• **Thanks to our partners:**
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  - NIST Boulder (Jeff Shainline, Sonia Buckley, Richard Mirin, Sae Woo Nam)
  - NIST Boulder (Dave Pappas)
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  - Stony Brook University (Xu Du, Dmitri Averin)
  - U. Rochester (Mishkat Bhattacharya)
  - RIT (Stefan Preble)
  - MIT (Dirk Englund)
  - William & Mary (Seth Aubin)
  - U. Maryland (Qudsia Quraishi)
• Order! Order!

From Devices To Complex Systems


https://www.computerhistory.org/revolution/digital

https://commons.wikimedia.org/wiki/File:AMD_Bulldozer_block_diagram_(8_core_CPU).PNG

• Quantum Engineering ← adopt the ‘manufacturability mantra’
Qubits Using 193 nm Lithography

Josephson Junction Arrays

48 junctions measured for each datum (JJ’s distributed over 25 mm x 16 mm area)

Qubit measurements at ~10 mK (LPS)

\[
\frac{\omega_q}{2\pi} = 4.76612 \text{ GHz} \quad \& \quad 4.70267 \text{ GHz}
\]

\[T_1 = 26.79 \mu s \quad \& \quad 25.93 \mu s\]

Foroozani et al, manuscript submitted (2018)
• New processes $\rightarrow$ New device architectures
• New devices $\rightarrow$ Better systems $\rightarrow$ larger horizons for imagination
Metal film CMP: Automated adjustment of zone pressures for thickness uniformity

Reactive Ion Etch: Optical endpointing frequently harnessed to improve processes

New 300mm tools have chucks with multi-zone temperature controls

Optical emission trace shows SiCN layer uncovered
• UV-PICs with Si/SiO$_2$/poly AlN at 300mm scale
• In partnership with RIT (Stefan Preble), AFRL (Mike Fanto) and MIT (Dirk Englund)

<table>
<thead>
<tr>
<th>Ion</th>
<th>λ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{199}$Hg$^+$</td>
<td>282</td>
</tr>
<tr>
<td>$^{171}$Yb$^+$</td>
<td>369.5</td>
</tr>
<tr>
<td>$^{88}$Sr$^+$</td>
<td>422</td>
</tr>
<tr>
<td>$^{138}$Ba$^+$</td>
<td>650</td>
</tr>
</tbody>
</table>

Crystalline AlN on Sapphire
Lu et al, *Optics Express* 26 (9) 11147 (2018)

Poly AlN on Si/SiO$_2$

**Electro-optic modulation with AlN**

Low loss waveguides, grating couplers ... for UV
AIN Deposition & Characterization

- AlN film characterization on 300 mm Si wafers

**Glancing Incidence XRD from ALD AlN variants**

**XRD spectrum from 20nm PVD-AlN film**

**SIMS analysis to quantify contaminants**

~20nm PVD AlN

~90nm ALD AlN

Thick oxide
Chemical Mechanical Planarization of AlN films

Pre CMP: 1.7 nm AlN roughness (XRR fit)
Post CMP: 0.6 nm AlN roughness (XRR fit)

Pre CMP: 1.6 nm Rq
Post CMP: 0.5 nm Rq

<100 defects post CMP (at ~0.12 um sensitivity)

• Next: 193nm litho & RIE + Cu for RF
In partnership with NIST Boulder (Shainline, Buckley, Mirin, Nam) and using AFRL-funded maskset

Josephson junctions (fast, sub-aJ pulses!) → 30,000x faster than brain
  → spikes/s/W ~ human brain

Cryo-photonics + SNSPDs → 1:1000 neuron connections

1 cm² die: 8k neurons + 330k synapses ...
and further scalable
Superconductors in our pockets

- CMOS-compatible Josephson junctions with $\alpha$-Tantalum & ALD-TaN
- PVD TaN-based SNSPDs

Measurements by Mike Hamilton group (Auburn University) not yet published
Light Emission by Si Defects at 4 K

- Si-defect based IR emission into SOI waveguides

**Cryogenic Si defect light emission**

*Si on 300 nm BOX for faster testing*

Measurements at NIST Boulder
(Buckley, Shainline, et al)

*Unpublished*

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**Graphs:**

(a) Si^10 Dose: $10^{14}$ cm$^{-2}$
- 900 °C
- 700 °C
- 500 °C
- 300 °C

(b) Dose: $3 \times 10^{15}$ cm$^{-2}$
- D1
- R
- 900 °C
- 700 °C
- 500 °C
- 300 °C

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• One Fab to Make Them All... And With Light Bind Them!

- Adv. CMOS: spin qubit compatible
- MTJs for cryogenic memory
- Superconducting Digital electronics
- Integrated Photonics
- SiC: Er quantum emitters
- SCOE-NM
- Superconducting Quantum Computing
- UV-PIC with AlN

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[2] SiC:Er research by S. Galis group
[3] 7nm CMOS test chip fab’ed at SUNY Poly
[5] alpha-Ta superconducting line
[7] fab-friendly UV-VIS waveguide material
[8] Supercond Optoelectronic Neuromorphic computing elements