Air Force Basic Research in Solid State Sciences

19 Apr 07

Dr. Patrick Carrick
Director, Physics and Electronics
Air Force Office of Scientific Research
Air Force Research Laboratory

Outline

- **Mission and Vision – AFRL**
- **Organization and Budget**
- World Strategic Environment
- Program–The Warfighter and AFRL Initiatives
- Solid State S&T Issues
- Current Investments in Solid State Arena
- Future of Electronics & Computational Physics

Our Mission and Vision

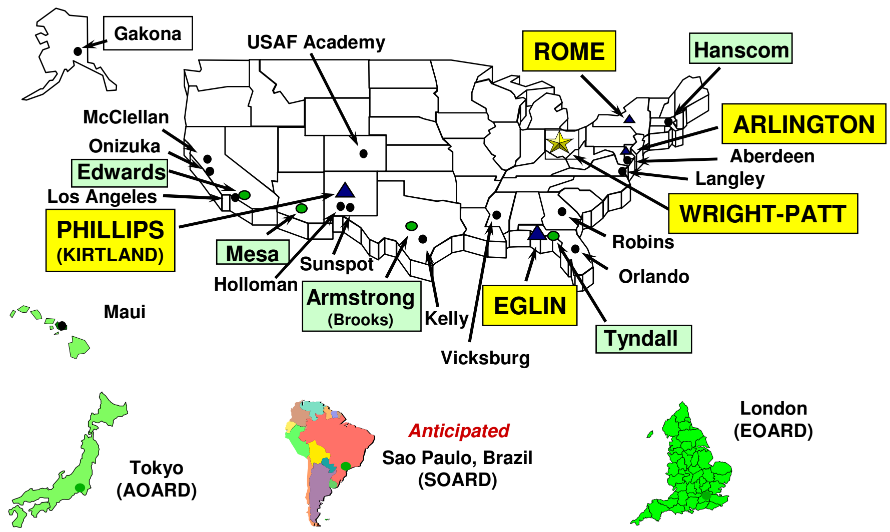
AIR FORCE RESEARCH LABORATORY MISSION

Leading the discovery, development, & integration of affordable warfighting technologies for our air, space and cyberspace forces

AIR FORCE RESEARCH LABORATORY VISION

We defend America by unleashing the power of innovative aerospace technology

AFRL Research Sites (World-wide)



AFOSR Organization Chart

DIRECTOR
Dr. Brendan Godfrey

CHIEF SCIENTIST
Dr. Thomas W. Hussey

DEPUTY DIRECTOR
Col. Michael Hatfield

SENIOR RESERVIST
Lt. Col. Joe Fraundorfer

PHYSICS AND ELECTRONICS
Dr. Patrick Carrick

AEROSPACE & MATERIAL SCIENCES
Dr. Thomas Russell

MATHEMATICS, INFORMATION & LIFE SCIENCES
Dr. Genevieve Haddad

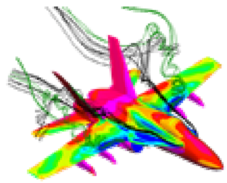
INTERNATIONAL OFFICE
Dr. Mark Maurice

ASIAN OFFICE OF AEROSPACE R&D (AOARD)
Dr. Ken Goretta

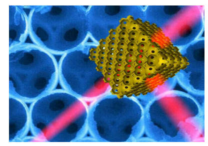
EUROPEAN OFFICE OF AEROSPACE R&D (EOARD)
Col. Stephen Pluntze

AFOSR Basic Research Areas

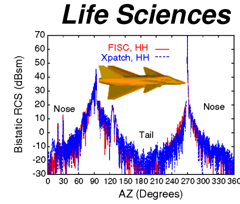
Aerospace & Materials Sciences



Physics & Electronics



Mathematics, Information & Life Sciences



Sub-thrusts

- Structural Mechanics
- Materials
- Chemistry
- Fluid Mechanics
- Propulsion

- Physics
- Electronics
- Space Sciences
- Applied Math

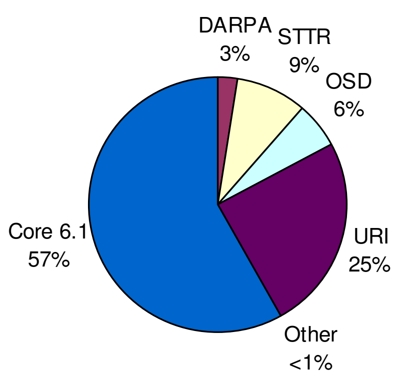
- Info Sciences
- Human Cognition
- Mathematics
- Bio Sciences

Areas of Enhanced Emphasis

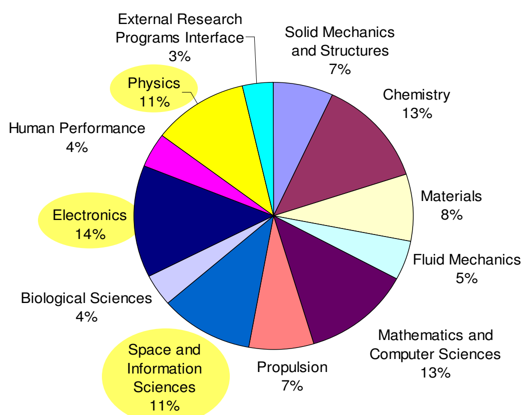
- Information Sciences
- Mixed-Initiative Decision Making
- Adversarial Behavior Modeling
- Novel Energy Technology
- Micro Air Vehicles
- Nanotechnology

AFOSR Budget

	FY2004PB	FY2005PB	FY2006PB	FY2007PB
PE61102F Core	$205M	$217M	$224M	$250M
PE61103F URI	$105M	$116M	$105M	$108M



FY06 Total Budget Authority: $425.5M



Total: $250M

AFOSR Leadership Roles

- Foster Revolutionary Basic Research for Air Force Needs
  - 852 extramural research grants at 215 universities
  - 215 intramural research projects at AF laboratories
  - 133 STTR small business - university contracts
- Build Relationships with Leading Researchers – Here and Abroad
  - 79 Summer Faculty; 40 Postdocs at AFRL
  - 264 Short-Term Foreign Visitors; 37 Personnel Exchanges
  - 58 technical workshops; 205 conferences sponsored
  - Liaison Offices in Europe and Asia
- Educate Tomorrow's Scientists and Engineers
  - About 2000 post-docs and grad students on research grants
  - 430 National Defense Science & Engineering Fellowships

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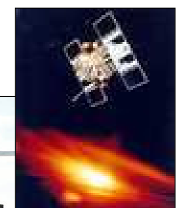
Strategic Environment

Global US Interests
Political - Economic - Humanitarian

Globalization of Technology
Production – Trade - Investment

Asymmetric Threats
In any domain - Air, Land, Sea, Space or Information



Focus on Warfighter's Needs

Basic Research ⟷ **Future Warfighter**

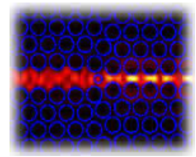
Air Force
Overarching Objectives

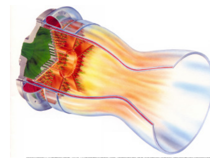
- Aerospace superiority
- Information superiority
- Rapid global mobility
- Agile combat support
- Precision engagement
- Global attack

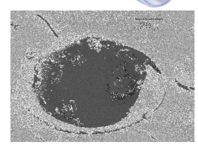
- **FLTCs (Focused Long Term Challenges)**
  - Describe AFRL investment in terms of capability
- **DCTs (Discovery Challenge Thrusts)**
  - Identify and support portions of problems captured within FLTCs whose solution clearly depends on new basic research
  - AFOSR responsibility
- **STTs (Strategic Technology Thrusts)**
  - Identify and support technology areas that cut across multiple technical directorates (TD) that may not be adequately supported by any single TD
  - AFOSR plays a leading role

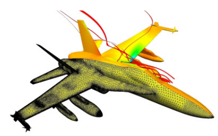
Discovery Challenge Thrusts (DCT)

- Systems and Networks
- Integrated Sensors, Algorithmic Processors & Interpreters (I-ATR)
- Radiant Energy Delivery and Materials Interactions
- Thermal Transport Phenomena and Scaling Laws
- Super-Configurable Multifunctional Structures
- Robust Decision Making
- Self-Reconfigurable Electronic/Photonic Materials & Devices
- Socio-Cultural Prediction
- Turbulence Control & Implications
- Space Situational Awareness
- Devices, Components, and Systems Prognosis









Physics and Electronics

Technologies	Capability & Payoff
Semiconductor Materials	Real-time adaptive signal & image processing
Optoelectronic Information Processing	Expanded transmission bandwidth
Nanotechnology - Micro Propulsion - Miniaturized Sensors	Reduce Weight 1/3, Increase Capabilities 3X
Space Electronics, Sensors & Propulsion	1000Xs improvement in data storage
Atomic & Molecular Physics	Processing speeds orders of magnitude faster than today
Lasers & Optical Physics	Recovery of images through atmospheric turbulence
Plasma Physics	Greater radiation tolerance
High Power Microwaves	Electronic Warfare & Non-Lethal Effects - New Capability

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Solid State S&T Issues

- Improved reliability (e.g. during energy fluctuations)
- Higher efficiencies (e.g. over 50% efficiency for space-solar cells)
- Thermal management (e.g. heat dissipation in high power devices)
- Durable device operation in extreme environments (i.e. space, dessert)
- Reconfigurable & tunable devices (i.e. lasers, microwaves)
- Data mining, information & design analysis (i.e. 3D modeling, trends)
- Protection–radiation hardening of electronics
- Detection of small signals (e.g. digital signal processing)

Why Solid State? -- Compact, lightweight, low cost systems

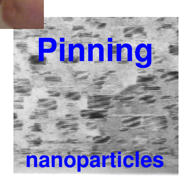
AFOSR FY06 Solid-State Basic Research Investment

236 projects, $60.6M total: (6.1 Core $29.0M; MURIs $10.5M; $21.1M other)

	# projects
Sensors	
➢ plasmonics	43
➢ UV, VIS, IR, THz	
➢ tunable-multi-spectral	
➢ photonic crystals	
EM Radiation Sources	38
➢ THz	
➢ semiconductor lasers	
➢ non-linear crystals	
➢ high-power microwave matl's	
Data & Info Processing	51
➢ nanophotonic materials/devices	
➢ optical logic & processing networks	
➢ 2-D & 3-D negative index PhC lens	
➢ reconfigurable electronics	
➢ novel imaging techniques	
➢ radiation & reliability physics	
High-Density Memory	17
➢ non-volatile phase change	
➢ multi-state analog	
➢ holographic memory	
➢ magnetic storage	
Communications	68
➢ superconducting-based devices	
➢ wide-bandgap matl's/devices for RF	
➢ quantum cryptography	
➢ negative index materials	
Univ NanoSatellite Prog	12
➢ compact & efficient electronics technology & space flight demo	
Compact Efficient Power	8
➢ superconductors	
➢ multi-junction photovoltaics	
➢ novel thermal control	

Quantum Electronic Solids Superconductivity, Nanoelectronics

- **Superconductivity**
  - Coated Conducting Tapes (YBCO)
  - Microwave Properties of Films
  - YBCO Josephson Junction Circuitry
  - Quantum cryptography
- **Nanoelectronics**
  - Super-dense, non-volatile memory
  - Circuit and memory concepts using spin-polarized electrons
  - **Carbon nanotubes:** detect biological and chemical agents; GHz and THz sources/sensors
  - **Multifunctional nanosensors:** e-m signals, chemical and biological agents; transmit information to remote receivers



AF systems that are more efficient, smarter, smaller, faster

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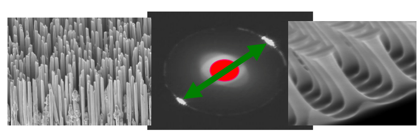
Future Air Force S&T Areas

Investment Changes

↑ GaN Growth and Characterization
↑ InN, AlN, Dilute & Magnetic Nitrides
↑ Zinc Oxide
→ Mid IR Lasers and Infrared Materials
→ Superconductive Materials
↑ Band-Gap Engineered Materials
→ 3D Epitaxy
↓ Strained Si/SiGe and SiC/SiGeC Hetrostructures
↑ Multifunctional Materials
↑ Quantum Dot-Based Device
↑ Multi-Modal Sensing Devices



Additional Research

- Spintronic Materials
- Superconductive Materials
- Engineered Band-Gap Materials
- Chalcogenides (eg. GeSbTe)
- Materials for UV Detectors
- QD Embedded Materials
- Multi-functional Materials (Oxides)
- Nano-electronics
- Develop Denser Logic & Memory
- Superconductivity Digital Elect
- Performance-Driven Sensing

Greatest Future 6.1 Challenges

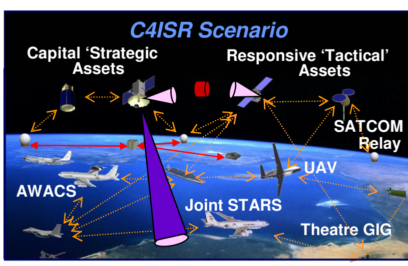
Target Mid-Far-Term C4ISR Needs: Sensing + Processing + Storage + Comm

C4ISR Electronics	*RF Radar & Comm*
Far Term Reqt's	• comm: 60-94GHz (V-W band) • radar: high-power → Ka-band • ultra-linear-wideband amp/circuits • constant- eff.-amplifier circuits • shared aperture concepts
Basic Research Vision	• monolithic multi-functional $\vec{E}$ & $\vec{B}$ matl's • novel solid-state thermal control • novel 2-D electron gas devices for high-speed (>60Hz) HPA applications • ultra-high-speed wide-bandgap bipolar technology for >90GHz HPAs • novel high-mobility wide-E_g matl's
Greatest 6.1 Challenges	• III-V material hetero-epitaxy • electrical/structural defect mitigation • novel thermal control concepts

BACKUP

Current Investment in Electronic Devices and Multi-modal Sensing

Envision, invest with the best, and innovate mid-far term electronic & photonic materials, devices & implementation schemes to enable 'quantum-leap-game-changing' capability breakthroughs for C4ISR



C4ISR Electronics Requirements

- **ISR: Radar:** ↑↑ RF power-amp f_{max} & PAE
  UV-IR Sensing: ↑ adaptable multi-modal & D*
  Electronics (ROICs): ↑ dyn range/speed, reconfig.
  (ICs): ↑ FPGA speed → Tflops, dense NV memory
- **Com:** ↑ data-rate & BW → 60GHz for secure comm!
  - ↑ RF power-amp F_T, PAE, ↓ noise-figure to ↑ BW
  - ↑ FPGA IC speed & ↑ software-reconfigurable
- **Reliable, Survivable, and 'Intelligent'**
  - Reconfigurable, responsive, & autonomous

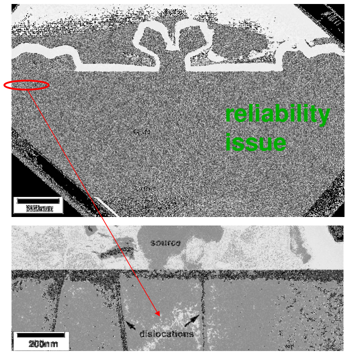
(Increased efficiency & reliability especially important for space)

6.1 Research Thrusts

- Integrated Adaptable Multi-Modal Sensors (EO thru RF)
- RF-Power Materials & Devices (radar & communications)
- Breakthrough-Speed Electronic Devices & Architectures
- Electronics Radiation Effects Physics

Attacking Basic Material Reliability Issues for Wide Bandgap Semiconductor Devices

PM: D. Silversmith AFOSR/NE, LAB POCs: J.D. Albrecht AFRL/SNDX, K. Averett AFRL/MLPSM



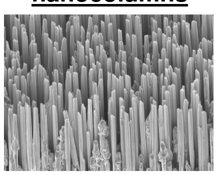
Problem: Strained GaN Templates Lead to Defects

- defects strongly limit available device area
- performance and lifetime limitations
- no native substrate solutions are feasible
- thermal management through templates is difficult

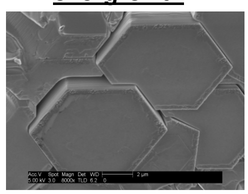
Approach: Low-Defect Overgrowth of Nanocolumns

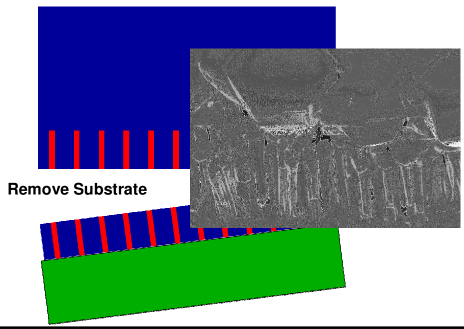
- Strain-free, crystalline nanocolumns serve as "perfect" seeds for high-quality template overgrowth
- Substrate removal for thermal control is possible

nanocolumns



overgrowth





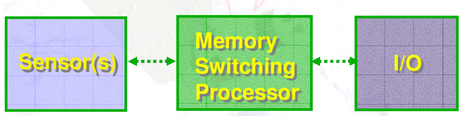
K. Averett, et al. J. Cryst. Growth **287**, 500 (2006)

Current Investment
Optoelectronic Information Processing

PM: Gernot S. Pomrenke

- Small platform advanced optoelectronic/photonic sensors, storage, and communications
- Electrical power consumption & dissipation of processing: greater speed (>10GHz), scaling, densities, bandwidth and interconnects.

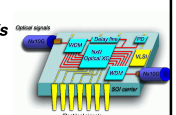
- Main focus is the use of nanotechnology approaches & inorganic material systems.



As on-aircraft bandwidth and EMI immunity and weight reduction requirements continue to escalate in the new world of Network Centric Warfare … develop and transition novel and cost effective photonics technology to AFRL

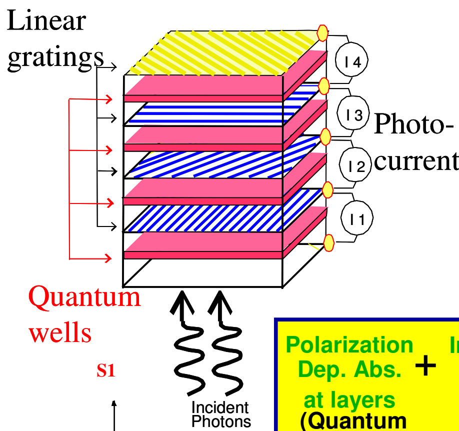
- Device oriented – includes materials & processing, characterization, device design & fabrication, architecture, and tools, simulation and modeling

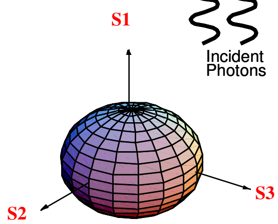
Terabits/s



Polarimeter-in-a-Pixel

(PI: Sanjay Krishna, UNMCollaborator: Dave Cardimona, AFRL)





- **Detects**
  - **All 4 polarization parameter**
  - **Single physical pixel**
  - **Single camera frame**
  - **Single wavelength** $\Delta\lambda < 0.02\ \mu m$
- **Principle of operation:**

Polarization Dep. Abs. at layers (Quantum Wells)	+	Interference b/w many diffracted light paths	+	TE & TM mixing (gratings at diff angles)	=	Fully polarization dependent readouts

Poincaré Sphere $S_0^2 = S_1^2 + S_2^2 + S_3^2$

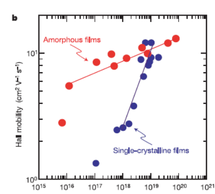
- **Stokes Vectors fully describe Polarization**

NEW Transparent Conductors & Electronics: AFRL/SN

Objective: Exploit the unique electronic and optical properties of nanocrystalline wide bandgap oxide ZnO:Al thin-films for applications in transparent semiconductor conductors for varied device applications

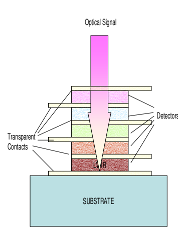
Approach:

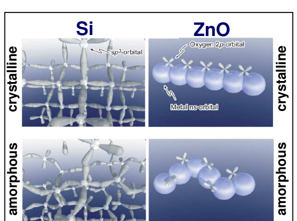
- *Task 1: Develop optically transparent and electrically conductive ZnO-based thin films using RF sputtering and Laser Pulse Deposition techniques. Optimize layer properties through modeling and experimental verification.*
- *Task 2: Investigate low resistance ohmic contact formation mechanism for ZnO layers on semiconductor UV detectors.*
- *Task 3: Investigate the possibility of using transparent films for interconnecting non-planar device structures.*



Most semiconductors can only operate in single crystal form
- *When the lattice order is disturbed, electrical bonds are broken.*

Some heavy metal oxide semi-conductors have large e- orbitals.
- *Nanocrystalline films retain single crystal electrical properties.*
- *Many are transparent in IR-vis-UV wavelengths*

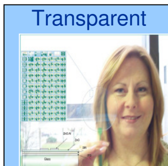




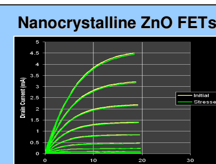
How It Works

Recent Results

Transparent



Nanocrystalline ZnO FETs



- Demonstrated high current density operation of nanocrystalline TTFTs
- Obtained > 6W/mm power operation
- Demonstrated solar-blind detector operation

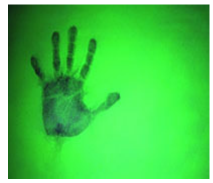
Luminescent Polymers for Explosive Sensing

MURI - Integrated Nanosensors PI - Ivan K. Schuller - UCSD, AFRL

Objectives:

1. Synthesize inexpensive polysilole luminescent polymers for trace explosives detection.
2. Characterize photophysics of electron transfer quenching process and excited state properties.
3. Adapt for distributed sensing, as well as for vapor detection and sensing in aqueous solution

Visualization Trace (nanogram) Explosives.



•Left 'handprint' had trace amounts of TNT and is dark after application of polymer.
•Right control 'handprint' shows no explosive residue

•Left vial contains nanoparticles of luminescent polymer.
•Right vials show visible quenching in the presence of trace levels of TNT

Potential Benefits to Air Force:

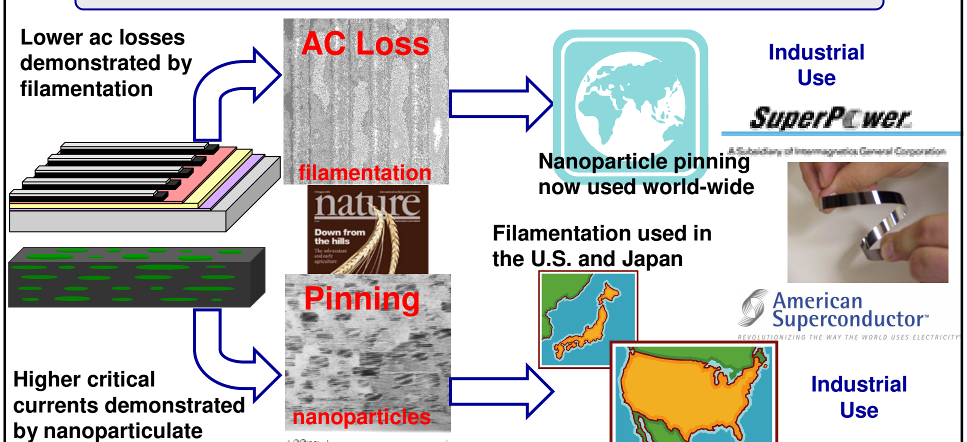
1. Personnel screening to identify bombers before they act
2. Visualize and identify trace explosive contaminants (TNT, RDX, HMX, and EGDN)
3. UV emitting polymers allow covert screening
4. Aqueous sensing relevant to contamination at munitions sites

Results:

1. Detected TNT, RDX, HMX, and EGDN at 2-10 nanogram levels.
2. Licensed patents to RedXdefense, who are constructing a prototype fieldable instrument for suicide bomber screening tests in Iraq.
3. Synthesized a range of emissive polymers for detection from 360 nm to 520 nm and nanosized for aqueous solution sensing.
4. Characterized the photophysics

Transitions for YBCO Coated Conductor Enhancements

Goal: Improve the conductor's critical current and lower ac losses

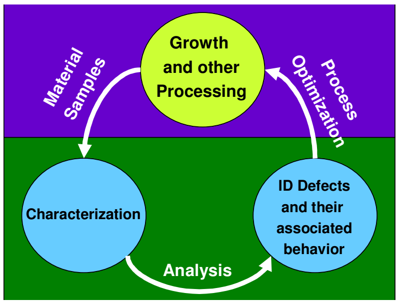


Payoff to Air Force
• Compact, lightweight power systems for directed energy applications
• Gyrotron magnets for active denial technology

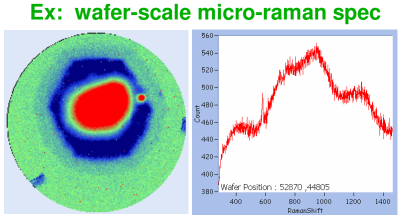
Dr. Paul Barnes, Air Force Research Laboratory

Addressing Reliability in Electronic Materials

PM: D. Silversmith AFOSR/NE, LAB POC:D. Dorsey AFRL/MLPSM



Ex: wafer-scale micro-raman spec



Representative reliability problem in emerging electronic materials:

- Electrical isolation of GaN-based devices (parasitic buffer conduction)
- Solved by analysis and development of high resistivity (>10^7 Ωcm) C:GaN

Approach

- Extensive materials characterization
  - core solid-state physics spectroscopy
  - characterization of heterogeneous materials under thermal, mechanical, and electrical stresses
- Critical analysis of material models used by the electronic device community for design and reliability prediction
- Introduction of emerging nanoscopic probes of microstructure and chemistry

Phase-Change Alloys

- Chalcogenides -

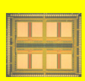
Exceptionally Strong Theoretical / Experimental Effort

- Leading world-renowned research team w/SNL, academia, and AFOSR -

Goal: Understand the chemistry and physics controlling the phase-transition and stability of $Ge_2Sb_2Te_5$ and its alloys

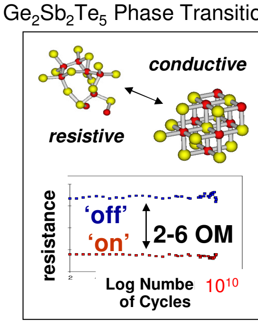
Applications:

- Next-gen NV C-RAM (higher endur. faster, lower power)
- Analog:
  - Multistate memory
  - Programmable resistors



Goal: 10^{15} cycles for 2^{nd} generation C-RAM (today: 10^{10} cycles)

$Ge_2Sb_2Te_5$ Phase Transition

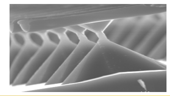


Approach:

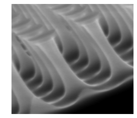
Perform atomistic modeling & expts. to understand:

- Chalcogenide/electrode interface
- Phase change physical/electrical mechanisms
- New alloy candidates (lower 'on-state' resistivity, higher 'off-state' resistivity, faster transition, lower power)

Nanoscale Structures & Devices: AFRL/VS & UNM



Materials at Nanoscale Dimensions Alter Normal Bulk Optical, Electrical, and Chemical Properties

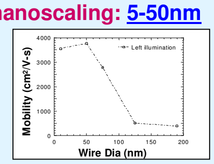


- Electrons start behaving more like waves than particles
- R*esistance*, *capacitance* and *inductance* change to nonlinear behavior
- Opportunities for faster, lower power, and more functional electronics than today

Nanoscale Material Property Studies

Investigating physics/material science of semiconductor nanoscaling: 5-50nm

1) Investigate role of carrier confinement on increased carrier mobility for selected structures



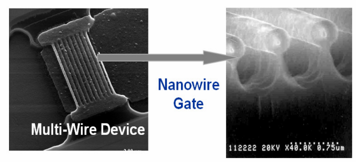
2) Investigate self-assembly mechanisms in composite materials (inorganic/DNA); the physical phenomena of *self assembly patterning of* electronic interconnections

Results: Achieved nanocrystalline CdS thin film by chemical bath deposition; Achieved hexagonal phase w/preferred (002) orientation; Measured Eg of 2.4eV

Article submitted to Journal of NanoTechnology 2/07

Nanowire MOSFET Studies

- Preliminary field dependent mobility values in nanowires (${}_n$= 4,000cm^2/V-s, μ_p=3,000cm^2/V-s)
- Low V_{DS} operation ~ 0.5V
- V_{Tn} immune to rad-degradation due to extreme small active volumes/conformal nanowire design



Article submitted to Journal of Applied Physics 1/07

Photonics and Nanotechnology

(nano-optical circuits)

PM: Gernot S. Pomrenke

Microcavities EIT PBG/PC Quantum Dots Plasmonics
Nanocrystals/particles QC optical methods
Refractive Index Engineering Dispersion Engineering

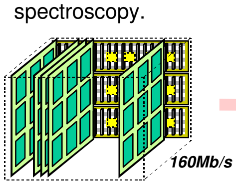
Nanophotonics: Extending the power of optics to the nanometer scale... The control and manipulation of light on this scale offers new approaches to photonic devices, as well as microscopy and spectroscopy.

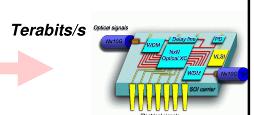
Nanophotonics:
Novel –
Materials
Devices
Phenomena
Tools

Silicon Photonics

Electrical power consumption & dissipation
Achieving greater speed (>10GHz)
Interconnects
Novel Computing

The combination of Nanofabrication & Photonics: Nanofabrication allows for the development of devices at the nanometer level. Photonics allow for the controlling of photons, or light, for telecommunications.

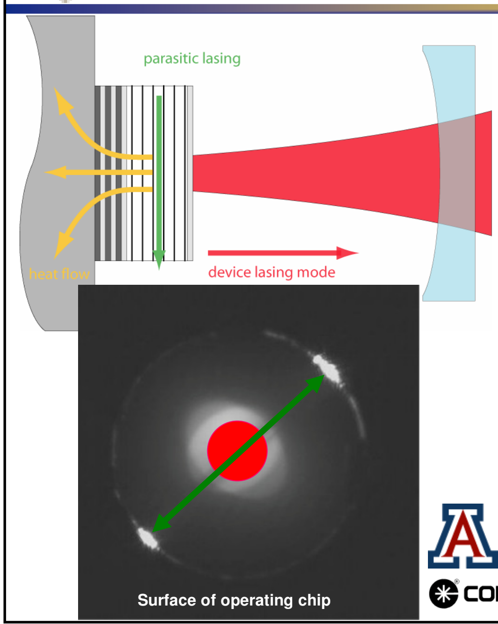




- Scalable; - High Integration
- Low power/small footprint

Reliability Concerns w/ Vertical External Cavity Surface-Emitting Lasers

PM: A. Nachman AFOSR/NE, LAB POC: R. Bedford AFRL/SNDP



Problem: Parasitic Lateral Lasing

- As the mode size increases, guided lateral modes are amplified in a parasitic cavity formed by the etched side walls of the semiconductor.
- Under high-power conditions, even poorly reflecting (<0.005%) walls are sufficient to develop parasitic lasing.

Issue: Unreliable Power Scaling

- Carrier non-uniformity shuts off single-mode behavior of surface emission.
- For large mode volume the threshold for parasitic lasing can be lower than for the desired surface emission.
- Typical results show that reliable power scaling is limited to 1mm spot sizes.

Approach

- Modify guiding structure
- Characterize parasitic lasing to avoid unreliable operating conditions leading to poor performance and physical degradation.

COHERENT

Multi-Spectral Detectors

The Warfighter Needs to See In All Spectrums At All Times