Accelerating Engineering of Quantum Systems

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Project Manager / Keysight Technologies
Agenda

• Global Investment in Quantum
• Challenges in Realizing Quantum Computers
• Keysight Solutions
Global Investment in Quantum
Major Economic Powers Are Ramping Quantum Investments

**USA**
- National Quantum Initiative passed Dec ’18 committing $1.3B over 5 years

**Canada**
- Invested over $1B in the last decade

**United Kingdom**
- $397M quantum program over 5 years, beginning in 2019

**European Union**
- Quantum Technologies Flagship Program worth $1.1B over 10 years

**China**
- Will create an $11B, 4M sq-ft national quantum laboratory for centralized research

**Japan**
- ImPACT project valued at $267M over 10 years to realize new quantum computing principles

**India**
- National Mission of Quantum Technology and Application spending $1.2B over 5 years

**Germany**
- National plan to promote quantum technologies with $720M commitment over 4 years

**Russia**
- Russia Quantum Center earmarked $3B for fundamental scientific R&D in 2018

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Americas: Public Investment

US & CANADA

US: NQI (NATIONAL QUANTUM INITIATIVE)

• $1.275B over 5 years, mostly by DOE, NSF & NIST funding a few large quantum centers
  • DOE: QIS Research Centers, $25M/year
  • NSF: Multi-disciplinary research, $10M/year
  • NIST: for quantum & to establish consortium (QED-C), $80M/year

• US: Federal agencies fund research worth $200M/year

• NIST, DOE, NSF, etc., provide basic research
  • IARPA, DARPA fund universities through grants

• Unknown investments

Canada

• Gov’t funded R&D > $100M/year expected to reach >$300M in 2024

• IQC : Institute for Quantum Computing (U Waterloo) $2.7M quantum radar

• NSERC grants $30M to support university research teams
Qubits are the Pillars for all Quantum Applications

**Quantum Computing**
- Noisy Gate-based Computers
- Quantum Annealers
- Quantum Simulators
- Universal Quantum Computers

**Quantum Communications**
- Secure Communications
- Distributed Quantum Computers

**Quantum Sensing**
- Quantum Magnetometers
- Quantum Accelerometers
- Quantum Radar

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Challenges in Realizing Quantum Computers
The Paradox

• Cannot observe a quantum system without producing an uncontrollable disturbance in the system.

• To use the quantum system to store & reliably process quantum information, need to keep it perfectly isolated from the outside world.

• At the same time, want the qubits to strongly interact with one another so that we can process the information.

These challenges have taken many years of development in materials, control & fabrication to get where we are now.

Quantum computing in NISQ era and beyond: John Preskill
What Determines Qubit “Quality”? 

- Number of qubits
- Decoherence times
- Error rate per qubit, per gate
- Limitations on circuit size
- Time to execute qubit gates
- Preparation & accurate measurement of qubit states
- Connectivity amongst qubits
- SCALABILITY

Quantum computing in NISQ era and beyond: John Preskill  
Qubit Technology Status: Fidelity & Gate Speed

1QB and 2QB Comparison

- Trapped Ions
- P-doped Si (nuclear)
- NV Center
- P-doped Si (electron)
- Silicon MOS
- Silicon Quantum Dots
- Neutral Atoms

Gate Speed (Hz)

# operations before error

- Best Performance
- Higher fidelity
- Superconducting Qubits

1-qubit gates
2-qubit gates

Gate Fidelity

Thanks to: P. Cappellaro, J. Chiaverini, D. Englund, T. Ladd, A. Morello, J. Petta, M. Saffman, J. Sage

Courtesy of Prof. William Oliver (MIT)
Challenge: Practical Problems

Intelligent Machines

We’d have more quantum computers if it weren’t so hard to find the damn cables

Quantum machines will deliver the next great leap forward in computing, but researchers building them can’t easily get some of the exotic components they need.

by Martin Giles  January 17, 2019

ENIAC: Electronic Numerical Integrator and Computer

“If you take this chip, I’ve got 49 qubits and 108 coaxial connectors to the outside world. What would it look if I had a million qubits? I can’t have 2 million coax cables to the outside world. Maybe that’s what an ENIAC system looked like in the 1940s, but that’s not what a conventional system looks like. So what worries me most is wiring your interconnects.” – James Clarke, Intel
Challenge: Complex Experimental Setup

Superconducting Qubits

Cryostat
Challenge: Decoherence

Requirements

• Stability
• Synchronization
• Scalability

Control instrumentation

Attenuation
Cabling
Low-noise amplifiers

Attenuation
Cabling
Low-noise amplifiers

Qubits
Decoherence is the enemy of every quantum system

- What is decoherence?
  - Anything that puts the qubit in an uncontrolled quantum state
  - Classical rather than quantum uncertainty

- Where does decoherence come from?
  - Imperfect qubits
  - Uncontrolled interactions with environment
  - Errors in classical control

Quantum uncertainty

Classical uncertainty

Defining Quantum Decoherence
Running Quantum Algorithms

CONTROL CHALLENGES IN QUANTUM COMPUTING

Quantum algorithm notation

Complex control system

• Generation
  • Phase-coherent pulses (μW, RF, or both)
  • Different lengths (ns-μs), frequencies (3-12 GHz), amplitudes & phases (I/Q modulations)
  • FDM to address several qubits with same channel
  • Spectral purity
  • Baseband pulses

• Acquisition
  • μW acquisition with real-time I/Q demodulation
  • FDM to address several qubits with same channel
  • Pulse counting & timestamping

• Scalable to hundreds/thousands of channels
• Tight inter-channel synchronization & phase control
• Real-time feedback for quantum error correction (QEC)
Qubits are delicate, losing their state with time ➔ decoherence
• Quantum error correction (QEC) must be interleaved in quantum computation to correct qubits

Complex control system
• Generation
  • Agile low-latency waveform selection
• Acquisition
  • Real-time low-latency qubit state decoding (DSP)
  • Real-time decision-making feedback
  • Low-latency communication between analyzers & sources

n error corrected physical qubits ➔ 1 logical qubit
Keysight Solutions
Quantum Solutions for Complete Product Life Cycle

QES SOLUTIONS

Quantum Computing
Quantum Communications
Quantum Sensing

Component ➔ Subsystem ➔ System

Technology Elements
Quantum Technology Applications

Keysight's Value in the Element Life Cycle

Design ➔ Prototyping ➔ Design Validation ➔ Manufacturing/Test ➔ Final Product ➔ Maintenance and Repair

Design ➔ Test ➔ Control

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Quantum Computing, Comms, Sensing – Control Solutions

**Examples:**
- Superconducting qubits
- Spin qubits
- ...

**Examples:**
- Trapped ions
- Neutral atoms
- NV centers
- Molecules
- Rare-earth crystals
- Non-linear crystals
- Electro-opto-mechanical devices
- ...

**QES SOLUTIONS**

End-to-end Qubit Control Systems

- Cryogenic Systems
- Non-cryogenic Systems

**MIMO uW/RF/BB Solutions**

- Open FPGA & HW Sequencer
- Quantum-specific FPGA & SW IP for Control and Readout
- High BW Solutions

**Interconnect Solutions**
Non-Cryogenic Quantum Systems – From Design to Test

QES SOLUTIONS

Control Systems

- Design
  - EDA Design Software
- Design Verification
  - Test Equipment
- Design Validation
  - Qubit Emulator (HIL)
  - MIMO Signal Tester
- Manufacturing
  - Room-temperature & Cryogenic Wafer Testing

Qubit ICs

- Design
  - EDA Design Software
- Design Verification
  - Network Analysis
    - Parametric Testing
- Design Validation
  - Qubit ICs
  - Functional Testing
- Manufacturing
  - Room-temperature & Cryogenic Wafer Testing

Room-temp & Vacuum Interconnects

- Design Verification
  - Network Analysis
- Manufacturing
  - MIMO Network Analysis
Scalability & Footprint: 5-Qubit Example

QUANTUM COMPUTING CONTROL/TEST SYSTEM

Scalability

- Hundreds of ports of AWGs & digitizers possible
  - With daisy-chained PXIe chassis
- Minimizing footprint & cost
  - With high channel density
Block Diagram: Quantum Engineering Toolkit

For more details visit: www.keysight.com/find/solution-QET
Hardware Components

**Q U A N T U M  C O M P U T I N G  C O N T R O L / T E S T  S Y S T E M**

**M3202A 1 GSPS AWG**
- 4 Channels
- 1 PXIe Slot
- Real-time Sequencer
- FPGA Programming

**U3022A Mixer Unit**
- 8 U/C or D/C
- 19” Rack Chassis

**M3102A 500MSPS Digitizer**
- 4 Channels
- 1 PXIe Slot
- Real-time Sequencer
- FPGA Programming

**M9347A 20GHz LO Module**
- 2 Channels
- 1 PXIe Slot
- World-class Phase Noise
- Phase Coherence

**Ex: 50 Qubits**

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（Newsbreak）幫助企業，服務提供商和政府加快創新的技術公司Keysight Technologies，Inc.宣布與MIT合作，並收購Labber Quantum，是德科技的大計劃與麻省理工學院量子工程中心合作，以建立一個新的64量子位量子計算實驗室，該測試平台將利用是德科技的量子工程工具包（QET），該工具包將其一流的硬件與最新收購的Labber Quantum軟件結合在一起。

“是德科技收購了MIT EQuS小組的創立公司Labber，這為推動量子技術的下一代創新提供了令人振奮的新機會。EQuS期待將是德科技新興的量子軟件和硬件解決方案應用於我們的新量子計算測試平臺，”麻省理工學院量子工程中心主任兼麻省理工學院工程量子系統（EQuS）負責人William Oliver教授說。）緊，測試床將位於其中。

是德科技通信解決方案事業部高級副總裁兼總監Satish Dhanasekaran說：“與MIT的合作以及將Labber Quantum添加到是德科技的解決方案產品組合中，表明了我們致力於發展量子計算的承諾，” “我們很高興能夠支持和推動量子生態系統的發展，以加速下一代計算和連接應用程序的創新。”
Challenge: Noise in the System

Control instrumentation

- Attenuation Cabling
- Low-noise amplifiers

- Qubits

Temperature: 300 K, 50 K, 4 K, 20 mK
Component Characterization

**VECTOR NETWORK ANALYZER**

Key specifications for network analyzer

- Stability
- Dynamic range
- Noise floor
- Phase noise
- Trace noise

Control Instrumentation

- Attenuation
- Cabling
- Low-noise amplifiers

Qubits

300 K
50 K
4 K
20 mK

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PNA-X Series Network Analyzers
OFFER HIGHEST PERFORMANCE & MORE

- 2- and 4-port versions
- Built-in 2nd source & internal combiner simplify measurement setups
- Unrivaled flexibility & configurability
- Internal modulators & pulse generators for fast, simplified pulse measurements
- High-accuracy noise-figure measurements using unique source-correction method
- Many software applications
- Large touch-screen display with intuitive user interface
Challenge: Wafer Testing at Low Temperature

Cryogenic operating conditions

Cryogenic device testing requires highly specialized probe system

- Control instrumentation
- Attenuation Cabling
  - Low-noise amplifiers
- Attenuation Cabling
  - Low-noise amplifiers
- Qubits

Cryogenic device testing requires highly specialized probe system.
Development Stages of Target Devices

CRYOGENIC TOOLS

**Exploration/research**
- Cryostat / dilution refrigerator
  + Low-cost entry point
    - Packaged devices only; single or small set, easy to load
  + Full cryo range 15mK to 77K
  - Low throughput
    - Days/weeks delay for packaging
    - New cooling cycle per device/set
    - Stalled by poor-yielding technologies (replace, then repeat cooling cycle)
    - ESD/H₂O risk (dice/bond/handle)
    - New load board for every package
    - Wafer destruction during dicing

**Engineering/development**
- Small / manual cryo probe station with probes
  + Improved throughput
    + Quicker sample prep (dicing only)
    + Test devices in series with no new cooling cycle; move stage/probes to next test site (select systems only)
    + Positioners for different pad patterns
    + Wafer OK for other tests/production
    + Same package test capabilities, plus simple structures (max 8 probes) on small wafer fragments (e.g., 100 mm with tens of devices)
  - Doesn’t cover full cryo range
    - 2K minimum temp available today

**High-volume engineering/production**
- Large / automated cryo probe station with probe card
  + Best throughput
    + Immediate wafer test (no prep)
    + Automated alignment once trained
    + Automated step-and-repeat testing across wafer; no operator delays
    + Higher throughput yields larger sample sizes for better engineering statistics & production output goals
    + Same package/fragment test capabilities, plus full wafers (up to hundreds of probes & devices)
  - Doesn’t cover full cryo range
    - <10K minimum temp available today
FormFactor’s Range of Cryo-Probe Systems

**INTEGRATION WITH KEYSIGHT INSTRUMENTATION**

**PLC50**
100 mm manual cryogenic probe system
Entry-level manual cryogenic wafer probing < 7 K

**PMC200**
200 mm manual cryogenic probe system
Advanced manual cryogenic wafer probing < 7 K

**PAC200**
200 mm semi-automated cryogenic probe system
Semi-automated cryogenic wafer probing < 20 K

**PNA - X**

**B1500A**

**B1505A**

**N6705C**

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Extraordinary progress in quantum device engineering has reached high levels of isolation from local electromagnetic environment.

Under these conditions, inherent material noises play an important role. Material-inherent fluctuations with 1/f spectrum present main limiting factor to quantum coherent behavior of nanodevices in present generation.

Has stimulated great effort in understanding & predicting decoherence due to 1/f noise and the closely related RT noise.

1/f noise: implications for solid state quantum information
E. Paladino et al
A-LFNA Connections

Source Measurement Unit (SMU)
Bias, Triaxial Shielded Cable

Input Module
Output Module
Substrate Module
Digitizer

Digital Control
Simulation

CROSS-TALK & OTHER CHALLENGES

- Any electrical circuit for implementing quantum bits will have channels through which microwave signals applied to one qubit will leak onto unirradiated qubits
  - Microwave crosstalk may occur through either intended coupling channels or through unintended stray elements

- In nanodevice fabrication, inductance, resistance & capacitance values determine resonant frequency of qubits & quality of connections

- Accurate 3D RF simulation of designs is paramount to higher qubit yield & better qubit quality
Summary

WRAPPING UP

• Quantum will enhance communication, computing & sensing
• Investment in quantum is rising around the world
• Realization of quantum computers faces major challenges
• Scalable solutions from Keysight & FormFactor can help