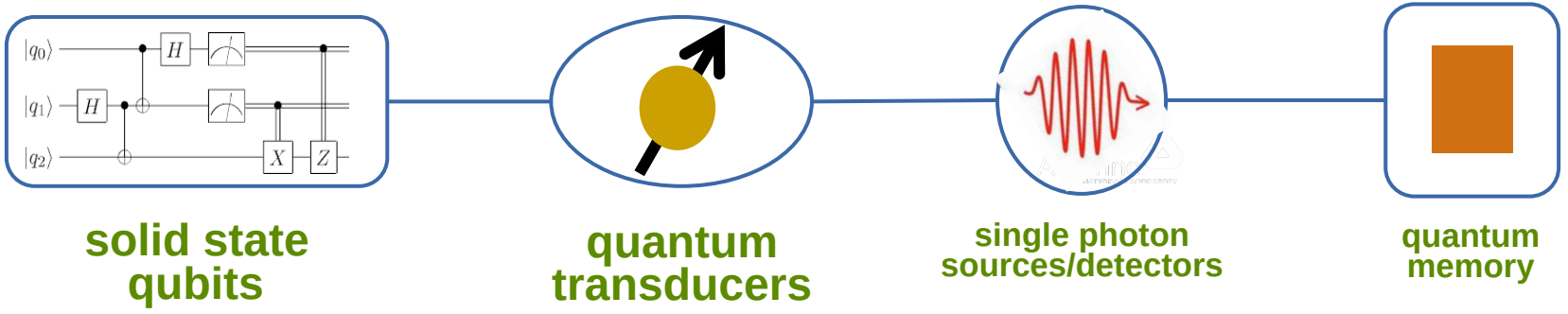
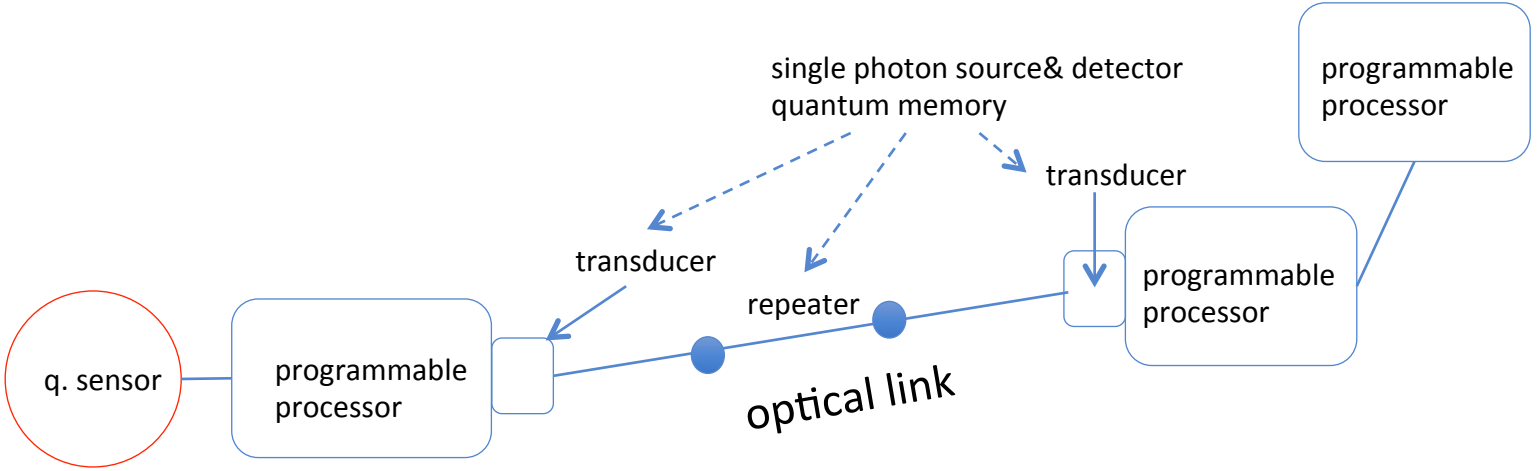
- ***Technology impact horizon***

In order of "earliest to market" probability:

- **Secure quantum networks for communications**
- **Quantum sensing that does not use entangled states**: *e.g. diamond NV Centers for temperature sensing & biological applications, atomic clocks, atomic interferometry for navigation etc.*
- **Quantum Computing**: *codebreaking, quantum chemistry problems, database sorting*
  - >1000 logical qubits for solutions of general usefulness, superior to classical
  - Fault tolerant error correction as yet not demonstrated experimentally
  - Logical: Physical qubit ratios undetermined and as yet high
  - Quantum volume—error rates, no. of qubits, qubit connectivity, parallelism
- **Quantum sensing using entangled states**; 1/N uncertainty: *gravitational waves, magnetic fields, lithography*

Quantum Information Systems: scalable, patternable solid state systems





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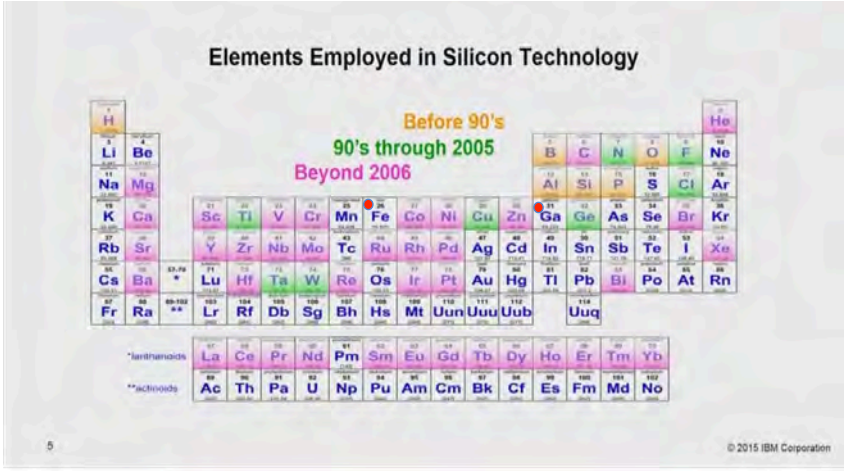
Major materials and process challenges

- Unlike Si CMOS: quantum processor system size (# of devices) is controlled by qubit error rates and not litho scaling.
- Very likely solid state coherent systems will be integrated with silicon at different intimacies—
- Needs are broadly compatible with exisiting process infrastructure (with some exceptions)

Challenges:

1) Miniaturization of devices: Bulk to nanoscale sizing
2) New materials discovery and integration with silicon tech.
    - Stability (such as coherence time) & variability (such as frequency) are key—materials response not well understood,
    - Master difficult to process and integrate material—tough oxides e.g.
    - Manipulation of quantum devices: nanophotonics becomes increasingly important
3) Atom scale nanofabrication—move away from non-deterministic processing



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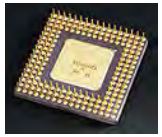
#1: Miniaturization of devices; example of the transducer

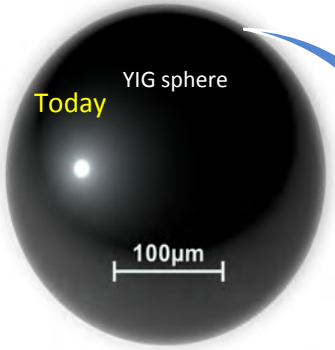
(Xufeng Zhang, Argonne)

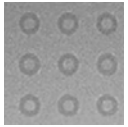
Transistor

Today



Quantum transducer





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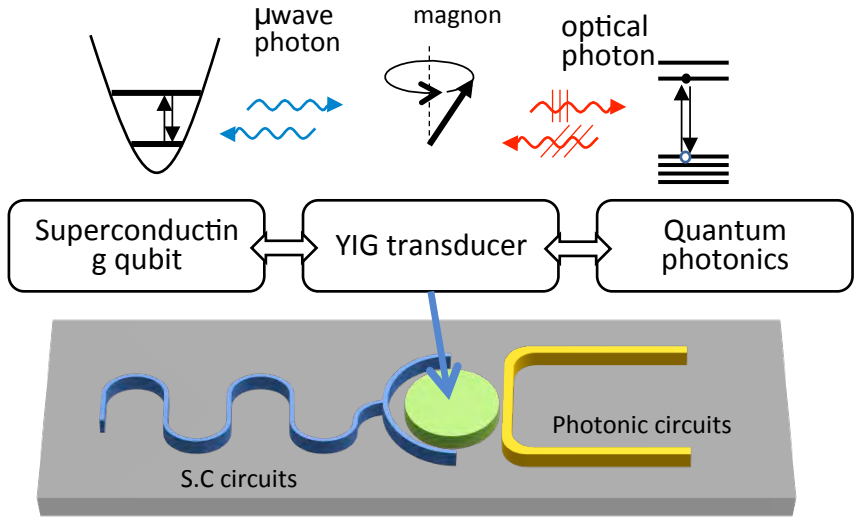

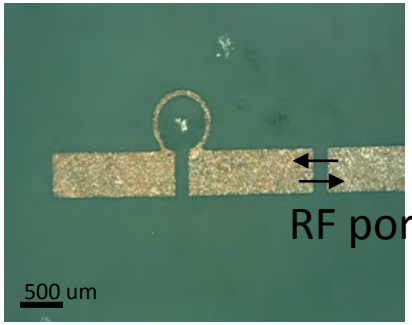

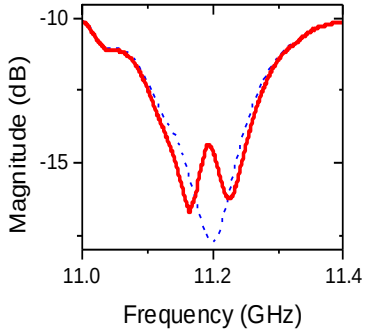

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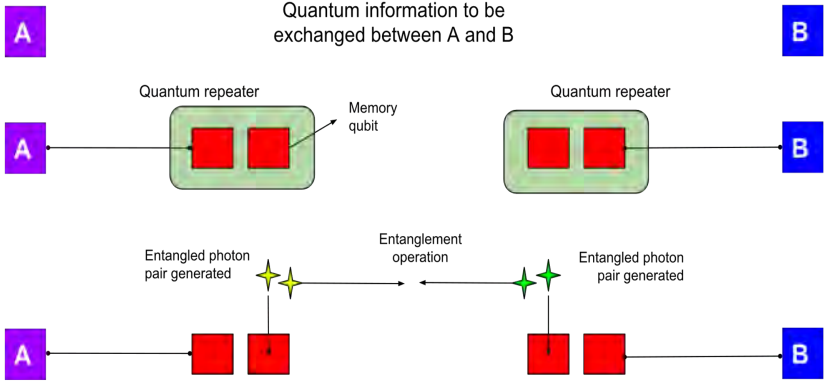
New materials discovery and integration with silicon tech……one more example

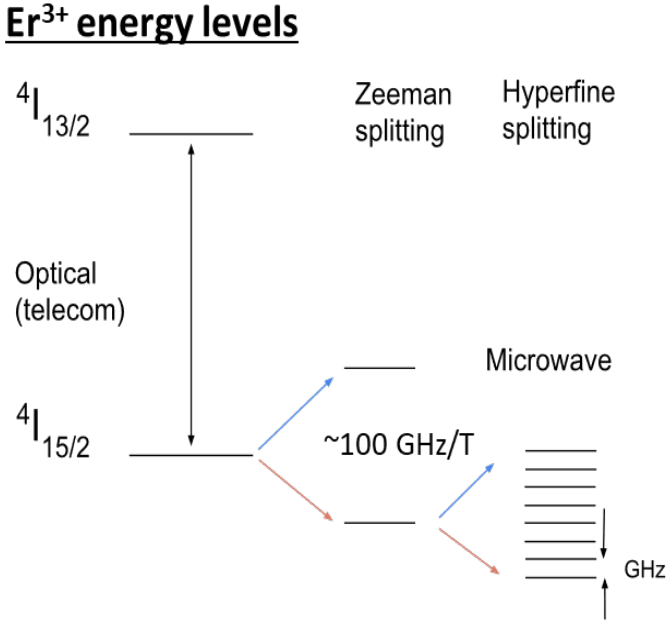
2) Oxides for solid state coherent quantum memory



- Implementing a long channel
  - Divide the channel into sections connected by *quantum repeaters*
- Quantum memories are central to these repeaters
- Large field of viable candidates
  - NV centers, defects in SiC, divacancies in Si/Ge, rare earth ions (REI) etc.

2) A scalable, oxide thin film platform for storing light qubits

Defect type	Coherence time (at mK)	Coherence time (at RT)	Retrieval Efficiency	Retrieval Fidelity
NV in Diamond	> 1 sec	> 100 us	> 75%	0.85
SiV in Diamond	> 10 ms	NA		-
SiC di-vacancies	> 1 ms	NA		-
Rare earth ions				
Eu in YSO	> 6 hours	NA	NA	-
Er in YSO	>1.3 sec	NA	>50%	0.93



- Er^{3+} optical transition lies in the telecom C band
- Yttria (Y_2O_3) is a low noise host material
- Y_2O_3 thin films can be grown epitaxially on Si
- Lithography can be used for at scale device development

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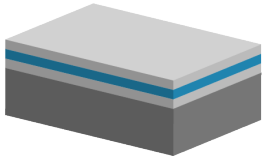
[1] Guha, Appl. Phys. Lett. 80, 766 (2002)

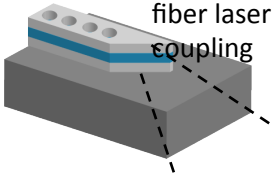
Coupling to nanophotonic structures for quantum memories

Epitaxial growth of high quality rare-earth thin films on Si

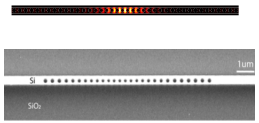
Qualify Er:Y_2O_3 as a quantum memory Optical & Spin T_1 and T_2 measurements

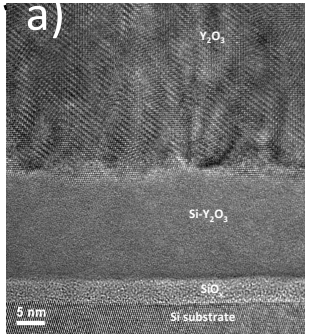
Demonstration of a working quantum memory

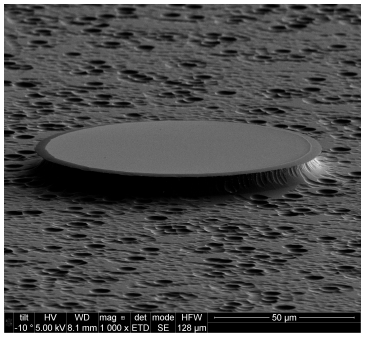


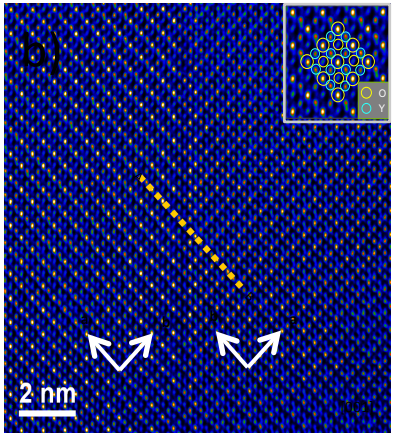


tapered fiber laser coupling









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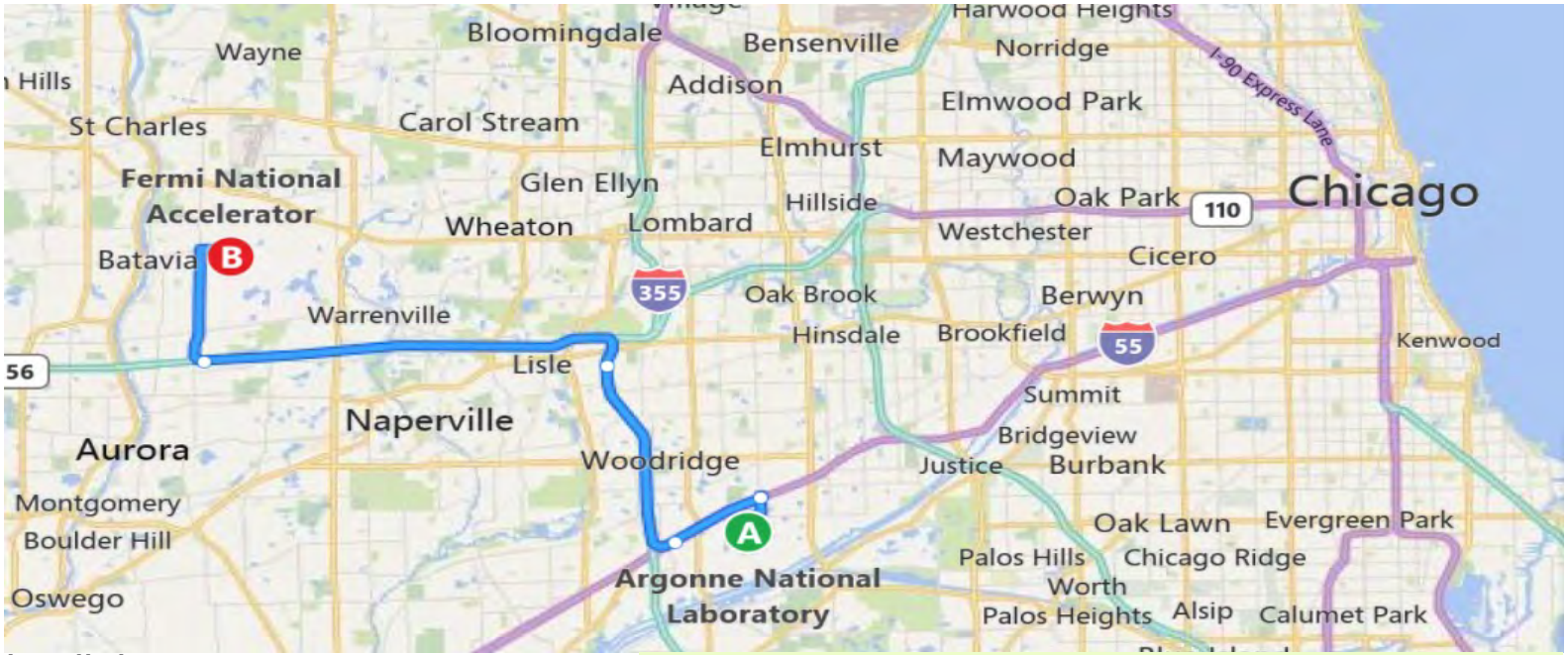
- A Growing Intellectual Hub for the Science and Engineering of Quantum Information Science

Launching a communications testbed



- teleportation link
- encryption testbed

30 miles of single-mode telecom fiber