Adaptive Combinatorial Multimodal Sensing Physics & Methods

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Integrity ★ Service ★ Excellence
### Report Documentation Page

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Vision

Accelerate & exploit discovery of novel solid-state materials science, nano/microstructure device physics, and implementation schemes for future breakthrough-generations of adaptive, intelligent, compact and affordable combinatorial-multimodal sensing and exploitation methods enabling for game-changing adaptive & autonomous ISR.
NAME: Kitt Reinhardt

BRIEF DESCRIPTION OF PORTFOLIO: Multimodal Sensing Physics & Methods

LIST SUB-AREAS IN PORTFOLIO:

• Heterogeneous Nanostructure Design & Synthesis
  - interface lattice-strain & defect mitigation in III-V & II-VIs
  - energy band-edge alignment & barrier manipulation

• EO/IR Photon - Micro/Nanostructures Interactions
  - new materials, structures, physics, and phenomenology
  - novel photon-property transduction physics & methods

• Novel Mixed-Mode Detector Design, Physics, Methods
  - adaptive spectral & polarimetric filters & tuning schemes
  - embedded adaptive broadband absorption approaches
  - embedded conductive conduits, transparent interconnects

• Optical/Electric $\mu$-Cooling, 3-D Memory/Exploitation, Solar PV
Motivation

Support Emerging Info-in-War Revolution:

- THREATS HAVE CHANGED → dispersed & elusive enemy
- Near-real-time full situational awareness of threats is paramount to maintain asymmetric advantage.
- Increased reliance on autonomous ISR platforms.
- Present com-links & exploitation methods and resources are struggling to keep up…

“our warfighters are swimming in sensors but drowning in data – proliferation of sensors and large data sets are overwhelming analysts, who lack the tools to efficiently process, retrieve, store, and analyze vast amounts of data”

“data-to-decisions, cyber and autonomy are three of the seven strategic science & technology priorities for the Department”

Testimony of The Honorable Zachary J. Lemnios
Assistant Secretary of Defense for Research and Engineering (ASD(R&E))
Before the United States House of Representatives Committee on Armed Services Subcommittee on Emerging Threats and Capabilities
March 1, 2011
Sensor Data Explosion…

- More global hot spots → greater ISR needs → more sensor data → DoD com bandwidth & exploitation bottlenecks

ISR Enables Tasking, Collecting, Processing, Exploiting & Disseminating Timely Target & Scene Data

(1) Surveillance Data Collection
Recon  ISR Sats
UAVs ??

(2) Transmission
Comm / Relay SATS
JSTARS
AWACS

(3) Fusion & Decisions (fundamental bottleneck today)
Fusion / Analysis / Exploitation / Decisions → Order of Battle Dissemination

4) C^2 of Forces
Space: Responsive Tactical & SSA Sats
Air: Precision Engagement

\[ t_{\text{KILL}} = t_{\text{find}} + t_{\text{fix}} + t_{\text{track}} + (t_{\text{COM}} + (t_{\text{EXPLOIT}}) + t_{\text{target}} + t_{\text{engage}} + t_{\text{assess}} \sim \text{goal is single digit minutes} \]

USAF RPA ISR Platforms: sensor packages include multi-spectral imagers, HD color & IR flowing video, laser designators, synthetic aperture radar, gnd moving target indicators…

Tremendous ramp-up of UAS systems is planned - ‘nano,’ ‘micro,’ ‘man-portable,’ ‘air-launched,’ ‘multi-mission’

... Entirely new classes of detectors are needed:
→ smarter, more capable, compact, affordable
→ REAL-TIME ADAPTIVE SENSING would reduce data/com bottlenecks!
Real-Time Adaptive Sensing Can Quicken the Kill-Chain

Provide RPA Sensor-Operators/analysts vastly greater flexibility (knobs to turn in REAL-TIME) in choosing optimum sets of EO/IR sensor data to sense, collect & transmit.

- **Real-time** optimum selection of perfectly registered spatial, spectral, polarimetric, phase signatures for a given scene to dramatically increase decision speed and accuracy.

- Trained operators (would) know the most probable ‘layers’ (modes) of sensor data to query in a given scene to achieve a specific knowledge objective – including which specific elements in the scene (pixel location) to collect, stamp, encrypt and forward – → could dramatically reduce onboard processing & com bandwidth needs for the feed.

- **EXAMPLES:**
  - **Real-time tuning** of EO/IR (UV-IR in space) spectral bands to optimally filter dynamic-clutter for enhance target-scene contrast → REAL-TIME target discrimination, ID confidence, & extended range
  - **Real-time tuning** of 5-10 EO/IR spectral bands for REAL-TIME optimized of temp/shape profiling and reflectance spectra for unique materials and subject identification.
  - **Real-time selection** of wavelengths for polarimetric measurements for REAL-TIME surface feature contrast and discrimination of natural versus manmade objects

Great! So where can we find one of these magical Real-Time Adaptive sensors?
Sensing Modes

**Spatial (imaging):** shape, internal features, context, range profile

**Spectral (wavelength):** materials characteristics & phenomenology

**Polarization:** shape, surface roughness, natural vs. manmade

**Phase:** 3D shape, interferometry

**Time (temporal):** motion, dynamics, vibration

### Spectral Bands

- **VLWIR: 14-30μm**
  - very cold body detection
  - future STSS, SSA, ...
- **LWIR: 8-12μm**
  - midcourse track for STSS
  - cold body detect for SSA
- **MWIR: 3-5μm**
  - missile boost detect/track against Earth background
  - SBIRs-High, future SSA
- **SWIR: 1-3μm**
  - missile boost acquisition for SBIRs-High & STSS
  - air/gnd target ID and track
- **VIS: ~ 0.4-0.7μm**
  - midcourse track for STSS
  - SBSS, NFIRE, future SSA
- **UV: ~ 0.1-0.35μm**
  - future SSA

### S/M/LWIR Spatial Discrimination

**LWIR (14 μm)** vs **VLWIR (28 μm)**

**VIS Imaging for SSA**

**Earth is ~ Dark in UV → great for SSA**

**XSS-10 viewing Delta II 2nd Stage**

**300 K object**

**240 K object**

**DOLP**

**Intensity image**

**S, Intensity**  
S, 0°/90°  
S, 45°/135°

**Polarization imaging adds contrast for enhanced discrimination**
6.1 Opportunities in Real-Time Adaptive Sensing

A Multitude of Fundamental Materials Science & Device Physics Challenges & Opportunities

- Sensor (FPA) mode agility/addressability (pixel location, multiple wavelengths, polarization)
  + compactness + affordability → vertically integrated-monolithic device constructs
- Must innovate integrated-multi-functional structures & new interactions/transduction methods

**Desired New Functional Capabilities**
(a) integrated sense-modes \( (r, \lambda, S, \phi \text{ vs. } t) \)
(b) vertically-aligned (boresight) modes
(c) real-time mode addressing, tune & read
(d) … the holygrail: \( \int [(a) + (b) + (c)] \, dt \)

**Key Scientific Challenges**
(for which no suitable solutions currently exist)

- **Heterogeneous Matl’s Integration**
  - novel strain mitigation methods
  - band-edge alignment manipulation
  - nano-structure interface compliancy

- **Novel Dynamic Sensing Methods**
  - dynamic mat’l & device property tuning:
    - band-gap, abs. coef., carrier transport,
    - low-D structure energy levels, \( N_{ss} \), etc.
  - ‘functionalized’ nano-structures

- **Novel Interconnect Schemes**
  - grp II-thru-VI-based transparent (UV-IR)
    - films & electronics → reconfigurable
  - embedded 3-D transport conduits & adaptive switching schemes; color & absorption-rate sensitive ‘functions’
Desired ‘Functional’ Breakthroughs
(A) epi/sub mismatch strain mitigation methods
(B) epi-dislocation blocking barriers
(C) band-edge alignment manipulation
(D) dynamic bandgap/absorption-edge tuning
(E) dynamic optical absorption-depth tailoring
(F) dynamic wavelength & polarization filters
(G) photon property-matter transduction methods
(H) 3-D transparent pixel interconnects/conduits

Scientific Opportunities & Potential
(1) carbon nanotubes: (A)-(H) 
(2) coaxial nanorods: (A)-(H) 
(3) core-shell nanocrystals: (A)-(H) 
(4) Q-dots / wires / wells: (A)-(G) 
(5) metamaterial structures (D)-(G) 
(6) functionalized (1-4) nanostructures: (A)-(H) 
(7) plasmonic structures & methods: (A)-(G) 
(8) novel transparent thin-film synthesis: (D)-(H) 
(9) compliant heterointerface methods: (A)-(C) 
(10) combinations & integration of (1)-(8): (A)-(H)
Diamond Nanowires – an accidental discovery

Jimmy Xu (Brown University)

All the fun discoveries in Carbon

- all experimentally discovered -
- all forms on sp2 bond side -

Accidental discovery of diamond nanowires – grown in CVD

- Crystallography checked!
- Raman spectroscopy checked!
- e\textsuperscript{-} energy loss spectroscopy \checkmark

IT ALL CHECKED OUT!

First found in 2008 - 1 atm and 900C.
Did not know beforehand.
Did not know the growth mechanism, still don’t know.
Worse - could not reproduce it for 3 yrs!
Diamond Nanowires – an accidental discovery

Invited Feature Article in “Nanoscale” of RSC (Royal Society of Chemistry) 2012

… then on Nov 11th, 2011, after 100’s of trials in 2 CVD reactors… reproducible Diamond Nanowires!

Potential Applications

Superior single-photon source vs. CNTs. Another spectral peak at 415nm, even brighter, stable at room temperature, achieved in 2011.
→ new options for high-speed computing, advanced imaging & secure communication.

EO/IR Sensing applications -- potentially
→ tunable absorbers & current conduction conduits
→ patterned elements for adaptive thin-film spectral and polarization filters and modulators

Open Questions:
- Does physics allow the growth of diamond nanowires under atmosphere pressure & 900C?
- Was the well-established graphite-diamond phase transition condition wrong?

Multi-Phase III-V Nanocrystals
- A New Generation of Electronic Materials -

Science: understand & exploit novel formation methods $\text{Ga}_x\text{Er}_{1-x}\text{Sb}$ nanowires in GaAs; growth condition dependencies of $\text{Ga}_x\text{Er}_{1-x}\text{Sb}$ nanostructure geometry, optical & electrical properties.

Novel Monolithic Heterogeneous Structures

- RE-V’s are thermodynamically stable with III-V’s
- Share a common fcc sublattice
- Layers are semimetallic
- Growth of III-V epitaxial overlayers over percolated layers of RE-V layers

Embedding high concentrations of epitaxial $\text{Ga}_x\text{Er}_{1-x}\text{Sb}$ nanostructures in GaAs


Phys. Rev. Lett. 107, 036806, July 2011

DISTRIBUTION A: Approved for public release; distribution is unlimited.
Scientific Problem: Innovative novel methods for epitaxial semimetallic ErAs nanostructures/films in III-V stacks without degrading III-V layers grown above.

Epitaxial Metallic NanoStructures & Films

Developed Templated Regrowth

Approach:
1. ErAs growth on patterned templates:
   - ErAs, ErSb, ErP nanorods or nanowires
2. Embedded film growth method:
   - 100 nm ErAs

- *in situ* atomic hydrogen clean prior to regrowth:
  - No contaminants evident in MBE
  - PL comparable for structures grown before & after regrowth
- AFM: nanoparticle size & density vary based on surface orientation
  - Preferential LuAs growth on (111) and (211) planes
  - Signature of LuAs similar to AFM expts of ErAs on (100) GaAs
Embedded Ordered ErAs Metal Nanostructures

Seth Bank (UT Austin)

Novel Embedded Patterned Films

- GaAs spacer thickness
  - 0.0 nm (Conventional)
  - 3.0 nm
  - 2.0 nm
  - 1.5 nm
  - 1.0 nm
  - 0.5 nm
  - 0.25 nm

- Embedded Film Characteristics
  - Temperature-dependent conductivity
    - Films exhibit band-like transport
    - Distinct from thermally-activated hopping for interconnected islands

- nanoparticle-seeded films
  - 10 ML Film
  - 5 ML Film

- Interconnected ErAs Islands
  - \( E = 24 \text{ meV} \)

Films are continuous and suitable for buried contacts, conduits, and multifunctional patterned structures.


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Lead Chalcogenide Nanorod Liquid Crystals

Joe Tischler & Janice E. Boercker (Navy Research Lab)

Science: innovate, understand, exploit synthesis of PbSe liquid crystals for polarization appl’s

Vision: bias-tunable thin-film polarizers, modulators, filters

Approach: investigate viability of PbSe nanorod liquid crystals suspended in TCE – TCE transparent to 11μm.

Increased nanorod density and aspect ratio: 4 → 12

Increased bandgap from to 1.0-2.0 μm
Lead Chalcogenide Nanorod Liquid Crystals

Joe Tischler & Janice E. Boercker (Navy Research Lab)

Electrical Configuration

Alignment occurs between contacts and substrate, not the neighboring contact.

10 MHz ~10 V_{pp}

Au pad

SiO_2

DISTRIBUTION A: Approved for public release; distribution is unlimited.

Novel Periodic Nanostructures and Apertures for Multifunctional EO-RF Tuning

Yalin Lu (USAF Academy)

Tunable transmission, enhanced emission and modulation in ordered metallic nanostructures having varying channel shape; selective enhanced photon absorption and carrier generation in novel solar cells structures: → Tailored effects via localized plasmonic resonance, Fabry-Perot cavity resonance, waveguiding, antenna effects, etc.

Novel PV Cells: selective photogeneration and photocurrent enhancements of 30-50%

'Adding a thin metallic layer to silicon thin film solar cells', Y. Lu et al., Physica Status Solidi (c), 8, 843 (2011)
'Enhanced Absorption in Si Solar Cells via Adding Thin Surface Plasmonic Layers & Surface Microstructures', Y. Lu et al., PIERs Online, 7, 331 (2011)
Breakthrough Carrier Lifetimes in Type-II Superlattice (T2SL) IR Photodetectors for Increased Temp Operation

carrier lifetime in LWIR T2SL improved by 13 times from ~30 ns to 412 ns !!

Carrier lifetime for **Ga-free InAs/InAsSb type-II superlattice of 412 ns** was achieved
→ within the same order of magnitude of the reported record for **HgCdTe (1 μs)**
→ **could potentially lead to background limited T2SL MWIR-LWIR (3-12μm) performance higher operating higher temperatures than HgCdTe**!

**Detailed calculations in mid 90’s predicted advantages of T2SLs**

**T2SLS detectors offer potential for:**

- larger effective mass than HgCdTe for the equiv. $E_g$ → less band-to-band tunneling
- suppressed Auger recombination in both the conduction & valence bands; generation & recombination can be reduced w/wider $E_g$’s.

However, the predicted enhanced lifetimes in T2SLs have eluded the community, until now.
Breakthrough Carrier Lifetimes in T2SL Detectors

Yong-Hang Zhang (ASU) - jointly supported by ARO MURI (Bill Clark)

How did they do it? → replaced Ga in conventional InAs/InGaSb T2SL with As → InAs/InAsSb

PL Intensity Comparison Between ASU Grown AsInAs/InAsSb and State-of-the-Art InAs/InGaSb Grown by an Industry Vendor

Breakthrough InAs/InAsSb T2SL Carrier Lifetimes


Why is carrier lifetime in Ga-free T2SL longer?

Possible explanation: The energy level of Ga related broken bonds are possible in the middle of the energy gap, causing SRH recombination traps.

Possible explanation: No Ga related bond. The energy level of In related broken bonds are in the conduction band, minimizing the SRH recombination traps.

Y. H. Zhang et al., SPIE Defense and Security, Apr 2012
Novel Interband Cascade IR Photodetector (ICIP)

Rui Yang (U. of Oklahoma)

Innovation: novel quantum-engineered interband cascade (IC) structures for near room temp mid-IR detector operation → ultra-low dark currents - detectivity close to $10^{10}$ Jones or higher.

Key Features of ICIPs:
- Conventional depletion region is eliminated → suppression of SRH gen-current
- Discrete architecture → signal to noise ratio $S/N \propto 1/N_{a}^{1/2}$ ($N_{a}$: No. of absorbers) → circumvent the diffusion length limitation → high absorption QE
- Photo-carriers move over a short distance, i.e. one stage → fast response → viable for high-speed devices: lasers-free-space com & heterodyne detection

The Johnson-noise limited detectivity ($D^{*}$) exceeding $10^{12}$, $10^{11}$, $10^{10}$, $10^{9}$ Jones at 80, 160, 230, 300 K, respectively.
Novel Tunable NIR/LWIR Photodetector

Yong-Hang Zhang (ASU) – with joint support from ARO

2-Terminal Dual-Band IR Detector

NIR/LWIR optical addressing demonstrated for the first time...

- A 2-band photodetector consisting of NIR, PIN, LWIR & QWIP was demonstrated.
- The device is compatible with low-cost standard ROICs for two-terminal FPA.


Other Pioneering Work Underway on Grant
- 3-color photodetectors using NIR PIN, MWIR QWIP and LWIR QWIP.
- 4-color InAs/InAsSb T2SL photodetectors in MWIR and LWIR ranges.
- UV to IR multi-color photodetectors using 6.1 Å II-VI and III-V materials.
Novel Plasmonic Focal Plane Array

Sanjay Krishna (U. of New Mexico)

**Innovation:** 1\(^{st}\) focal plan array (256x320) with integrated plasmonic resonators → 160% enhancement!

**Approach:**

Results:

Plasmonic Enhancement

... Raytheon has expressed strong interest in transitioning into their next generation (4\(^{th}\)) detectors!
Three Color InAs/GaSb Superlattice IR Detector

Sanjay Krishna (U. of New Mexico)

Innovation: 1st 3-terminal detector pixel implementing unipolar nBn/PbIbN architecture

Approach:

Results:

For T=77K:
- SWIR at $V_b = +0.01V$, $D^* = 1.8 \times 10^{12}$ cmHz$^{1/2}$/W
- MWIR at $V_b = -0.3V$, $D^* = 1.4 \times 10^{11}$ cmHz$^{1/2}$/W
- LWIR at $V_b = -0.01V$, $D^* = 9.9 \times 10^{10}$ cmHz$^{1/2}$/W

Three color infrared detector using InAs/GaSb superlattices with unipolar barriers


Department of Electrical and Computer Engineering, Center for High Technology Materials,
University of New Mexico, Albuquerque, New Mexico 87106, USA
Other Portfolio Investments

- **Electron Processes & Physics of Correlated Doped Q-Dots & Barriers (UB)**
- **Doped Q-Dot PV Cells (ARL & UB)**
  - Sablon et al., *Nanoletters*, 11, 2111-2317 (2011)
- **Novel Q-Dot nipi PV Cell (STTR w/RIT)**

- **Nanotemplate-Enabled Highly-Heterogeneous Q-Nanostructure & Metamaterials Systems (USC)**
- **Tunable MEMs for Δ λ & S (RIT)**
- **Peltier Cooling (Northwestern U.)**

- **Functionalizing Coupled Nanorods, Nanotubes and Core/Shell Nanocrystals (U. Arkansas)**
- **IR-Transparent CNT Membrane-based Tunable Spectral Filters (U. Mass Lowell)**
- **Ridge-Waveguide Laser Cooling**
  - based on novel Q-well-Q-confined stark shifts...
  - (Northwestern U.)

- **Non-Radiative Energy Transfer (NRET) Sensing via Q-Composite Structures (USC)**
- **Monolithic Integrated Metamaterial-based Polarizer Grid (Tufts U.)**
- **Novel Conformal Apertures – STTRs via RY**
DoD Coordination:

- **ARO**: jointly fund efforts with ASU on novel detector materials science & device approaches
- **ARL**: support ARL in-house: novel Hg-based semiconductor epi-growth studies (Adelphi), collaboration with sensors group on doped Q-dot studies
- **NRL**: support in-house polarimetry filter research effort
- **DARPA**: coordinate w/Nibir Dhar in sensors -- their investments primarily ‘applied’ w/little 6.1
- **NSF**: follow nano-electronics investments, periodically attend reviews

Conferences/Workshops:

- SPIE DSS session organizer/speaker
- SPIE Photonics W. session organizer
- IEEE SISC: session organizer
- IEEE ICSC sponsor

International:

- National Cheng Kung University, Taiwan: CNTs
- Taras Shevchenko University, Kiev, Ukraine: polarimetry
Take Aways

- Portfolio targets crucial long-term USAF ISR capability needs.

- Strong thrusts established in multiple fundamental science challenge areas spanning novel solid-state nanomaterials and quantum structures synthesis, and breakthrough mixed-mode multi-discriminate sensor device concepts and methods.

- Good portfolio balance between theoretical and experimental research – most efforts include elements of both.

- Excellent progress achieved in novel heterogeneous nanostructures synthesis and integration, novel photon//detector materials interactions & phenomenology, and novel mixed-mode sensing device concepts and methods.