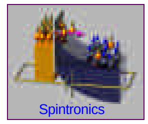
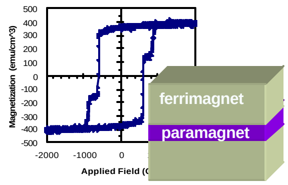
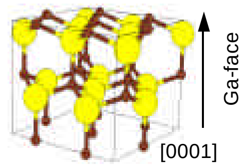


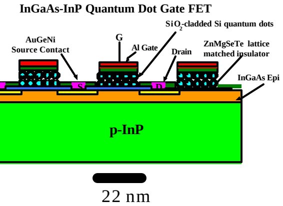




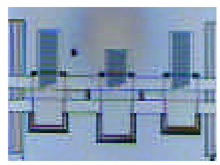
Gallium Nitride

Navy 6.1 Electronics Program

InGaAs-InP Quantum Dot Gate FET



SCE Filter

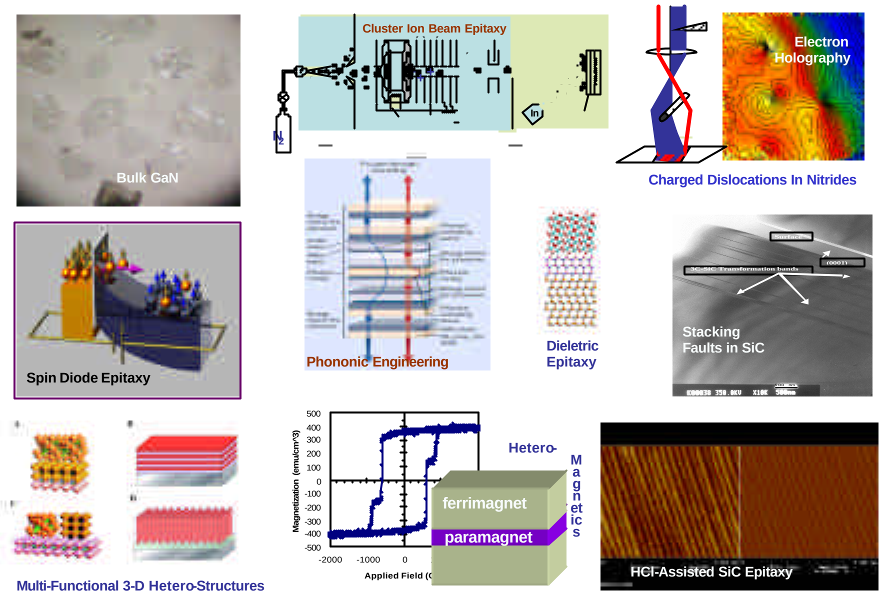


Navy 6.1 Electronics Program

- **Broad Based Program of scientific inquiry**
  - **Navy relevant research**
  - **Strong participation in research communities important to future naval applications**
  - **Harvesting and advancing research results from all sources in areas of potential naval payoff**
- **Electronics 6.1 Programs**
  - **Electronic Devices Materials**
  - **Nanometer Scale Electronic Devices and Sensors**
  - **Wide Bandgap Devices**
  - **Superconducting Electronics**
  - **Signal Processing Devices and Circuits**

Electronic Device Materials (EDM)

Colin Wood



Major Challenges of ONR's EDM Program

All devices:

- utilize specific material properties
- are made less effective by crystal defects, impurities etc.

Program seeks to understand, & invent techniques to:

1 minimize dislocations in nitride semiconductor devices

2 avoid stacking faults in silicon carbide

3 improve thermal dissipation in high-power RF and electrical devices

4 develop multifunctional materials

5 Invent structures and applications of monolithic MFM structures

Research Approach of EDM focus

Develop techniques for growth of :

Native (bulk crystal) nitride substrates.

Lower crystal-defect density nitride & SiC device films

Monolithic Multi-Functional Materials (MMFM) and Monolithic Hetero-Functional (MHFM) Materials structures and designer devices

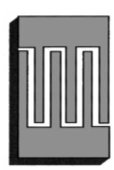
Conformal monolithic diamond/SiC and diamond/nitride thermal management films

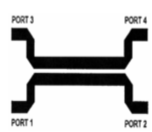
---

FERMI Project: **F**ield-tunable-**E**lectro-magnetic **R**F **M**aterials **I**nitiative

Monolithic Tunable Passives on mm wave & m-wave ICs

- **Capacitors**
- **Delay lines**
- **Inductors**
- **Filters**
- **Circulators**
- **Isolators**
- **Switches**





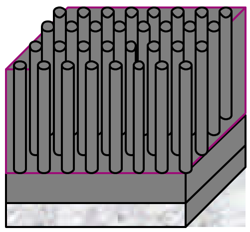
Stripline

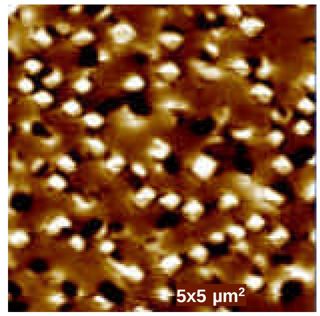
Srinivasan – Oakland U

Di

2-D Magneto-Electric Functionality (Spinel - Perovskite)

Ferro-electric nano-pillars / Ferri-magnetic film





MFM after electrical poling @ 12V

Ferro-electric - *$(Pb,Zr)TiO_3$*

Ferri-magnetic - *$(La,Sr)_3Mn_2O_7$*

Ramesh - Berkeley

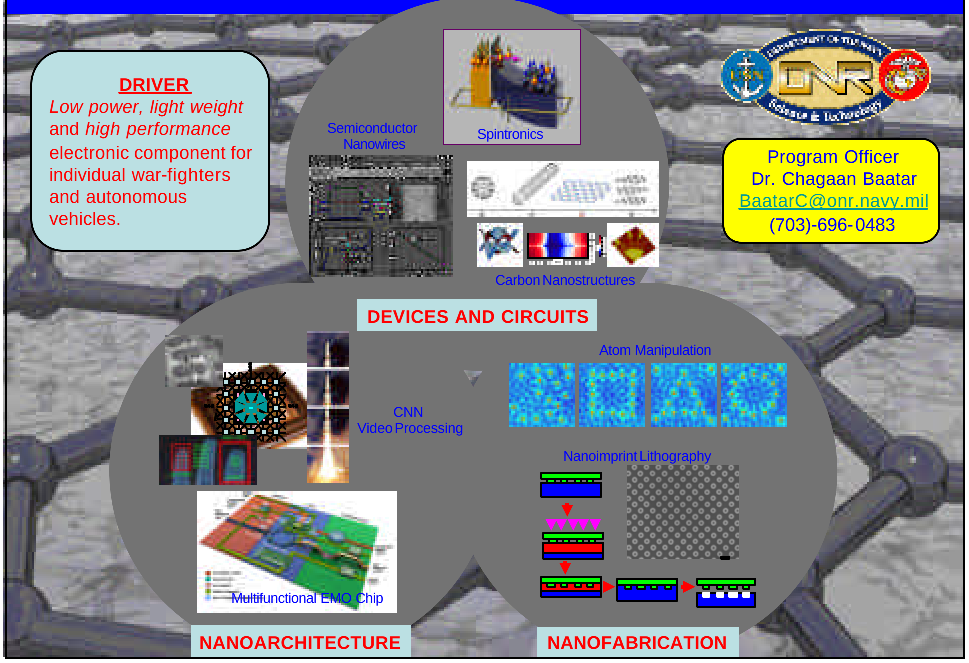
Track Record of Successes - (EDM)

- Materials developed for successful GaN RF Amplifiers, Blue LEDs, Lasers etc.
- SiC developed for solid state hi-voltage diodes, & high power RF base stations
- Diamond heat spreaders exploited in thermally challenged platforms
- Low loss Dielectrics
- Electro-statically modulated magnetism
- Tunable dielectrics & RF passive components
- Magnet-free, & tunable monolithic RF isolators, circulators, inductors, resonators, delay lines……

Synopsis of EDM Programs

- **Tackling shortcomings of advanced devices w/ basic materials science.**
  - **Dislocations in nitrides by Bulk GaN Growth**
  - **Stacking faults in SiC**
- **Improved growth for solid-state power devices**
  - **Halogen assisted SiC film and bulk crystal growth**
  - **Thermal management**
- **Pioneering Multi-Functional Materials, hetero-structures, device/system application**
  - **Tunable RF passives**
  - **Acoustic transistors**
  - **Electro-static magnetism control**
  - **etc. etc.**
- **Future advanced device and application concepts**
  - **Spintronics,**
  - **Phonon Engineering,**
  - **Thermal management etc., etc.**

Nanometer Scale Electronic Devices and Sensors



Major Challenges

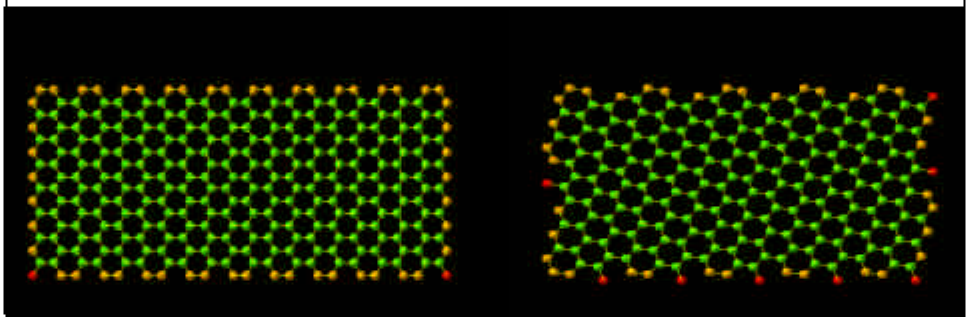
With the end of Moore's law in sight, we can no longer count on continued shrinking of transistor beyond 2015-2020. We face technical challenges at several levels:

- Device level: what is the fundamental building block of information processing BEYOND transistor?
- Architecture level: conventional von Neumann architecture may or may not be suited for the post-CMOS (complementary metal oxide semiconductor) era. What are the alternatives?
- Fabrication and manufacturing: need cost effective and reliable techniques and processes to assemble nano-scale devices into practical systems. Optical lithography will not work below 50nm.

Research Approach

- Exploit novel properties and functionalities of nanscale materials and structures
  - Electron spin manipulation
  - Low-D carbon (carbon nanotubes – CNT, and graphene)
  - Semiconductor nanowires
- Innovative architectural concepts and their practical implementations
  - Cellular Nonlinear Network (CNN) based intelligent vision system
  - Multi-functional electrical, magnetic an optical (EMO) chip
- Unconventional nanofabrication techniques
  - Nanoimprint
  - Maskless lithography
  - Atom assemble

Carbon in 1D & 2D: CNT vs Graphene



METAL

~1/3 of CNT's are metallic, with good electrical and thermal conductivity

SEMCONDUCTOR

~2/3 of CNT's are semiconducting, with bandgap inversely proportional to the diameter

Bandgap Engineering via Lithography

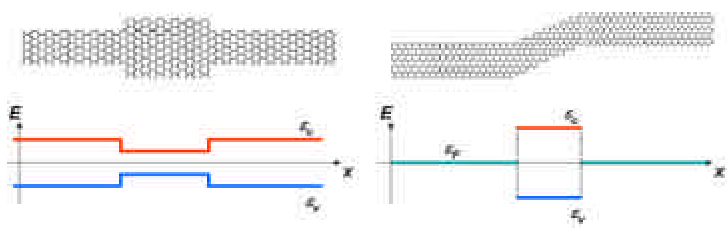
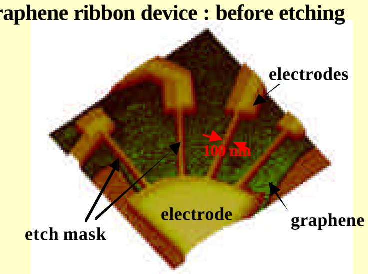
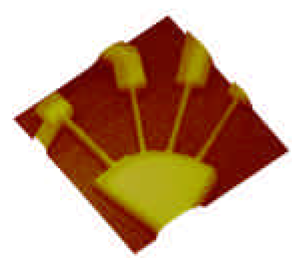


Fig 6. Examples of all graphene device with their band diagram





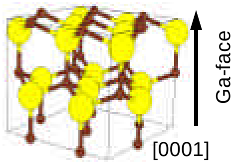
Philip Kim – Columbia Univ.

Success Record

- ONR's original investment and leadership in electron spin related research has led to an emerging new field of research, now known as spintronics.
  - ONR investment in spintronics research laid the ground work for the introduction of the first commercial magnetic random access memory (MRAM) product by Freescale in 2006.
- Cellular Nonlinear Network (CNN): ONR played a pivotal role from the invention of the mathematical concept, practical implementation using CMOS circuits, and identification of an application area that is of tremendous DoD value.
  - Ultra-fast image processing is essential for target tracking and recognition in missile defense, UAV navigation and rapid screening of biometric data sets, where conventional approaches are simply too expensive, too heavy and consumes too much power.
- ONR's early support for nanoimprint technology has led to the creation of two successful companies and is now viewed by semiconductor industry as a leading candidate for the next generation lithography technology.
  - Nanonex Corp., Princeton, NJ
  - Molecular Imprint Inc., Austin, TX

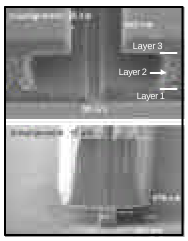
Summary

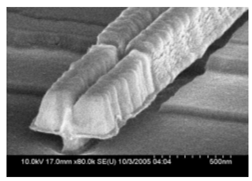
- As electronics enter the nano era, we face challenges at multiple fronts
- ONR nanoelectronics program strives to maintain a balanced portfolio to maximize future impact for naval applications
- Past ONR investment has led to significant advances in both scientific knowledge as well as industrial recognition
- Maintaining ONR leadership in nano science and technology research will be a key competitive advantage for the Navy in the 21st century

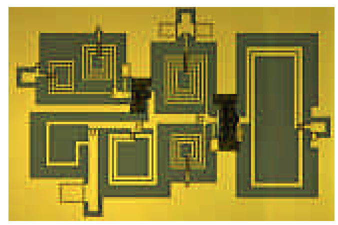


Gallium Nitride

Wide Bandgap Devices



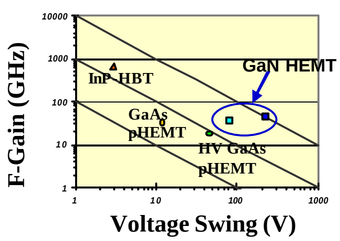


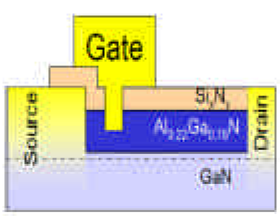


Dr. Paul A. Maki, Paul_Maki@ONR.NAVY.MIL

Wide Bandgap Device Challenges

Johnson's figure of merit for various III-V devices





- Develop materials and devices that fully realize the properties of Gallium Nitride
  - Johnson's figure of merit for GaN is 10X larger than other III-V materials (5X the power density of GaAs, with the potential for very high frequency performance)
  - Higher breakdown E-field of GaN and high power density will require robust device structures.
- New Approaches needed
  - Highly scaled device technologies
  - New dielectrics and passivations
  - Maximize device efficiency, minimize power dissipation
- Efficient amplifier strategies
  - Switched mode

Approach
Wide Bandgap Devices

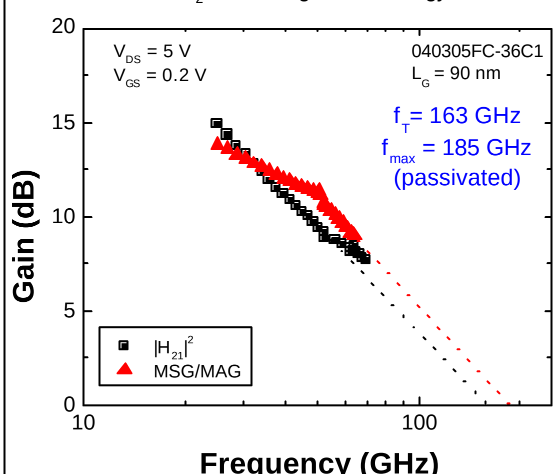
- Research on Gallium Nitride (GaN) Technology for solid state RF amplifier applications
  - Advancement of GaN High Frequency Transistors
    - Millimeter-Wave Initiative for Nitride Electronics MURI (UCSB, Mishra)
    - Processes and Device Technologies for AlGaN/GaN High Electron Mobility Transistors (U. of IL, Adesida)
    - New Technologies for mm- and sub-mm wave AlGaN/GaN HEMTs (MIT, Palacios)
  - GaN Device materials and process development
    - Fundamental Studies of GaN HFET Synthesis on SiC (Duke, A. Brown)
    - Basic Materials Studies in MBE-Grown III-Nitrides for Advanced Electronics (UCSB, Speck)
    - Investigations of Deep Level Defects in Next-Generation III-Nitride Materials for Electronics (Ohio State, Ringel)
    - Dielectrics for Improved Compound Semiconductor Device Performance (U. of FL, Abernathy)
  - GaN Device failure physics
    - Degradation Mechanisms of Wide Band Gap Devices (Skowronski, Carnegie-Mellon)
  - GaN Electron transport physics
    - Theory of Electron Transport at High Electric Fields in Nitride Structures (Ridley, U. of Essex)
    - Gallium Nitride Electron Devices for THz Oscillators (Eastman, Cornell)
- Investigate new device and materials research areas
  - Power switching devices
    - Optically triggered GaAs switched power device (Mazumder, U. of IL, Chicago)
    - GaN power switch (Mishra, UCSB)
  - Optical properties of materials
    - Studies of Nanoscale Deep-Centers for Large Dense Arrays of Fast Optical Emitters at 1.4-1.8um in GaAs for Multispectral Eye-Safe Infrared Applications (Yale, Pan)
- Collaborate with other agencies to evaluate and advance emerging applications
  - NSF program (1/3 ONR funded) on undersea optical communications (Muth, NC State, new start Sept. 06)
  - DARPA funded seedling effort on wafer-bonded heterogeneous device devices for efficient, high frequency electronics (included in ONR MINE MURI at UCSB)

GaN Device Physics Research

mm-Wave Initiative on Nitride Electronics (MINE) MURI

UCSB

SiO_2-sidewall gate technology



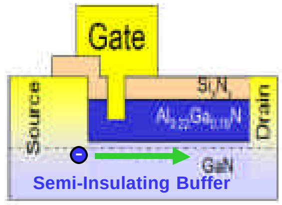
- **Oxide sidewalls after Gate recess lithography and etch**
- **Gate edge electric field tailoring**

Record f_T and f_{max} performance

- Gate length reduction to 90 nm
- Scalable to ~20 nm gates
- No gate leakage degradation

300 GHz GaN Transistors Likely → Power and Gain at 94 GHz

Deep Level Trap Reduction in GaN HEMT Buffers
Collaboration between Ringel, OSU and Speck, UCSB



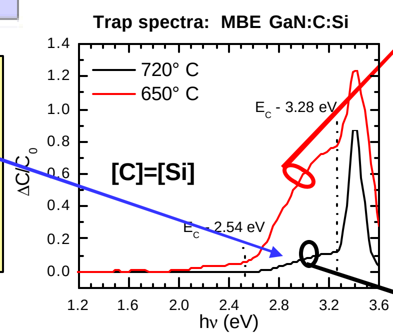
Goal: understand semi-insulating mechanism in MBE GaN material

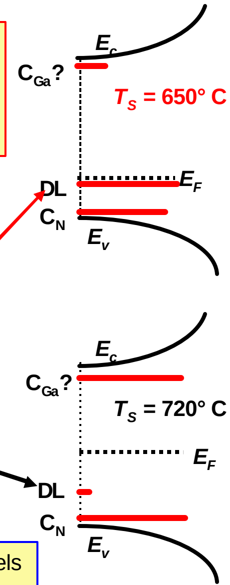
- Deep Levels in Semi-insulating (SI) Carbon-Doped GaN buffers
- Current Collapse in HEMT

Research Outcome: Higher resistivity, lower trap concentration GaN through optimized MBE growth

Deep Level Optical Spectroscopy shows DL concentrations 10X lower

10X lower Carbon needed, and results in higher resistivity buffer





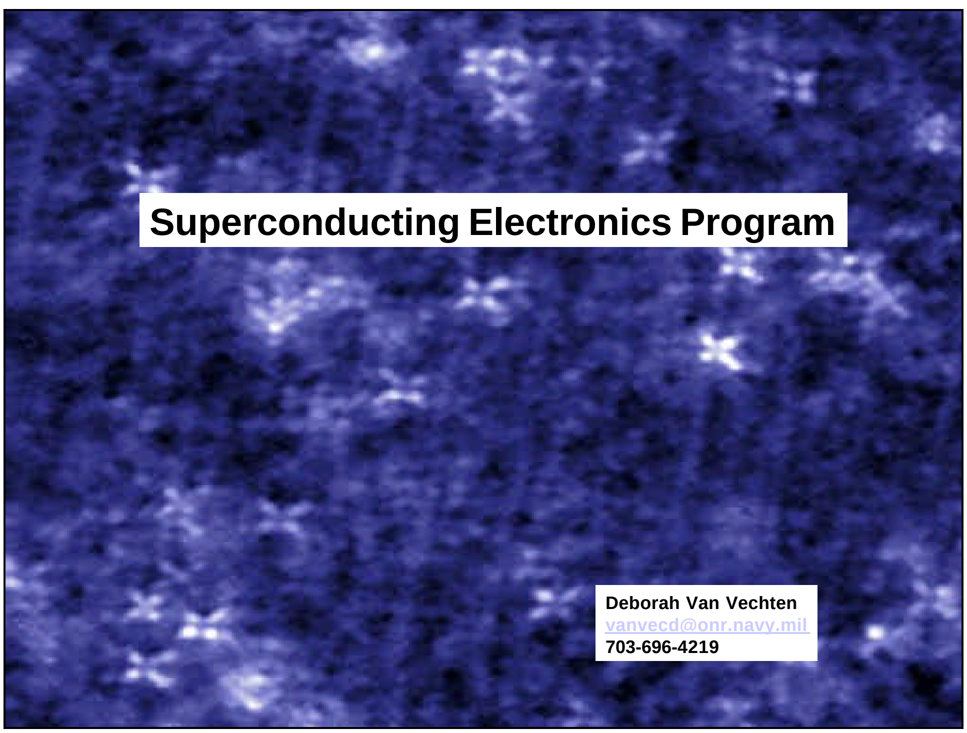
Higher growth temperature → ~10X Less Carbon and Deep Levels
GaN HEMT Device impact → Better SI buffer, no current collapse

WBG Success Record

- Highest Frequency GaN transistors demonstrated (MINE MURI)
  - Result sets benchmark for electron velocity
  - Focuses research efforts on critical device parameters
- Significant impacts: 6.1 innovations into 6.2 efforts
  - Back barrier structures such as InGaN picked up in DARPA WBG-RF
  - Fluorine treatment effects recognized in Gate recess processes
  - Ion-implanted contacts and source access regions
  - Deeply recessed HEMT's

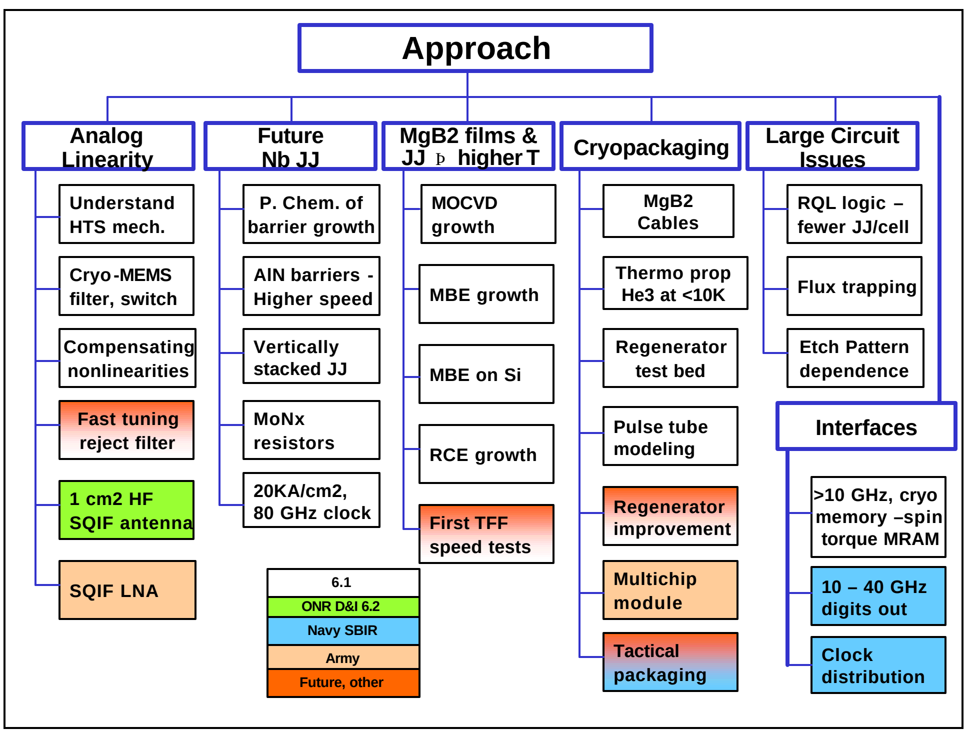
Summary

- High Frequency Wide Bandgap transistors
  - Improve device materials through detailed studies of device structures
    - Electron transport in small geometries
    - Electric Field concentration effects, power density
    - Defect generation, measurement and characterization



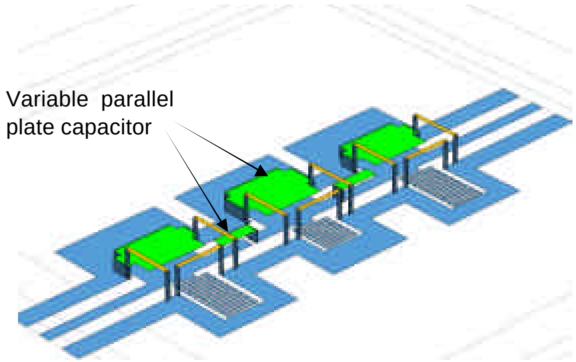
Challenges

- Wide band, RF reception in dense signal environments (6.2 goal) requires filters with extremely linear response. Early YBCO (HTS) filters displayed substantial intermodulation distortion. Why? Is it possible to develop work- arounds?
- Second generation systems, will need tunnel barriers of improved devices to be thinner (<1nm), yet more homogeneous, for greater speed and higher operating temperatures.
- 4K cryopackaging in infancy --- poor energy efficiency (low % of Carnot) results. Basic materials science and thermal engineering research needed to remedy.
- Ultra-low power of SCE technology creates circuit issues at interfaces to other technologies – need to generate patches or alternatives
- Larger circuits reveal underlying physics issues



Integrable Nb, MEMS Tunable, Notch Filter

Made on Same Wafer as Digital Devices
Q>10,000 expected



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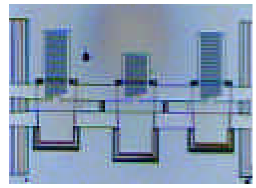
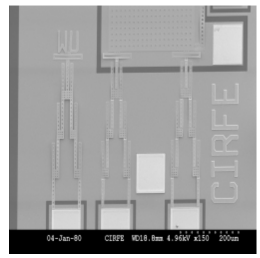




High Tuning Range Variable Capacitor

Demonstrated Record Resonator size:

$\lambda_o/390$

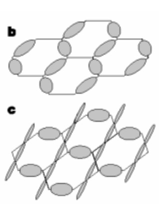
University of Waterloo

MgB_2 **Josephson Junction Development**

Transition temperature = 4X Nb: Usable as faster, warmer digital device?

- Covalent bonding produces disjoint pair populations
- Tunneling occurs between allowed states of pairs, same or different populations
- Want to have only $\sigma\sigma$ tunneling, get mostly $\pi\pi$ today

s States



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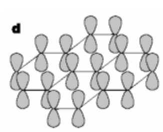
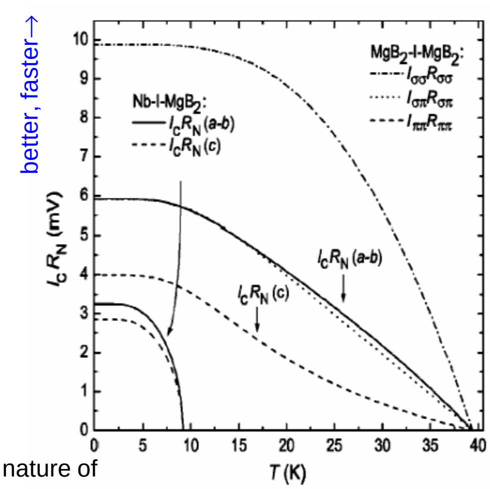




theoretical predictions

Current focus of efforts: Exact chemical nature of surface species as a function of deposition details, especially native oxides and start of counter-electrode

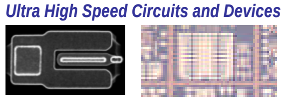
Success Record

- Determined that moderate intermodulation distortion in YBCO (HTS) is inherent property of D wave superconductors; lower in S-wave (Nb and MgB_2).
- Began eliminating proposed HTS mechanisms by developing measurement techniques that reveal local value of exchange energy (boson) responsible for HTS pairing; identified candidate responsible phonon modes.
- Identified candidate noise mechanisms in Nb qubits
- Demonstrated first 100 JJ logic cells using 20 kA/cm^2 JJ
- Demonstrated feasibility of 10 W cw, <ns turn on power limiter, linear DC to 40 GHz, with <0.1 dB insertion loss
- Developed 4 MgB_2 thin film deposition techniques
- Built worlds-first regenerator test bed for T<10K.

Summary

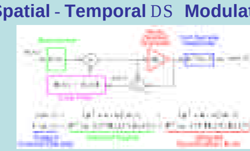
- Superconducting electronics identified by ITRS as lowest technical risk technology to replace Si. But needs maturation and early experience in low complexity, high performance, fielded systems to reveal real worth.
- Wide band, many simultaneous signal receivers a DoD relevant example. (TRL 6 achieved March 2007.)
- Nb JJ is where 6.2 engineering focus is feasible – requires working
  - Improved tunnel barriers for higher speed devices
  - 4K cryo-packaging energy efficiency issues
- YBCO useful for some analog functions. Mechanism beginning to be fully understood
- MgB_2 still hopeful for digital applications but 2 gaps complicates physics of Josephson tunnel junctions
- Richness of physics complicated engineering with superconductors.

Ultra High Speed Circuits and Devices

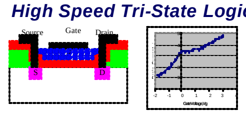


Analog and Digital Conversion

Spatial - Temporal DS Modulator



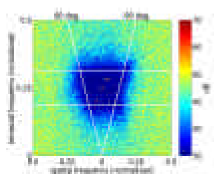
High Speed Tri-State Logic



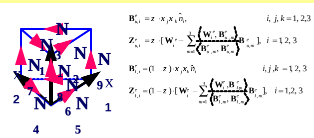
Signal Processing Circuits and Architectures

Dr. Dan Purdy

Spatial Noise Shaping:



Precision 3D Mixed Signal and Nonlinear Circuit Modeling



Major Challenges

Signal Processing devices, circuits and architectures

The ability to possess information and fully utilize the electromagnetic spectrum are fundamentally dependent on the agility needed to adapt to the analog world via digital control. This agility requires an interface between analog and digital consisting of mixed signal circuits. Challenges in analog-to-digital conversion (ADC), and digital to analog conversion (DAC) are:

- Greater bandwidth, resolution and dynamic range are needed
- Device parasitics and circuit level interactions degrade performance
- More digital bits require greater scale of integration and complexity
- Digital “quantization” noise and a related noise artifacts
- Faster devices are needed (eventual goal of millimeter wave conversion)

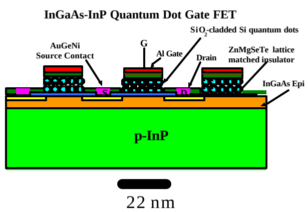
Research Approach

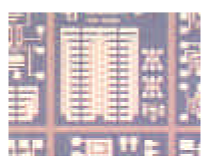
Signal Processing devices, circuits and architectures

- Suppression of noise and provide increased bandwidth, high spectral purity in efficient, digital transmit arrays
  - Joint Spatial-temporal Noise shaping in sigma delta arrays to improve bandwidth and dynamic range
- Explore novel array based analog and digital conversion architec tures
- Increase bandwidth and resolution of ADCs, DACs
  - Reduce feedback latency using optical circuit architectures in ADCs
- Improve device performance, yield and scale of integration with sufficient number of devices (> 10k) for practical, affordable use
  - < 10 ps access non-volatile RAM compatible with monolithic InP processes
  - Reduce contact resistance to improve speed of devices will enable a 1+ THz HBT at room temperature
- Investigation of clock-less (asynchronous) circuits and architectures that mitigate fundamental ADC problems of aperture jitter thus enabling greater bandwidth and dynamic range

UConn Proprietary

Ultra-fast InGaAs-InP Devices and Nonvolatile Memory for mixed signal Circuits





QD-gate InGaAs Devices

Objectives:

- *Ultra high speed devices and high density Nonvolatile Memory* which can be monolithically integrated into high performance InP analog-digital converters (ADC's and DAC's)

Approach:

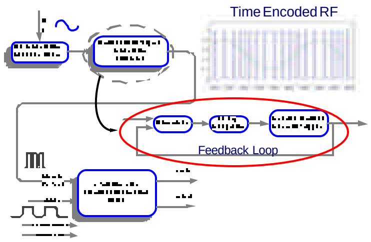
- Investigate Quantum-Dot-gate InGaAs / InP tri-state devices (ONR Emphasis is speed)
- High density (sub-22 nm gate) flash memory with fast access time in <50 ps to support 200+ GHz logic cycles and f_T>500 GHz.
- Leverages work funded under both ONR (N00014-06-1-0016) and NSF (ECS 0622068)

Prof. Frank Jain, Univ. Conn.

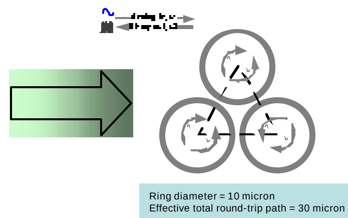
UConn Proprietary

Novel devices and circuits for Analog and Digital Conversion

Proposed Optical ADC Architecture



Optical ΔΣ Time Encoder

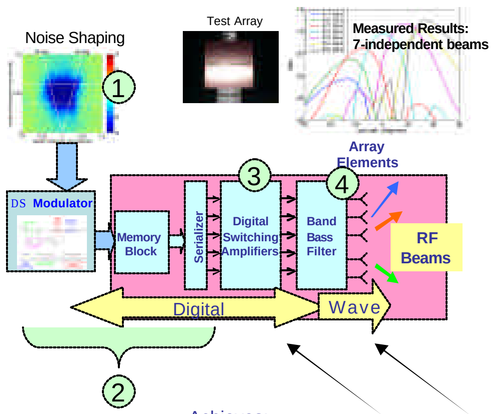


Objective: Investigate novel optical time encoder circuits that generate THz rate binary sequences

Approach:
- Novel ΣΔ architecture implemented with optical devices performs time encoding of analog signals
- Reduce latency using optical resonator (feedback for ΣΔ) < 1 picosecond
- Architectural approach suitable for monolithic integrated ADC circuits
- Clock-less architecture mitigates aperture jitter limitations

Potential Payoff: THz oversampling rate ΣΔ modulators will enable analog-to-digital conversion at millimeter wave frequencies.

Spatial-Temporal ΣΔ Array Aperture Converts Digital to RF Wave



Basic research areas:

1. ***Noise shaping*** to improve dynamic range (NRL)
2. Joint space-time sampling algorithms (Sparse Nyquist, U. OK, NRL)
3. New amplifier classes optimal for digital operation (U. CO)
4. Improve reactive filter and broad element match in situ (U. CO)

Achieves:
- Direct conversion of ***digital to RF Waves***
- Multiple simultaneous beams

Novel approach to digital beamforming that best utilizes high efficiency digital amplifiers

Key Accomplishments

Signal Processing devices, circuits and architectures

- Showed it is possible to spatially shape quantization noise into non-propagating regions thus allowing faster DACs with greater bandwidth and dynamic range.
- Bench top demo of a Novel Optical time encoding circuit architecture
- Development of basic fundamental groundwork for of millimeter wave conversion
- Invention of a novel quantum dot tri-state devices that supports faster ADCs and DACs

Summary

Signal Processing devices, circuits and architectures

- Current research efforts are exploring novel signal processing based architectures that perform analog and digital conversion.
- Key challenges are bandwidth, dynamic range, and frequency
- Discoveries in low contact resistance processes will enable a room temperature HBT that operates at 1+ THz and supports 400 GHz clock circuits.
- A possible pathway to analog and digital conversion at mmWave frequencies is being investigated
- ONR's has a proven track record of world class D&I 6.1 research with clearly measurable impact

6.1 Electronics Program Summary

- Navy 6.1 Electronics Program focused on key science opportunities with high Naval payoff
- Program has significant scientific accomplishments
- Coupling to 6.2 an integral part of program