SAND2020-8681C

Sandia National Laboratories

Exceptional service in the national interest

Sandia National Laboratories Microsystems Capabilities

DARPA ERI

August, 2020

Sr. Manager, Advanced Semiconductor Technologies **Rick McCormick**

U.S. DEPARTMENT OF ENERGY NNSA

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

SAND#:

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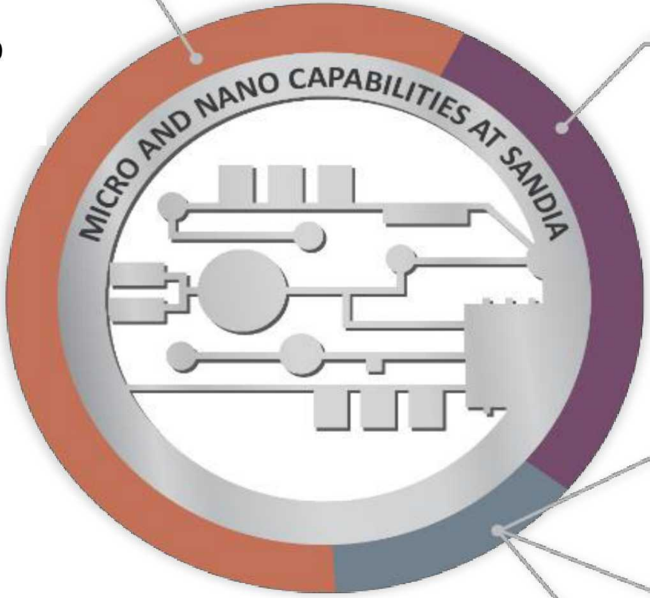
Sandia's microsystem capabilities

MESA

MICROSYSTEMS ENGINEERING, SCIENCE, AND APPLICATIONS



CDC

COUNTERFEIT DETECTION CENTER

CINT

CENTER FOR INTEGRATED NANOTECHNOLOGIES

IBL

ION BEAM LABORATORY

RAD TEST FACILITIES

- HERMES III ACCELERATOR
- Z ACCELERATOR FACILITY
- ANNULAR CORE RESEARCH REACTOR (ACRR)

One of 3 DOE Nuclear Deterrence Labs (primarily "non-nuclear components")

Missions: Nuclear Deterrence, Nonproliferation/Global Security, Energy & Homeland Security, and DoD and OGA support

Broad, unique capabilities & facilities:

- Deep electronics & microsystems S&T capabilities: process technologies, materials science, reliability physics, extreme environments
- Facilities: MESA fabs, Center for Integrated Nanotechnologies (CINT), Ion Beam Lab (IBL), Radiation Testing/Modeling, High Performance Computing

Sandia Partnering and Technology Transfer

Gov't Agencies & Labs

AFRL
U.S. ARMY
Office of Naval Research ONR Science & Technology
DARPA
NASA
ARL
Missile Defense Agency Department of Defense
Defense Threat Reduction Agency United States of America
National Reconnaissance Office United States of America
Aviation & Missile AMRDEC Strength Through Technology RD&E Center
Armament Research Development Engineering Center Picatinny, NJ
Fuze Division ARDEC
Air Force Technical Applications Center
Science & Technology Facilities Council Rutherford Appleton Laboratory

Large & Small Businesses

Raytheon
Plasmonics Inc. Infrared Nanotechnology
ATA
Northrop Grumman
Parker
Rockwell Collins
Draper Laboratory
Lockheed Martin
Xerox®
PSI Physical Sciences Inc.
Boeing
L3 communications
General Atomics
Honeywell
Scientic Vires Est

Universities

The University of New Mexico
The University of Texas at Austin
Cornell University
Berkeley University of California
Columbia University in the City of New York
UCSD
The University of Arizona
Massachusetts Institute of Technology
Yale University
LPS The Laboratory for Physical Sciences

Many partners/projects for DARPA

Sandia's microsystem capabilities

MESA

Microsystems, Engineering, Science & Applications

- Federally Funded Research & Development Center (FFRDC) with the broadest and deepest micro and nano expertise, providing what industry <u>cannot, will not, or should not</u>
- Only source for custom trusted strategically radiation hard (TSRH) microelectronics for the Department of Energy's (DOE) National Nuclear Security Administration (NNSA)
- Largest government owned microfabrication facility with two (Silicon and Compound) fabs

Research & Development — Si µSys (CMOS) — III-V µSys (HBT) — MEMS — Photonics (Si, III-V) — Production

Trusted
Design – Fabrication – Packaging
Heterogeneous Integration
Reliability & Failure Analysis
Radiation Effects Testing
Qualification – Product Acceptance

~300,000 parts across 44 products:

- 13 Si CMOS7 ASICs
- 8 III-V HBT SSICs
- 1 multi-kV GaN Diode
- 1 MEMS Sensor
- 2 Photonic Arrays
- 1 Optoelectronic Device
- 2 Focal Plane Arrays
- 16 RFICs

- 40 yrs. of Research & Product impact
- >300 Patents
- Tech. Transfer
- 45 R&D 100 Awards
- Seminal contributions to radiation hardened microelectronics, MEMS, & photonics

https://www.sandia.gov/mesa/

SANDIA'S MICROSYSTEM CAPABILITIES

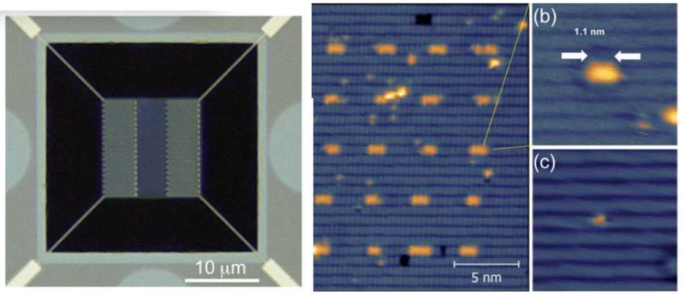
DOE Nanoscale Science Research Center (User Facility)

CINT

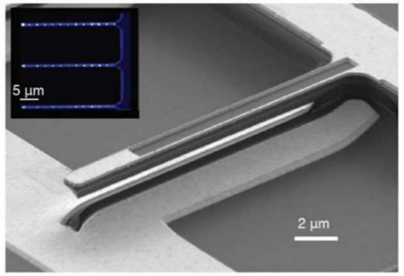
CENTER FOR INTEGRATED NANO-TECHNOLOGY

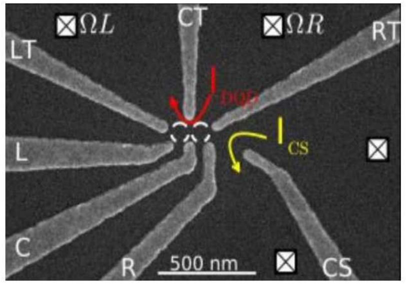
- User-project proposal process
- 250+ projects accepted each year
- No-fee for pre-competitive research
- Full recovery for cost proprietary research
- 2 Facilities (SNL/LANL-total 130,000 gsf)
- 55 scientists/techs, 32+ postdcs/stdnts
- 800+ users engaged
- 300+ publications annually

Forefront Lithography
- Atomic-Precision Lithography
- Focused ion implantation

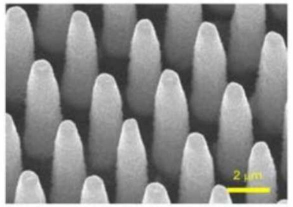


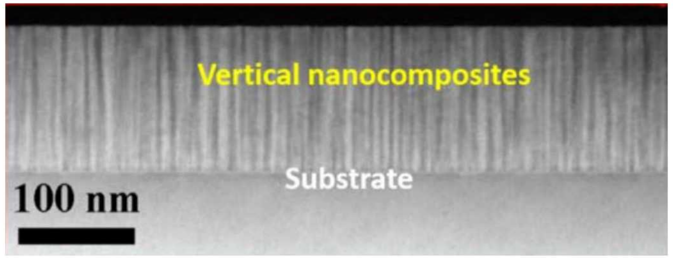
Quantum Science
- Quantum Transport
- Mean-field modeling for quantum materials





Materials synthesis
- Ultra-High Mobility MBE
- Complex Oxide PLD
- CVD Nanowire Growth





Nanophotonics
- Semiconductor metasurfaces
- Plasmonics, nanoparticles

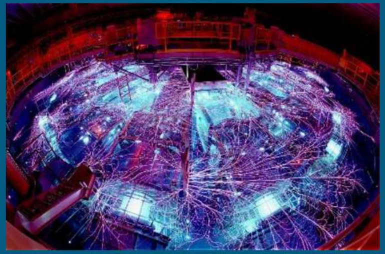
https://cint.lanl.gov/index.php

SANDIA'S MICROSYSTEM CAPABILITIES

IBL

ION BEAM LABORATORY

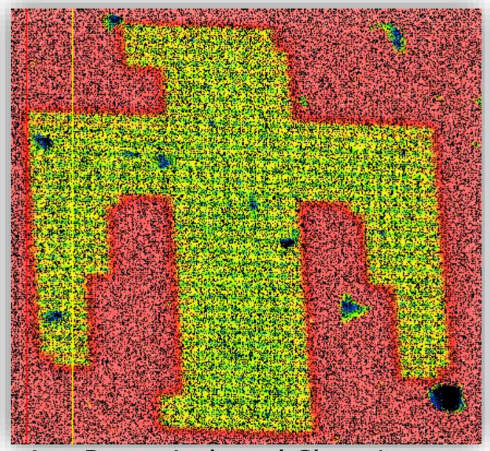
- 6 Operational nano-implant systems
- Spot sizes from 0.5nm to mm's
- Energies from 5keV to 70MeV
- Single ion implantation
- <40nm targeting resolution possible
- 26 ion species in use, 40+ ions possible



RAD EFFECTS

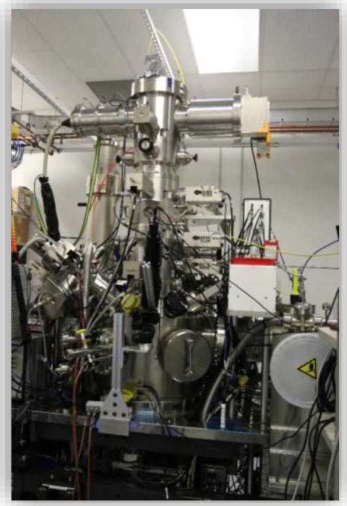
- Reactors, Accelerators, Z-machine
- Neutron, Gamma, X-ray, EMP
- Broad suite of RadFx Models/Codes

IBEC



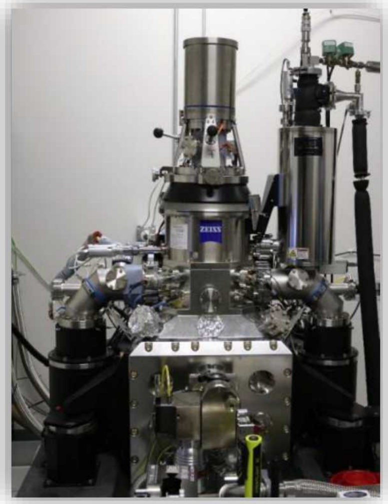
Ion Beam Induced Charging on PIN Diode

NanoImplanter



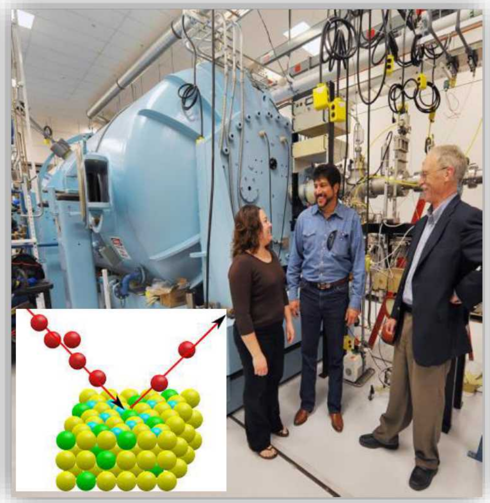
100 keV A&D FIB100NI

He microscope



100 keV Zeiss Orion Plus

Ion Beam Spectroscopy



HVE 6 MV Tandem

FIB-SEM NanoFab

35 keV Raith Velion

AC-STEMs

200 keV FEI Titan G2 8200

https://www.sandia.gov/research/facilities/technology_deployment_centers/ion_beam_lab/

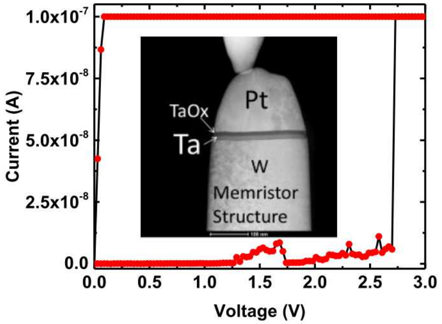
https://energy.sandia.gov/programs/nuclear-energy/advanced-nuclear-energy/radiation-effects-sciences

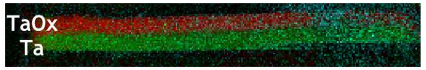
Neuromorphic science, processors, & applications R&D

Basic Science: 2011-Today
Memristors: HP Labs, Stan Williams
Matl Sci, Rad Fx, ReRAM NVM,
Neuro computing start
IBL nImplater, AC-STEM

Multiscale Integration:
Hardware Acceleration of Adaptive Neural Algorithms
(HAANA) Grand Challenge,
$15M, 3 yrs, ~30 staff, 3 divisions at SNL

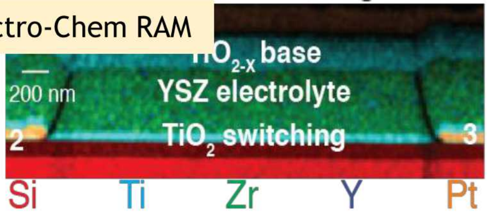
Application engagement:
Integration with Rad-hard CMOS,
National security and commercial
applications





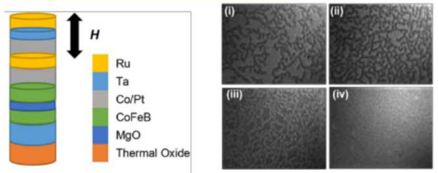
Electron Energy Loss Spectroscopy

Electro-Chem RAM

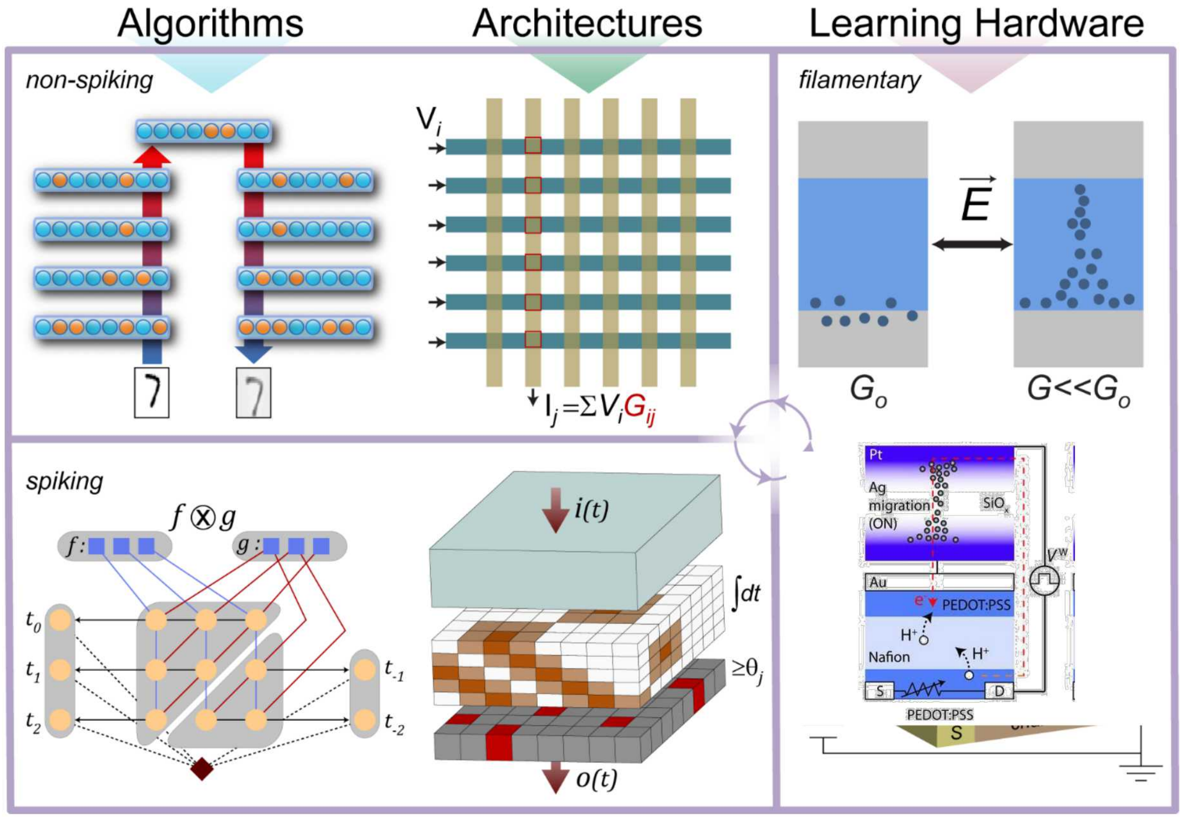


Y. Li, et al., *Adv. Materials*

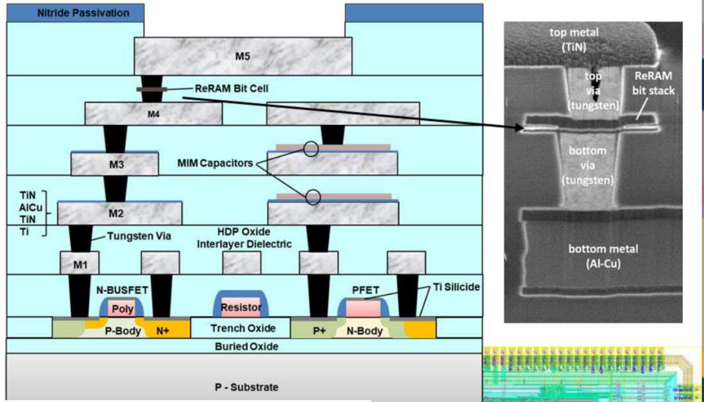
Rad Effects in STT pMTJs



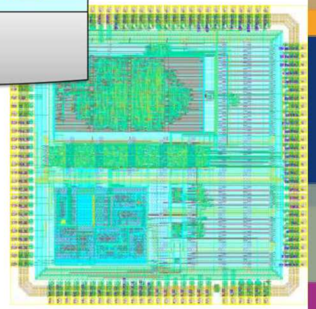
M. Alamdar et al., *NSREC 2020*



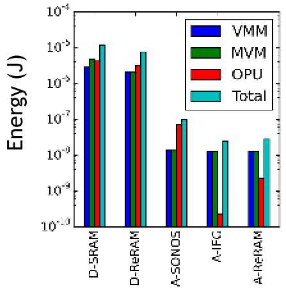
Fuller et al., Science 2019

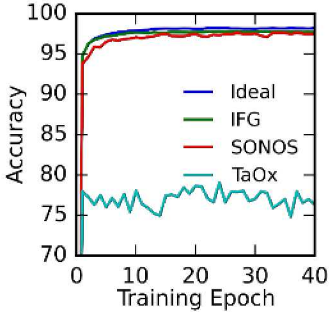


Level 5 full autonomy

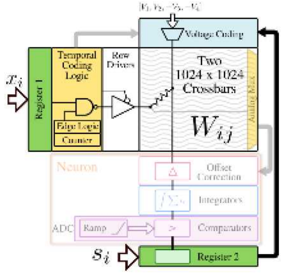


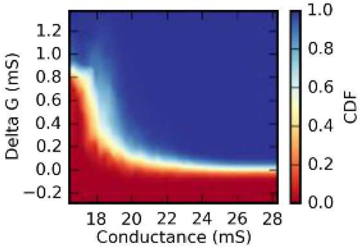
Multiscale CoDesign for Neuromorphic Accelerator





Energy/Performance Model
Model performance and energy requirements

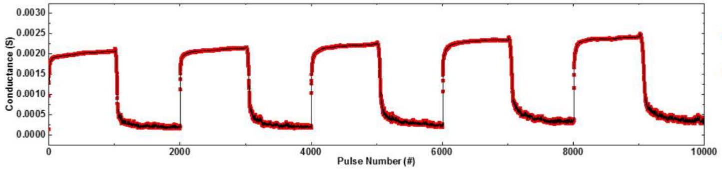




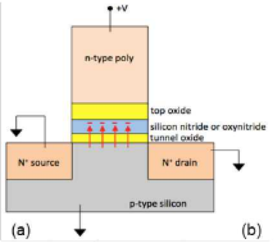
CROSS SIM

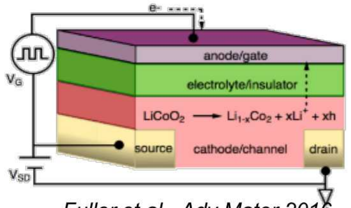
Sandia Cross-Sim:
Translates device measurements and crossbar circuits to algorithm-level performance

Marinella, Agarwal et al JETCAS 2018



Analog characterization





Fuller et al., Adv Mater 2016

Algorithms

Architecture

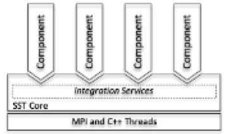
Circuits

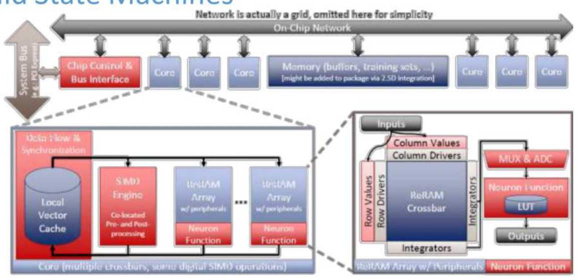
Devices

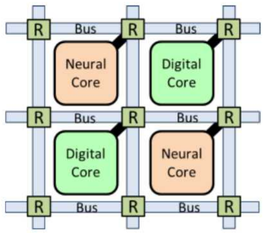
Materials

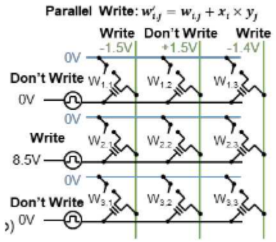
Target Algorithms
- Deep Learning
- Sparse Coding
- Liquid State Machines

Architecture Simulation

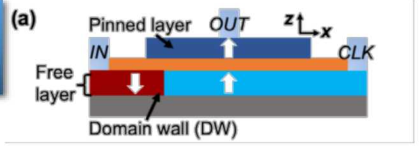


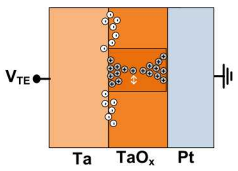


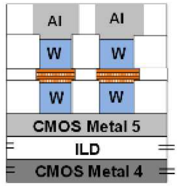


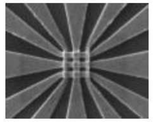


Drift-diffusion model of transport

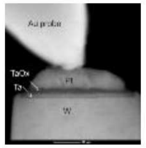


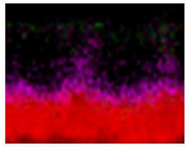


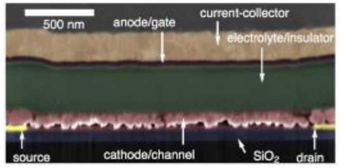




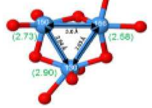
In situ Characterization







Ab Initio Modeling



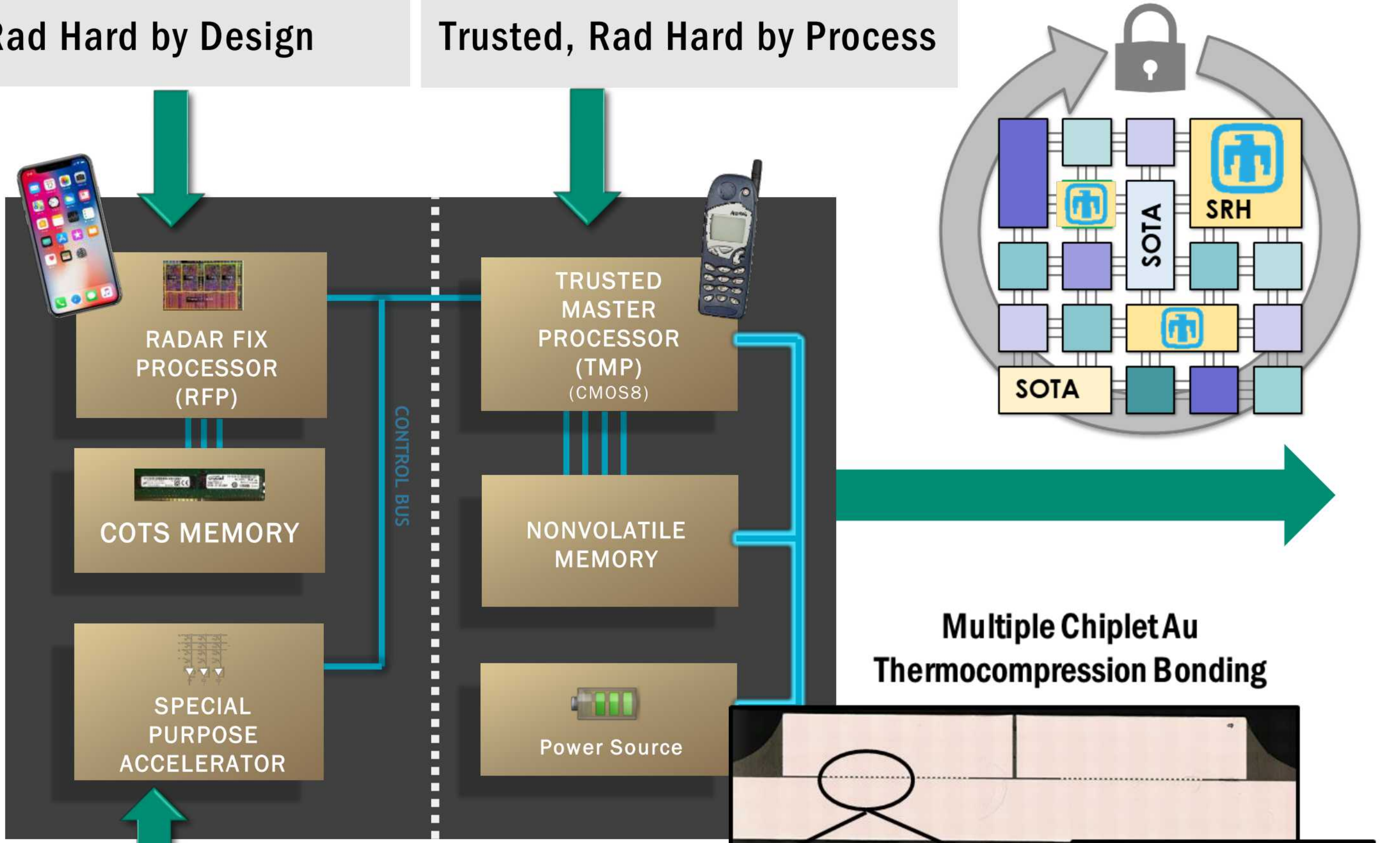
BACKUPS

SEEEC (Secure Efficient Extreme Environment Computing) High Performance Heterogeneous Rad Hard Architecture

$9M, 3 yrs, ~30 staff, 4 divisions at SNL

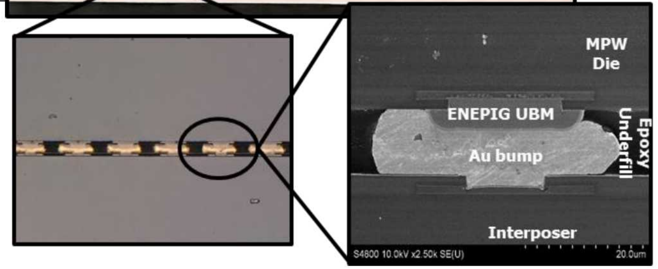
High Perf. Commercial Tech
Rad Hard by Design

Lower Perf. Gov. Fab
Trusted, Rad Hard by Process

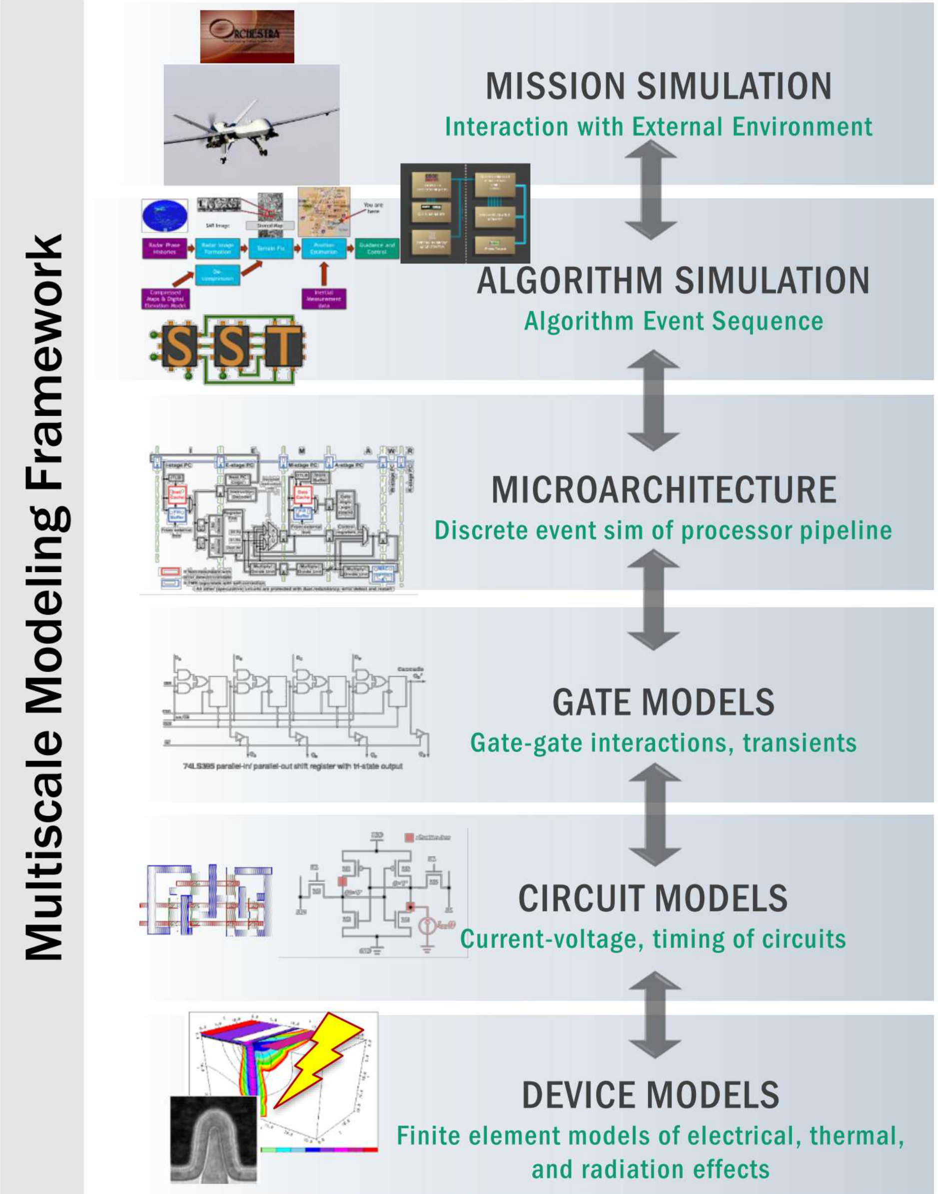


Analog Neural Network Accelerator

Multiple Chiplet Au Thermocompression Bonding

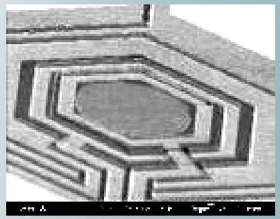
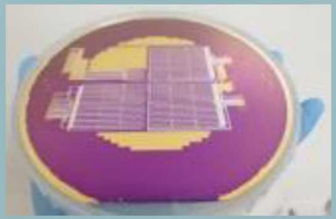


Multiscale codesign & analysis framework



HETEROGENEOUS INTEGRATION CAPABILITIES

Microsystem-Enabled Photovoltaics

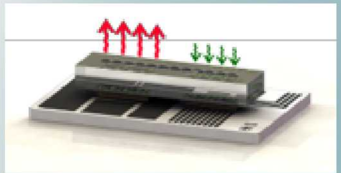
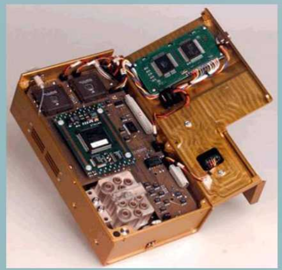



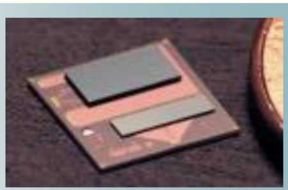

- wafer-level bonding for multi-junction solar cells
- InGaAsP/InP and InGaP/GaAs devices on silicon
- dielectric interfaces with III-V substrate removal
- integration with collection optics

Heterogenerous integration of Si and other materials

- Integration of $LiNbO_3$ and III-V technologies on silicon microelectronics and photonics
- Non-traditional materials such as Al_2O_3, epsilon-near-zero In_2O_3 and CdO, graphene
- Integration of CMOS with InGaAsP/InP, InGa/GaAs, silicon photonics, and other materials

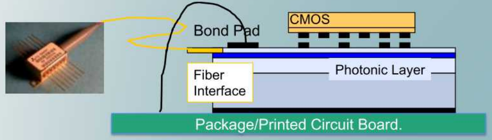
Optical and MEMS-based Microsensors

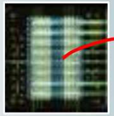
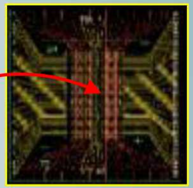
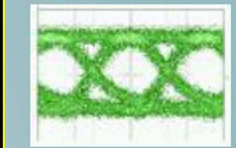



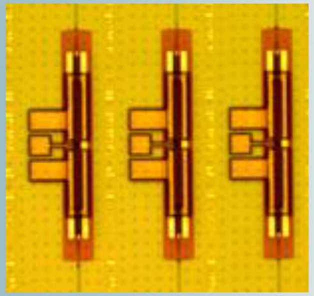



- chemical and bio sensors using MEMS and SAW devices
- g-hard optical microsensors with in-house photonics
- hybrid device integration with custom micro-optics

CMOS / Silicon Photonics / III-V Integration



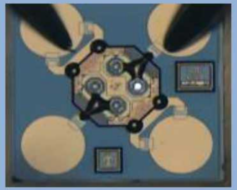

Tx/Rx Si Photonic Chip


- silicon photonics on high-speed silicon ASIC
- independent optimization of electronics & photonics
- Gain and laser sources on silicon

Compound Semiconductor Technologies Enable Microsystems

Optoelectronics (OE)

GaN LED



Surface normal emitter/detectors

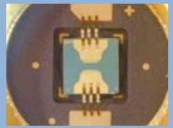
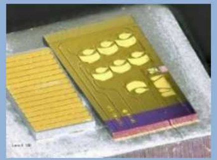
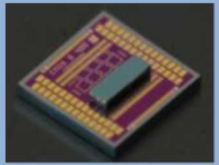


Photo-conductive Semiconductor Switch

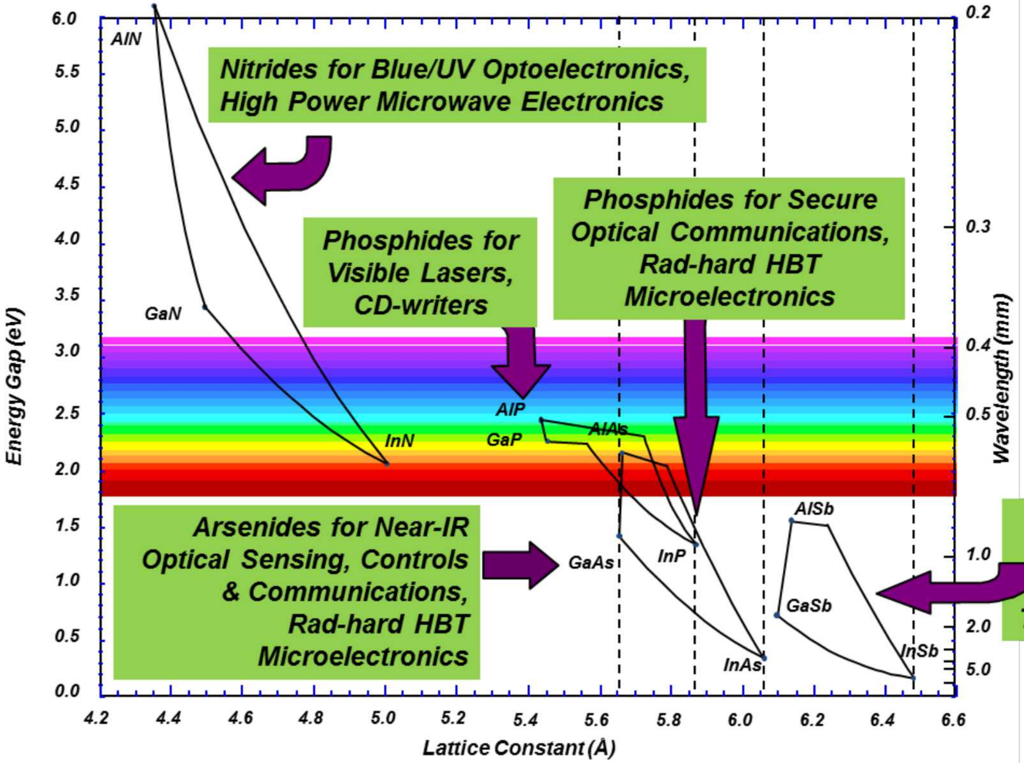


Photonic circuits

Hybrid Integration (HI)



Integrated OE and ME microsystems

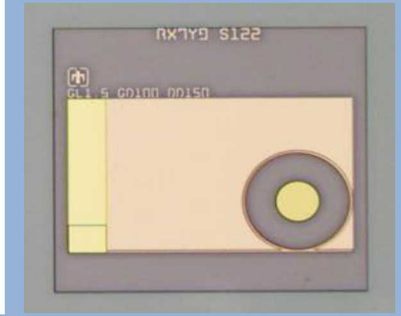


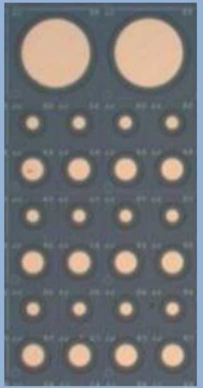
SNL has capability across full spectrum of III-V compounds

- **Arsenides**
- **Phosphides**
- **Antimonides**
- **Nitrides**

6 – MOCVD: As, P, Sb, N
6 – MBE: As, P, Sb
Production and R&D

GaN HV diodes

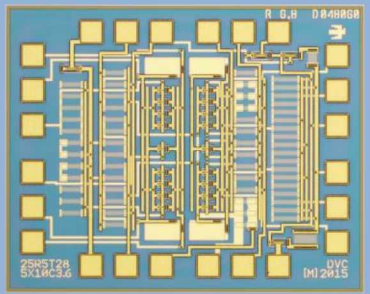




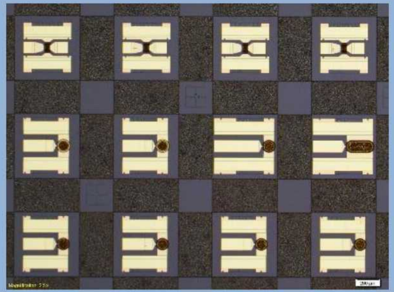
Focal Plane Arrays

SNL FPA IR Image

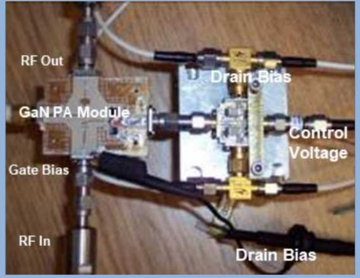
Microelectronics (ME)



HBT-based ICs



III-Nitride Power Transistors



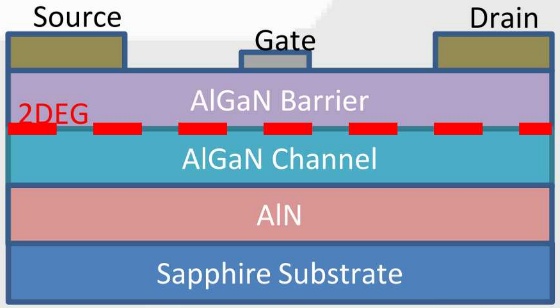
III-N RF Power Amplifier

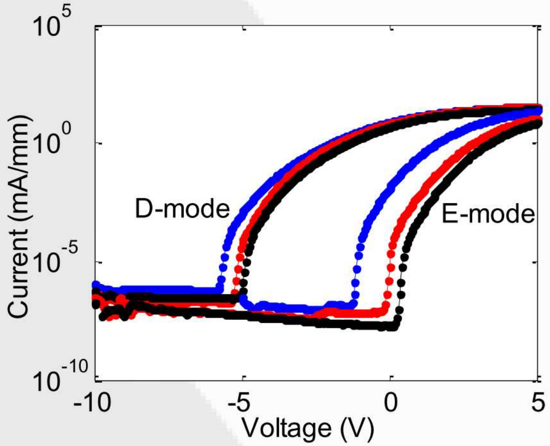
Digital Logic Gates for Extreme Environment Applications

Extreme environment hardening through intrinsic material properties

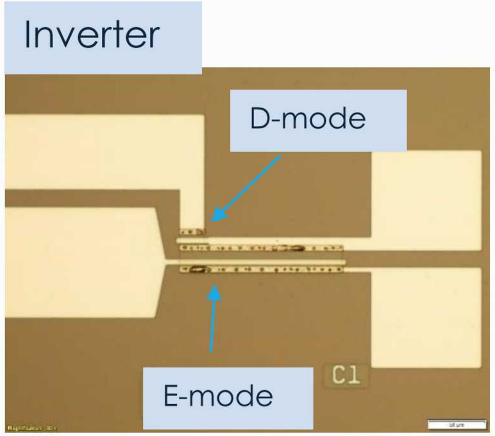
500 deg. C digital logic without extensive protection: Exploit ultra-wide bandgap AlGaN's superior electrical performance at elevated temperatures and high intrinsic material radiation tolerance

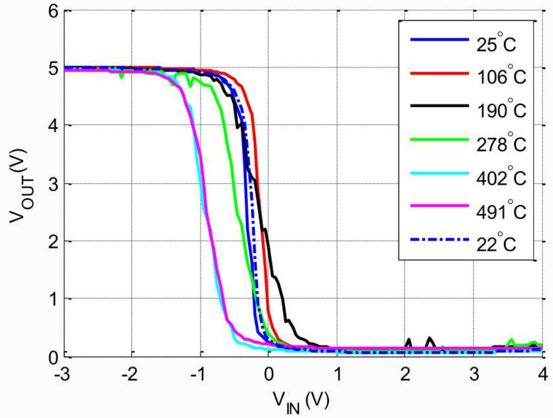
AlGaN High Electron Mobility Transistor (HEMT)





Adjacent enhancement- and depletion-mode switches.





Demonstration of $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ Inverter Operation from 25°C to 491°C.

Material	E_g (eV)	E_{crit} (×10⁶ V/cm)	v_{sat} (×10⁷ cm/s)	Mobility (cm²/ V s)	Thermal Conductivity (W/m K)
AlN	6.0	15.4	1.3	426	319
Al_xGaN	5.0-6.0	13.5-15.4	Interpolation	~150-400	Interpolation
GaN	3.4	4.9	1.4	1000	253
b-Ga_2O_3	4.9	10.3	1.1	180	11-27
Diamond	5.5	13.0	1.9-2.3	4500-7300	2290
SiC	3.3	2.5	2.0	1000	370

The ultra-wide band gap and high bond strength make AlGaN HEMTs promising for applications in extreme environments. The high critical electrical field may enable higher power density for switches.

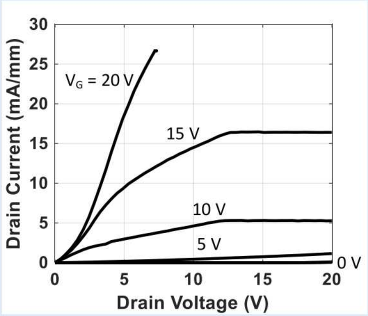
Academic Partner: Georgia Tech: Sam Graham/Nick Hines

Compound Semiconductor Advanced R&D

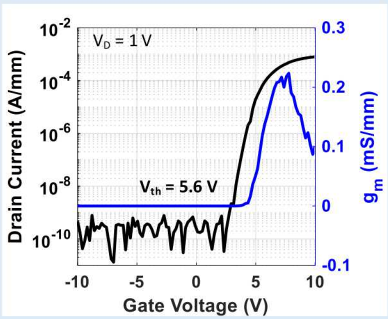
- Leveraging Expertise:
  - Materials Science
  - Materials Synthesis
  - Modeling/Simulation
  - Nanofabrication
  - HV Characterization
  - Reliability Science
  - Radiation Effects
  - Failure Analysis
- Striving to Improve:
  - Predictive Reliability
  - Qualification Confidence
  - Manufacturing Tolerances

High-Voltage, Solid-State Switch (GaN MOSFET)

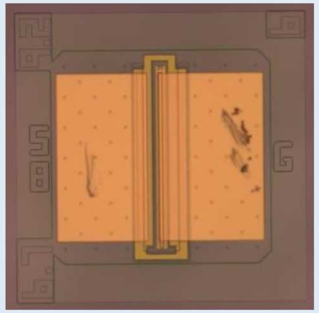
Low Current $I_D V_D$ Curves



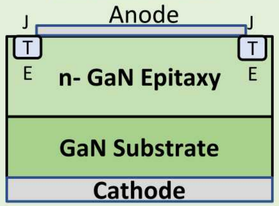
$I_D V_G$ – Transfer Characteristics



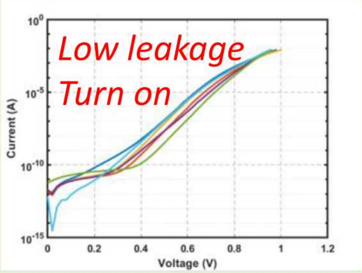
Optical Image

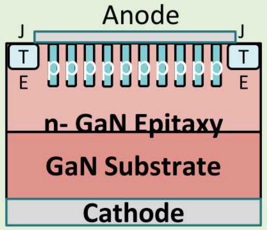


DOE-VTO GaN Power Diodes

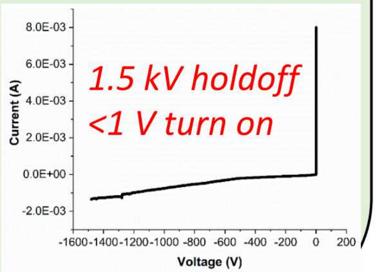


GaN Schottky Barrier Diode (SBD)

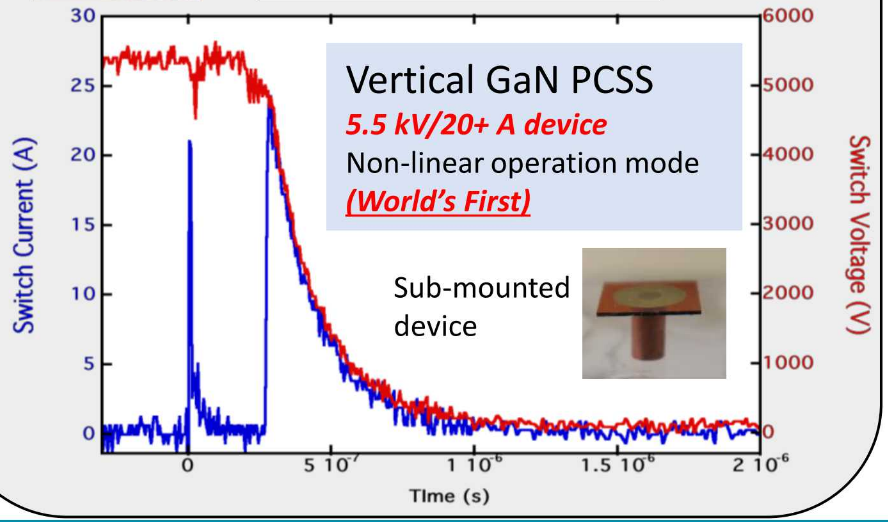




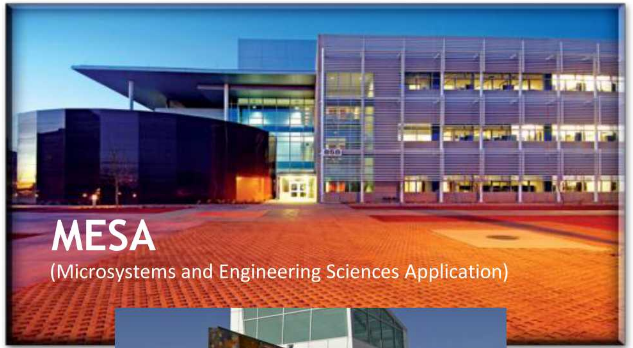
GaN Junction Barrier Schottky (JBS) Diode



ARPA-E BREAKERS DC Circuit Breaker



Sandia's National Security Photonic Center



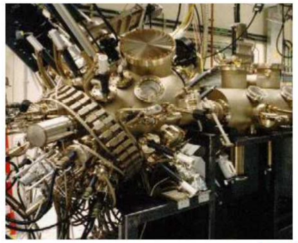
Silicon Fab:
Silicon Photonics

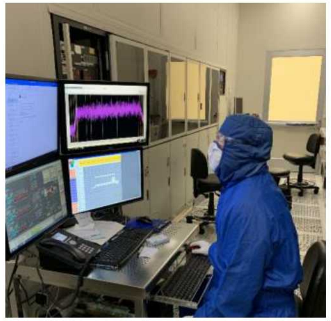
PDK and
8" Multi-Project Wafers

Microfab:
Compound Semiconductor
Photonics

Member of

Custom Epitaxial Growth & III-V Devices
(GaAs, InP, GaSb, GaN) – **11 Growth Chambers**
PDK and Multi-Project Wafers (InP)

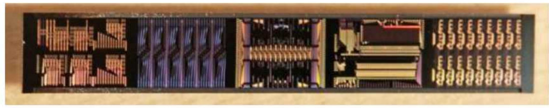




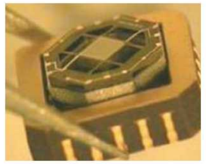
60+ Photonics Staff

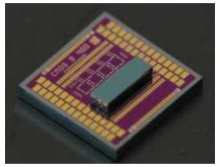
Device Design, Modeling, Simulation
Semiconductor Device Fabrication
Microsystem Fabrication
Testing, Rad Effects, Cryo
Reliability

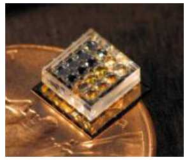
Microsystems and Heterogeneous Integration
(Flip Chip Bonding, micro-optics, assembly, packaging)

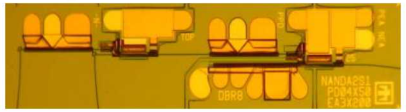


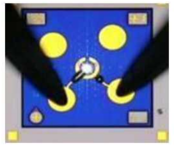
Photonic circuits











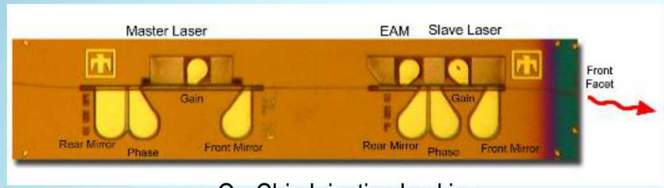
Photonic circuits & Lasers

Multi-Project Wafer Offerings

InP Photonics

- **3 tier offerings at 1550nm**
  - Tier 1: one regrowth
  - Tier 2: 2 regrowths (High P_{sat} Amplifier)
  - Tier 3: Full custom process

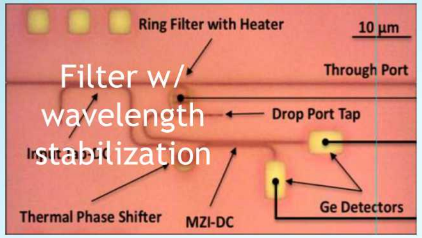
RF-Optical Channelizing Filter
1-20 GHz RF on C-Band Light



On-Chip Injection Locking
Enhanced Modulation > 50 GHz, C-Band

Silicon Photonics

- **MPW Device Library**
  - 20 Active, 22 Passive Components
  - Synopsis OptoDesigner
  - 200mm SOI Platform
  - Three Deliverables
    - Passive
    - Passive + Active
    - Passive + Active + Germanium



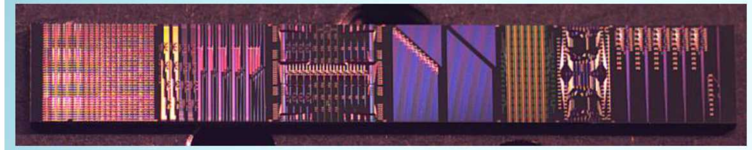
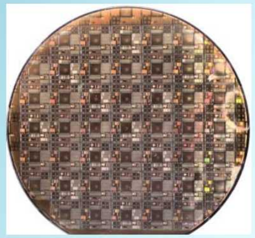
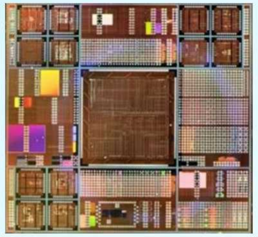


Image of MPW run, supporting Columbia, U of AZ, UC Berkeley, UCSD & Caltech

CMOS7

- **Multiple Engagement Models**
  - Full design & implementation by customer
  - Full design & implementation by Sandia
  - Anywhere in between
- **Non-Standard, custom processes**
  - AlN for resonators
  - Large-area graphene deposition
  - Deep trench capacitors
  - Prototype non-volatile memory
  - Thick metal
  - RF devices





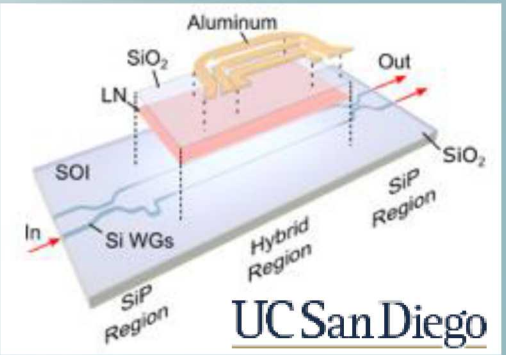
For more information:
photonics@sandia.gov

MPW & CMOS Design Contact:

Ann Petersen, Manager
Advanced CMOS Products/Design
505-844-3160
annpete@sandia.gov

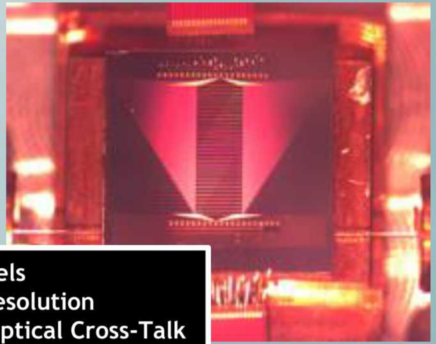
RF PHOTONIC SIGNAL PROCESSING

Optics Express 26 (18), 23728-23739, July 2018

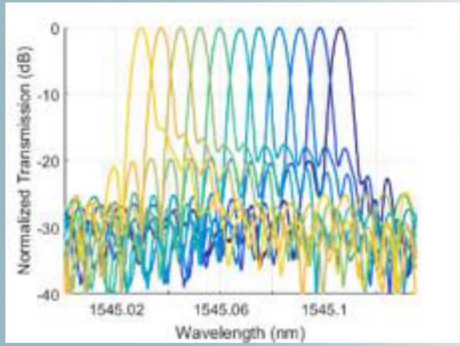


Lithium Niobate on Silicon
100+GHz Bandwidth demonstrated

Optics Express 25 (6), 6320-6334, Mar. 2017



11 Channels
<1 GHz Resolution
<-15 dB Optical Cross-Talk
1.1 cm^2 Total Area

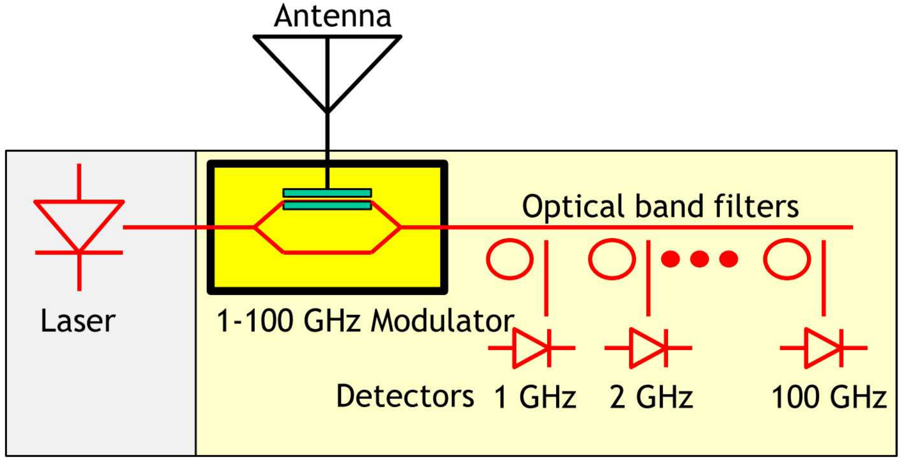


1st Demo of 1GHz RF Channelization in a Si Photonics Array Waveguide Grating

Photonic processing of RF signals provides significant reduction in SWAP-C for high frequency applications (>40 GHz)

Applications in space and avionic platforms for electronic warfare and situational awareness

- Frequency up/down-conversion
- Antenna remoting
- RF over fiber
- Wide-band channelization
- Low loss RF delay lines



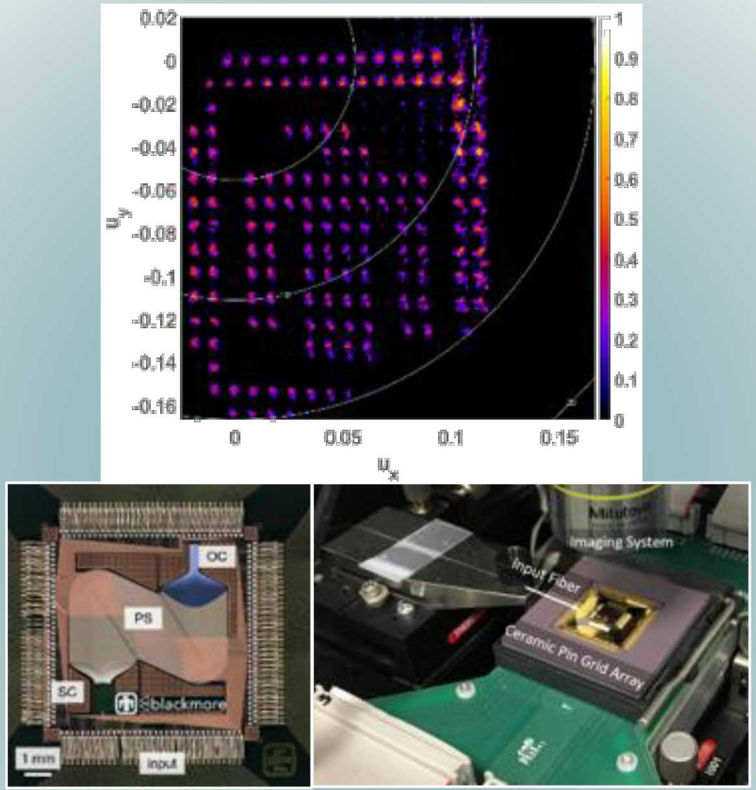
Example integrated wide-band channelizer

CHIP-SCALE OPTICAL BEAM STEERING

blackmore

2D Silicon Photonic Optical Beam Scanner

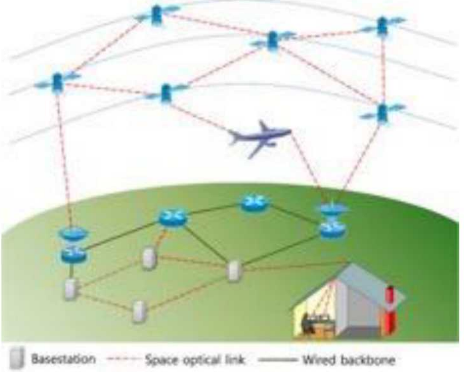
- Electronic (low-power EO phase shifter) and wavelength steering
- field of view: $24^\circ \times 10^\circ$; divergence angle: $0.3^\circ \times 0.3^\circ$
- 256 independent channels with 3-μm pitch
- Area: 750m x 750μm with high fill factor



Phase Optimization of Si Photonics
2D Electro-optic Phased Array
(CLEO 2019 JTh2A.39)

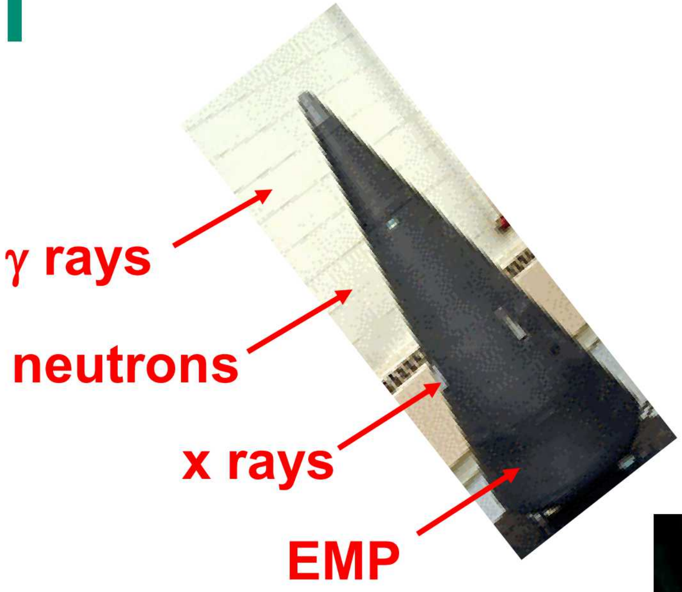
Applications

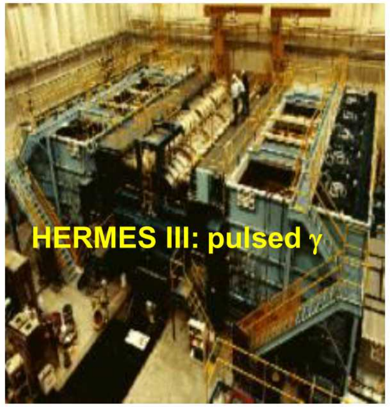
- Imaging and sensing
- Free-space communication

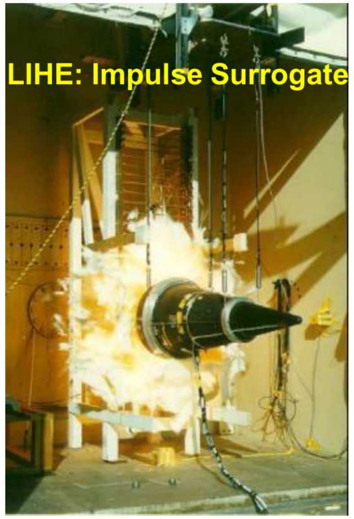


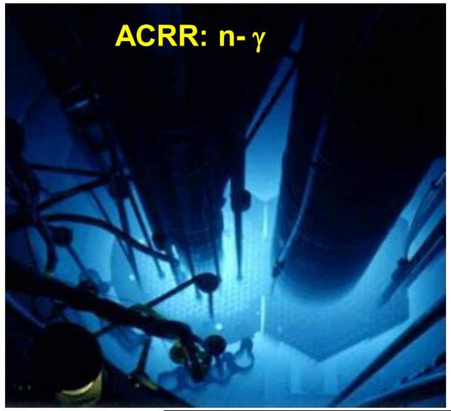
Digital Communications and Networks, 3(2), pp. 67-77, May 2017

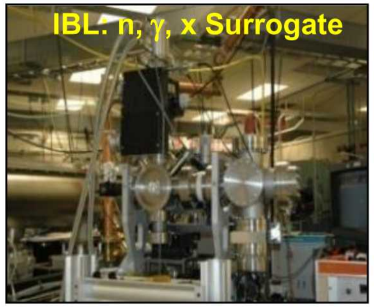
SANDIA RADIATION TEST FACILITIES



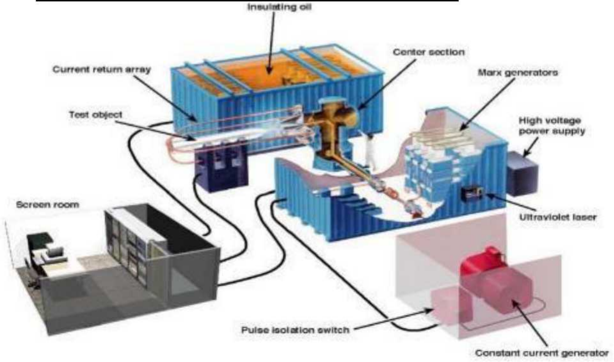








LIGHTNING: 1.6 MV, 200 kA



EMES: EMP (1 ns) ≤250 kV/m