a qubit
- Canonical example is spin up/down

\[ m_s = \pm \frac{1}{2} \]

\[
\begin{align*}
|0> & \quad \text{Electron aligned with magnetic field:} \\
|1> & \quad \text{Electron aligned against magnetic field:}
\end{align*}
\]

\[ \hbar \omega = E \]

\[ E_{\text{Zeeman}} \]

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Solid-state spin qubit example

- Field effect transistor scaled to single electron spin
- Artificial atom with orbital energy of 5 meV for 40-50 nm well (in Si)
- Control: cryogenic temperatures & electron spin resonance

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All leading qubit candidates use thin film processing

**Spins**

Intel, SQC, ST-Micro, HRL, NTT, ...

[de Leon et al., Science 2021]

**Superconducting**

IBM, Google, Rigetti, Alibaba, Amazon, ...

[Rudolph et al. IEDM 2018]

**Ion Traps**

Honeywell, IonQ, Alpine Quantum Technologies, ...

[de Leon et al., Science 2021]

- Several qubit platforms being pursued by a range of companies and research labs
- Today platforms are at the 10-100s of qubits
- Yield and integration challenge for the future – some analogies to IC fab

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Jim Clarke, Intel (IEEE Spectrum, 24 August 2020)

“It’s simple for us... Silicon spin qubits look exactly like a transistor... The infrastructure is there from a tool-fabrication perspective. We know how to make these transistors. So if you can take a technology like quantum computing and map it to such a ubiquitous technology, then the prospect for developing a quantum computer is much clearer.”
Process flow example – superconducting qubits

- Fabrication uses relatively standard processing
- Common materials
  - Substrates: Si or sapphire
  - Electrodes: Al, Nb, Ta
  - Junction material: Al2O3

- Qubit performance depends on interfaces & etch profiles

Nersisyan et al. (Rigetti)
Qubit and qubit metrics


Energy relaxation

- Superconducting qubit ‘lifetime’ has an analogy to circuit Q of resonator
- Qubit metric is ‘coherence time’
- Example: energy relaxation to defects

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Atomic scale perfection required

- Surface defects believed dominant source of decoherence in SC qubits
- There are challenges and opportunities for plasma-surface science in quantum computing
  - Defect reduction will be an enduring goal for quantum devices
Likely areas of opportunity for plasma processing

Smooth surfaces

Clean surfaces

Development of atomic layer control

Megrant et al. APL (2012)


Nersisyan et al., arXiv 1901.08042

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Challenges of atomic level control via plasma processes

- Basic principles of plasma etch reveal **challenges of true atomic layer etch**
  - Seek selectivity, anisotropy, high rates (as well as uniformity and low contamination)

- Purely chemical etch can be highly selective but is usually isotropic

- Plasma-induced positive ion bombardment is inherently directional but has little selectivity

- ‘Reactive ion’ etching is a compromise between the need for selectivity and anisotropy

- Ion-neutral synergy increases etch rates, while providing some selectivity and anisotropy: without these ‘tricks’ there would have been no ‘Moore’s Law!’
Ion-neutral synergy in plasma etch

Ion-neutral synergy: etch rates much higher when both energetic ions and reactive F hit surface

Winter and Coburn, (1979)
What happens when 200 eV Ar\(^+\) hits Si surface?

Impact of inert ion (Ar\(^+\)) adds energy to surface; promotes chemistry and mixing sub-surface atoms.
What happens when 300 K F atom hits Si surface?

F atoms (300K) etches Si spontaneously.
What happens when 300 K F atoms hit masked Si surface?

Chemical-only etching is isotropic – undercut of mask is key problem.

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Visualizing purely isotropic chemical etch

‘Snapshot’ movie links a series of individual F atom impacts

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Ar$^+$ impacting masked Si surface

Ar$^+$ - only provides no selectivity
Combining F atoms with Ar\(^+\): ion-neutral synergy results

Combining Ar\(^+\) and F atom allows for some degree of selectivity and anisotropy (100:1 F/Ar\(^+\))

But note final degree of surface amorphization from ion bombardment.
Complex mixed layers tend to form near-surface.

Combining etch (F) species with deposition (C2F4) species, energized by Ar⁺ ions.

Side view and depth profile of a cell from 5:5:1 C₄F₄/ F/ 200 eV Ar⁺ (Si=white, C=grey, F= black).
How to approach desired atomic-layer control?


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How to approach desired atomic-layer control?


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How to approach desired atomic-layer control?

- Separate chemical component and ion-induced removal: need as minimum a window of ion energies that allows product removal with minimal subsequent sputtering of underlying film.

- Ion energy needs to be low – especially when chemical component present; relatively thick mixed layers are common in plasma etch.

- Likely that we will need specially designed/operated plasma tools – e.g. e-beam sustained; B-fields; pulsing, etc.

- Can see that truly atomic layer etch with plasma will need careful control and better understanding of plasma-surface interactions!
Plasma nanofabrication science: coupled challenges

EM coupling: pulsed plasma science

plasma diagnostics and 3D, transient modeling

External control parameters:
> 10^{20} combinations (flow, composition, pressure, frequency, pulsing etc.)

plasma-surface coupling

surface & materials characterization; device physics; semiconductor/quantum materials; atomistic simulations of plasma-surface interactions

- near-surface atomic scale defects
- surface texture: atomic scale roughness
- electron-hole dynamics (e.g. plasmons/UV)
- complex surface composition/structures
- 3D nanofeature transport/chemistry

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Concluding remarks

- QIS materials and devices poised to make significant impacts

- Most QIS devices made via thin film processing and LTP is key technology, although there are major challenges ahead to minimize defects

- There is a strong need for highly interdisciplinary teams in this field: plasma science, surface science, material science and device science are all important

- A paper detailing these ideas is under preparation!

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