MIT Lincoln Laboratory
Advanced Technology & Microelectronics

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MIT Lincoln Laboratory

MIT Lincoln Laboratory is a federally funded research and development center (FFRDC) that

- applies advanced technology to problems of national security
- provides research and development activities focus on long-term technology develop
- provides rapid system prototyping and demonstration.

These efforts are aligned within key mission areas among 8 research divisions

- Air, Missile, & Maritime Defense
- Homeland Protection
- Cyber Security
- Communication Systems
- Engineering
- Advanced Technology
- Space Control
- Intelligence, Surveillance & Reconnaissance

Advanced Technology Division

Program Groups

- Chemical, Microsystem, and Nanoscale Technologies (Group 81)
- Laser Technology and Applications (Group 82)
- Radio Frequency Technology (Group 86)
- Advanced Imager Technology (Group 87)
- Quantum Information and Integrated Nanosystems (Group 89)

Laboratory Facilities

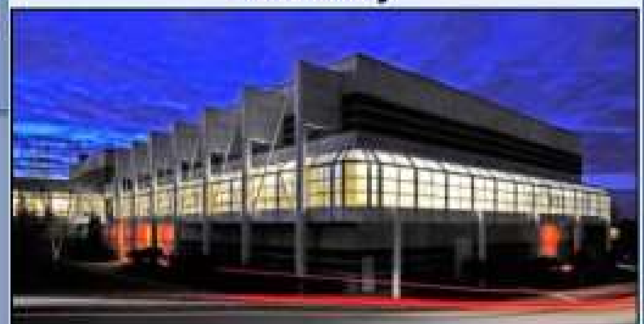
- Microelectronics Lab (silicon), Compound Semiconductor, Electronic packaging, Microsystems Integration, Optical coatings & fabrication, …

Microelectronics Laboratory's Position in the Silicon Fabrication Community

Research Flexibility

Universities
- Unrestricted materials and processes
- Limited integration and circuit complexity

Microelectronics Laboratory



Industry
- Highly restricted materials and processes
- < 22nm feature sizes
- Billions of devices on chip

Feature scaling / transistor count / process maturity

Microelectronics Laboratory is the most advanced Si-based fab facility in the country <u>dedicated</u> to supporting the research and development needs of the Government

Unique Focal Plane Technology in Support of National Security and Science Missions

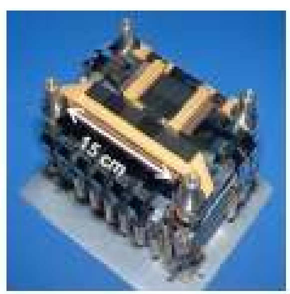
Charged Coupled Devices (CCDs) for
- Highest sensitivity and lowest noise
- Visible, near infrared, ultraviolet, and soft X-ray
- Applications for ground, air, and space

Geiger-Mode Avalanche Photodiodes (GM-APDs)
- Noiseless photon counting for low light and high speed imaging
- photon arrival time-stamps for active ladar and 3D imaging

Digital Focal Plane Array (DFPA)
- in-pixel computation and inter-pixel data communication
- image processing at the focal plane

Space Surveillance

Astronomy

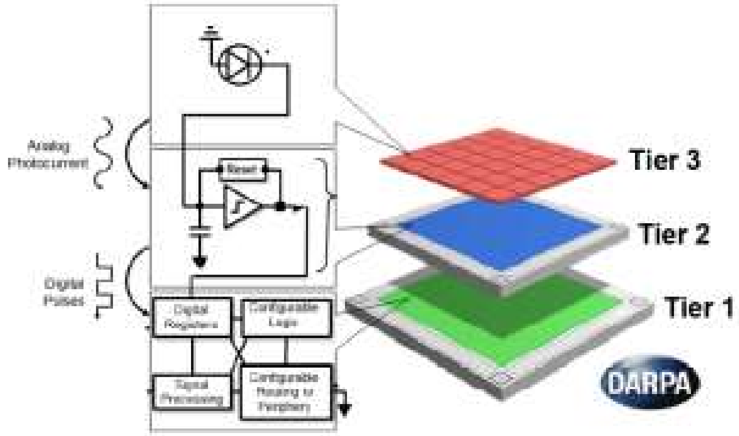


Space Science

DoD Satellites

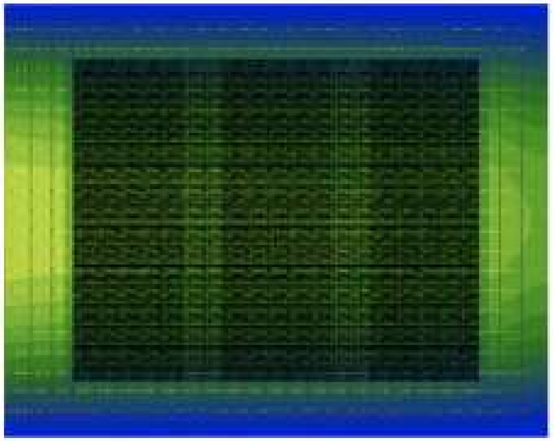
MIT LL Reconfigurable Circuit Development for ReImagine

DARPA Reconfigurable Imaging (ReImagine) Program 3D Sensor Architecture



Tier 3	Waveband Specific Detector Array	Industry
Tier 2	Detector Specific Analog Interface	Industry
Tier 1	Reconfigurable Digital Circuit with Integrated FPGA Processing	MIT LL

Griffin FPIA 14nm Design

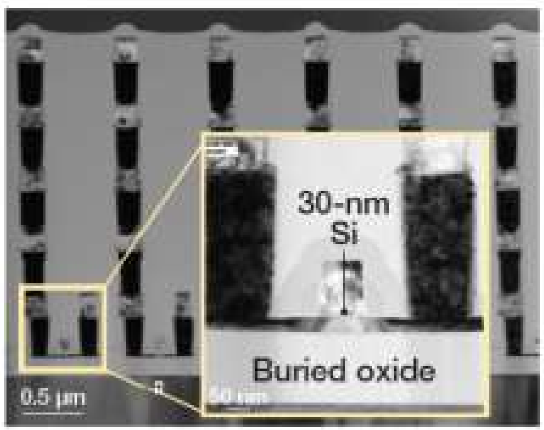


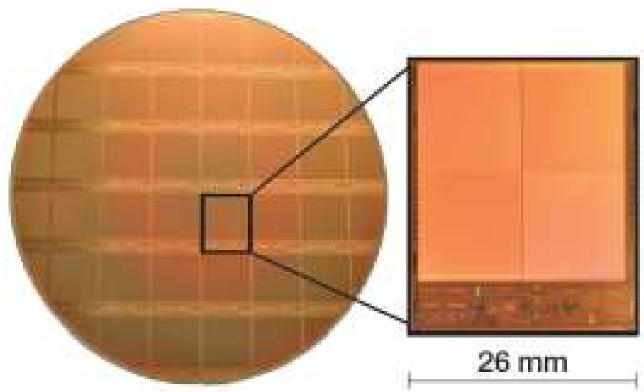
- Largest IC ever developed within the DoD
- Submitted for fabrication May 2018
- 6.6 Billion transistors
- 320 mm^2 chip area in a 14-nm FinFET process
- 9 km internal wiring

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

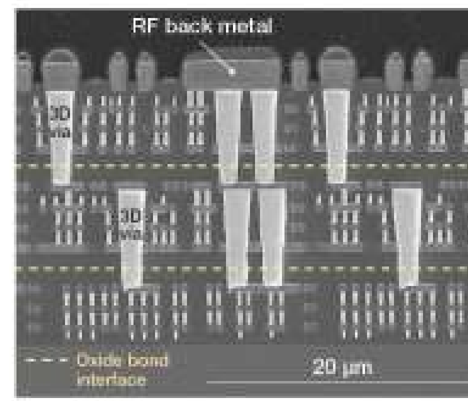
Fully Depleted Silicon-on-Insulator CMOS

- 90-nm FDSOI CMOS on 200-mm-diameter wafers
- Specialized process variants optimized for very-low-power subthreshold operation, high-performance mixed-signal and RF applications, and extreme environment (cryogenic, high-temperature, and radiation) operation
- Enabler for 2.5D and 3D heterogeneously integrated microsystems





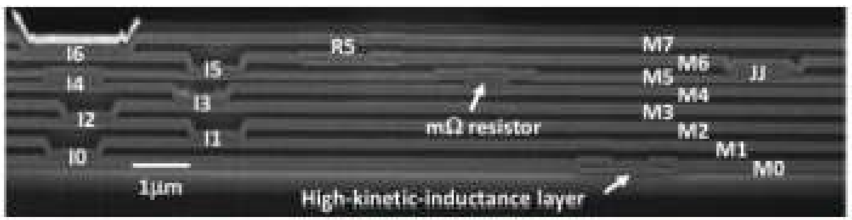
500M transistor FDSOI CMOS readout integrated circuit.

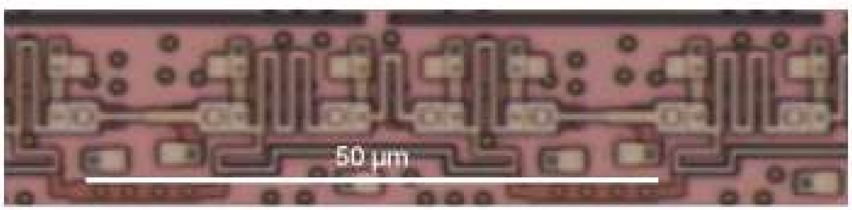


3D-integrated FDSOI CMOS circuit.

Superconducting Digital Integrated Circuits

- MIT Lincoln Laboratory has developed the world's most advanced single-flux-quantum (SFQ) integrated circuit process.
- This research foundry capability enables prototyping of advanced SFQ circuits along with flip-chip packaging on superconducting multi-chip modules
- All low temperature, "back end" metallization processing. Circuits operate at 4K or lower





Photomicrograph of superconducting single-flux-quantum (SFQ) shift-register integrated circuit fabricated at Lincoln Laboratory.

Fabrication Process Attribute		Units	Process Node					
			SFQ3ee	SFQ4ee	SFQ5ee	SFQ6ee	SFQ5hs	SFQ7ee
Critical current density		MA/m^2	100	100	100	100	200	100
JJ diameter (surround)		nm	700 (500)	700 (500)	700 (500)	700 (500)	700 (500)	500 (200)
Nb metal layers		–	4	8	8	9	8	10
Line width (space)	Critical layers	nm	500 (1000)	500 (700)	350 (500)	350 (400)	350 (500)	250 (300)
	Other layers	nm			500 (700)	500 (700)	500 (700)	350 (500)
Metal thickness		nm	200	200	200	200	200	200
Dielectric thickness		nm	200	200	200	200	200	200
Resistor width (space)		nm	1000 (2000)	500 (700)	500 (700)	500 (700)	500 (700)	500 (500)
Shunt resistor value		Ω/sq	2	2	2 or 6	2 or 6	2 or 6	2 or 6
mΩ resistor		mΩ	–	–	3–10	3–10	3–10	3–10
High kinetic inductance layer		pH/sq	–	–	8	8	8	8
Via diameter (surround)		nm	700 (500)	700 (500)	500 (500)	500 (500)	500 (500)	350 (250)
Via type, stacking		–	Etched, staggered	Etched, stacked \2/	Etched, stacked \2/	Stud, stacked \2/	Etched, stacked \2/	Stud, stacked
Early access availability		–		2014	2015	2016	2017	2018

Superconducting Electronics Application Domains

Digital Electronics

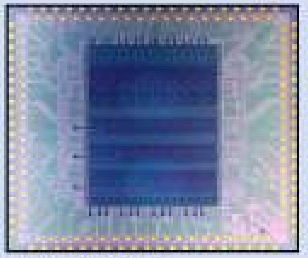


Image: HYPRES

- Digital circuits have been pursued since the early 1950s
- Increasing interest in both high-performance computing and control circuit applications
- Poised for significant progress in the next 5 – 10 years

RF Electronics

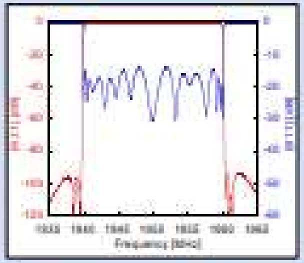


Image: IEEE Trans MTT (2000): 2519

- Extremely small RF electrical resistance enables very high quality factor components
- Used in particle accelerators and free electron lasers
- Maturation of fabrication processes can be leveraged to expand use in RF applications

Quantum Computing

Image: Google

- Superconducting quantum bits (qubits) are a leading candidate for quantum computation (QC)
- Dominant QC approach pursued by commercial companies
- Superconducting electronics are also being pursued for qubit control and readout

Detectors and Sensors

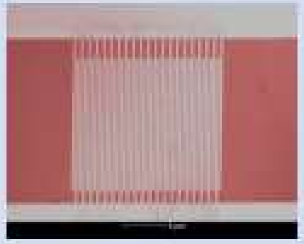


Image: NIST

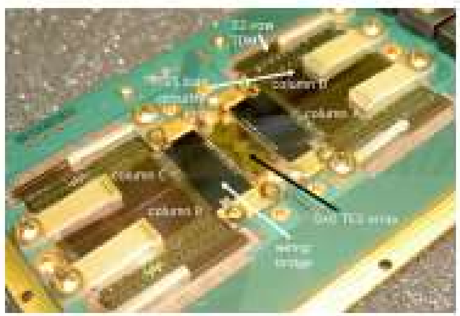
- Used in scientific, astronomy and metrology applications
- Voltage standard and high-sensitivity magnetometers
- Broadband optical detectors and unique energy resolution in the single photon domain

Control Electronics for Superconducting Devices

Superconducting Detector Arrays

MIT Lincoln Laboratory
Existing 4x4 element array of Superconducting Nanowire Single Photon Detectors (SNSPDs)

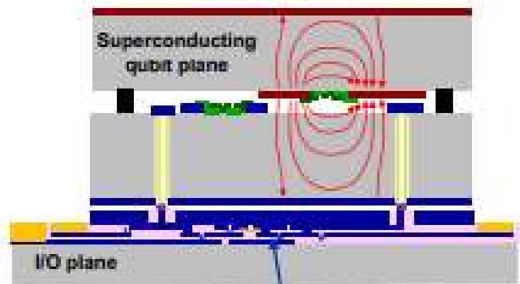
NASA Goddard & NIST
Existing 8x8 pixel Transition Edge Sensor (TES) array



MIT LL superconducting electronics fabrication paired with existing circuit design could enable multi-kilopixel detector arrays

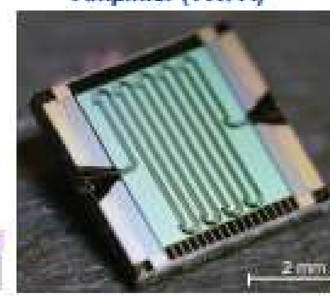
IARPA Quantum Enhanced Optimization (QEO) and Logical Qubit (LogiQ) Programs

MIT Lincoln Laboratory
3D Integrated Superconducting Qubit Platform



MIT LL multi-layer superconducting electronics is critical to achieving the required I/O density for quantum annealing systems

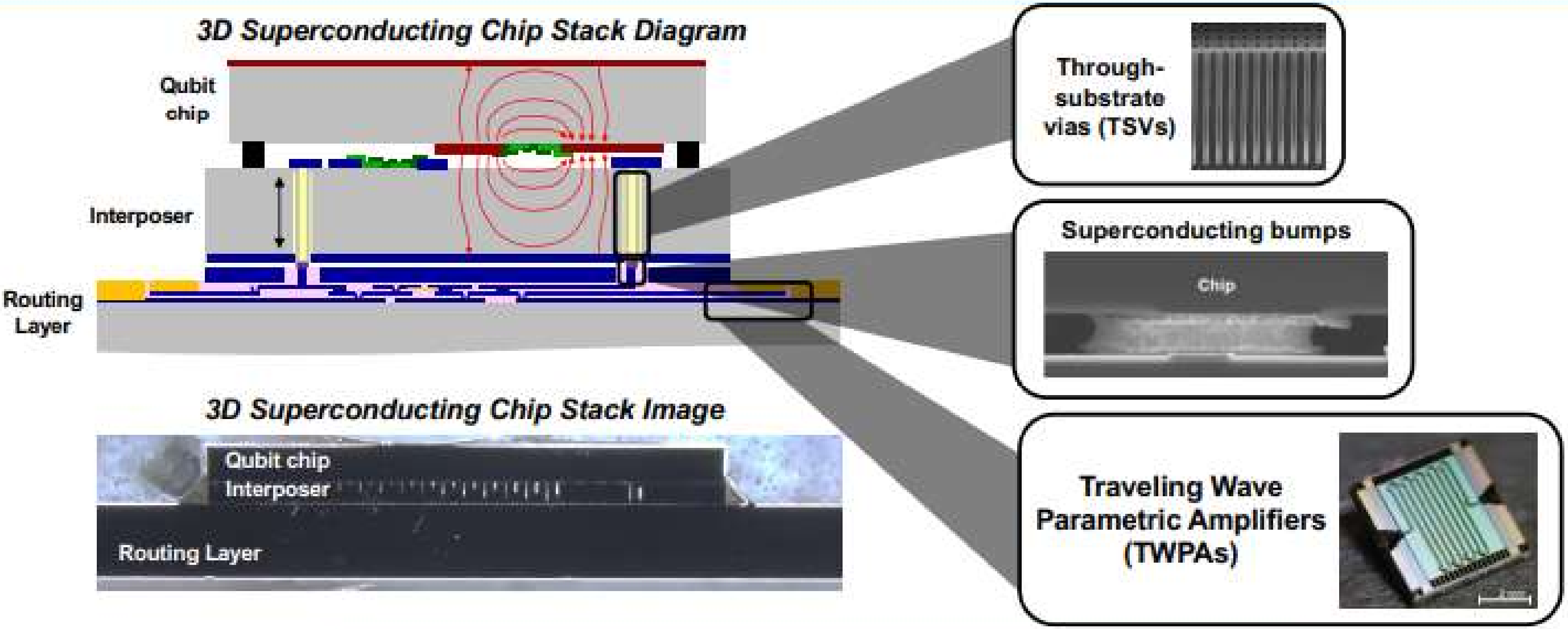
MIT LL & UC Berkeley
Traveling-Wave Parametric Amplifier (TWPA)



MIT LL superconducting electronics fabrication process enables multi-GHz bandwidth, near-quantum-limited amplification

Advances in superconductor electronics at MIT Lincoln Laboratory are enabling unique quantum systems

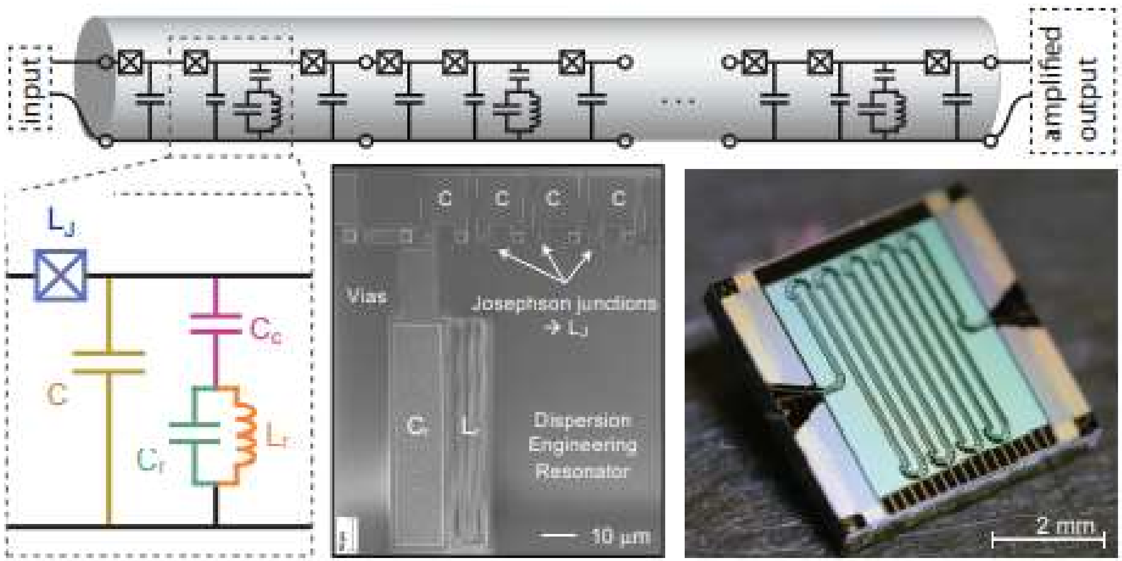
Technologies for 3D Integration of Superconducting Qubits



3D integration approaches are being developed to support required connectivity to qubits while maintaining high coherence

D. Rosenberg et al., npj Quantum Information (2017).

Traveling-wave Parametric Amplifier (TWPA)



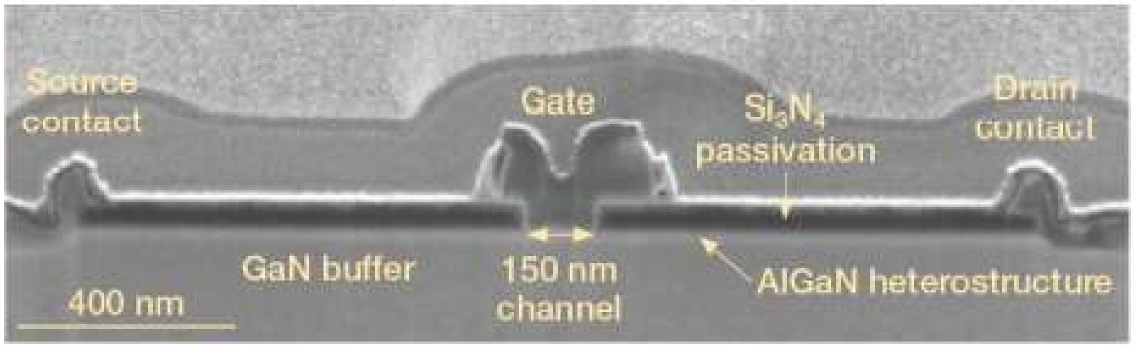
- Narrow-band Josephson parametric amplifiers first demonstrated in late 1980s
- Traveling-wave parametric amplifiers offer broadband, quantum-limited noise performance
  - >4 GHz bandwidth
  - 400 mK noise temperature
- Leverages unique multi-layer superconducting Nb fabrication process at MIT Lincoln Laboratory

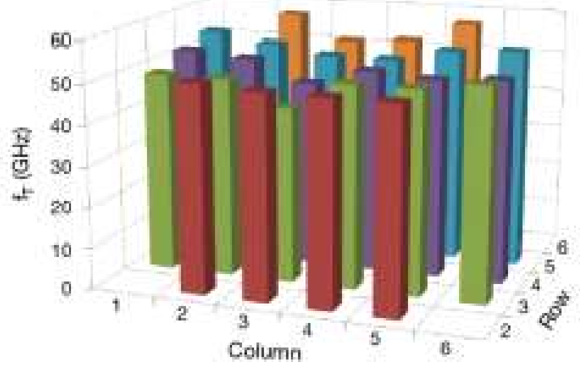
TWPA devices fabricated at MIT Lincoln Laboratory are supporting R&D at many universities, companies and Government laboratories

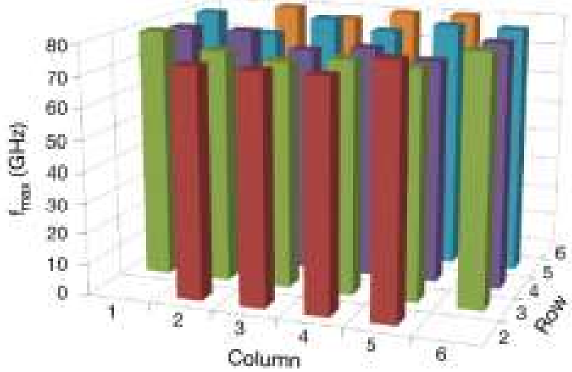
C. Macklin et al., Science 350, 307 (2015)

GaN HEMTs on Silicon

- The metallization is gold free and patterned by etching instead of liftoff to be fully CMOS compatible.
- High-performance HEMTs show the maximum drive current of 1 mA/mm and the peak transconductance exceeding 400 mS/mm.
- The breakdown voltage is approximately 90 V with 1 µm gate to drain spacing.
- Good processing control enabled the fabrication of the HEMT showing a tight distribution of f_T and f_{max} values. Such high yield and good uniformity is essential for delivering low-cost large-size GaN circuits.



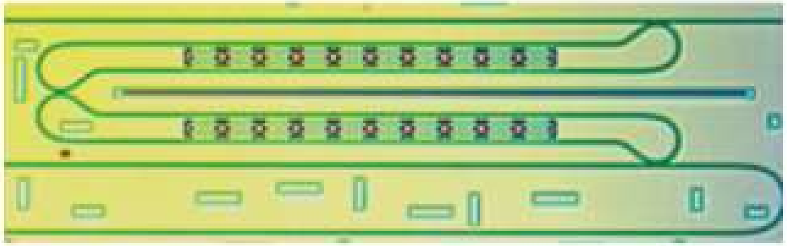




Photonic Integrated Circuits (PICs)

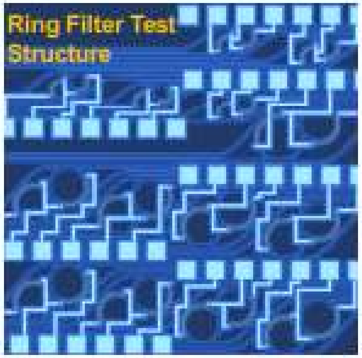
Component Information

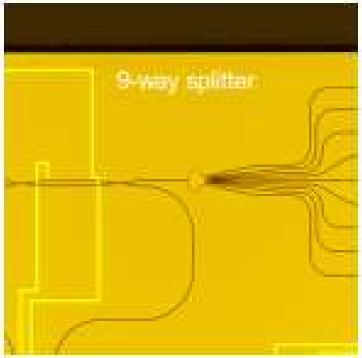
- Low waveguide losses and state-of-the-art component performance
- Si device library focused on telecommunication wavelengths (1550 nm)
- SiNx device library covering a variety of wavelengths from 600 nm to >1600 nm
- Gold-free metallization and CMOS-compatible fabrication of all components



Optical microscope image of narrowband optical filter fabricated in our active silicon photonics process.

SiNx Propagation Loss	
Wavelength (nm)	Measured Loss (dB/cm)
427	4-8
633	0.7
980	<0.5
1092	<0.2
1550	0.3



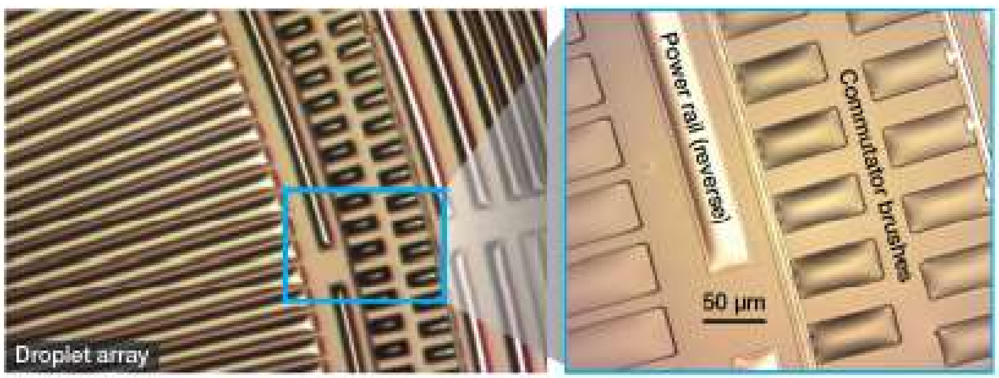


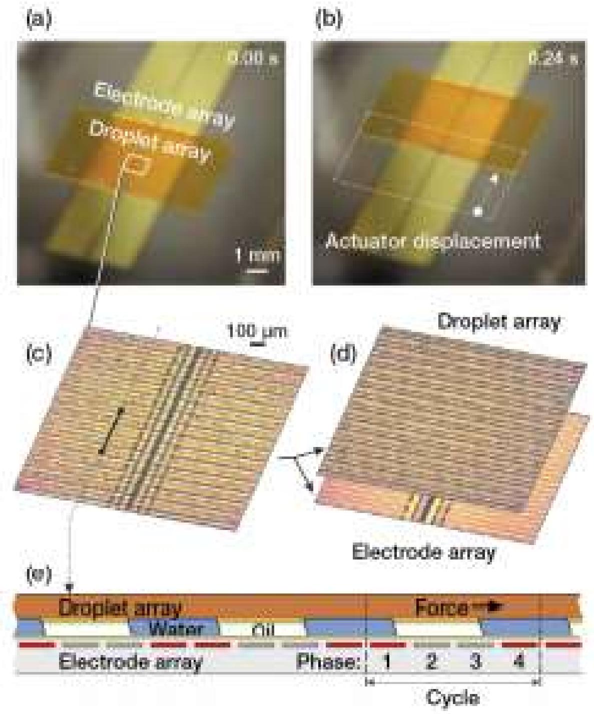
Microhydraulic Actuator Development

During operation electrodes are sequentially turned on, pulling the drops and the droplet array by electrowetting action

Potential Applications

- Actuators for efficient and scaled micro-robotics
- Artificial muscle-like material for flight control surfaces on unmanned aerial vehicle, exoskeleton, and artificial limb systems
- Micromotors and shape-change materials for scaled optical systems, such as gimbals, adaptive optics, and beam-steering systems





Partnering with Lincoln Laboratory

- Federal Government
  - MIT LL is a DoD FFRDC operated under a cost-reimbursement, no-fee agreement
  - Federal Government sponsors utilize this blanket Air Force contract
  - For non-DoD USG sponsors, this requires an Interagency Agreement (IAA)

- Small Business and Industry
  - Cooperative Research and Development Agreements (CRADAs)
  - Technology Transfer Agreements (TTAs)
  - SBIRs & STTRs
  - Test Agreements (TAs)

- Academia, Not-for-Profits, State & Local Governments
  - Collaboration Agreements (CAs)