U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

Army Ultra-wide Bandgap RF Electronics Center Introduction & BAA Overview

Drs. Peter Reynolds, Joe Qiu, Evan Runnerstrom, Purush Iyer, and Hamid Krim

Army Research Office

DEVCOM Army Research Laboratory

15 Dec 2020

OVERVIEW

Ultra-wide Bandgap (UWBG) RF Electronics Center

- Introduction of UWBG RF Electronics Center
- Technical scope overview
  - Topic 1: UWBG semiconductor physics/devices
  - Topic 2: UWBG materials
  - Topic 3: Physics-driven AI/ML for materials and device discovery
- Funding overview
- Submission process, Submission dates, Anticipated award timeline

BOTTOM LINE UP FRONT (BLUF)

DEVCOM ARMY RESEARCH LABORATORY

Center Goal:

- Develop ultra-wide bandgap (UWBG) materials for next gen RF semiconductor tech
- Enable advanced, robust, high-power RF electronics

Robust high power operation means longer ranges for sensing and effect-on-target under adverse conditions. Improved SWaP will give small systems new capabilities

Products:

- Extreme physics models of UWBG materials and devices (Topic 1)
  - New physical models for understanding interactions between carriers, phonons, and photons
  - Electrical & thermal characterization under extreme fields and temperatures
  - Novel device design and integration concepts enabling operation in extreme conditions
- New high-quality UWBG materials with extreme RF performance (Topic 2)
  - Novel approaches to wafer-size, electronic-grade materials growth
  - Fundamental advances in understanding of UWBG growth processes
  - Novel materials discovery
- Physics-driven AI/ML models for UWBG materials and device design (Topic 3)

Payoffs:

- Ability to design new UWBG materials with tailored characteristics
- Accelerated materials discovery and development
- Fundamental understanding of properties and device physics of UWBG materials
- ARL-academic collaboration and tech transfer in materials growth, knowledge products, device design, and training next generation of researchers

BLUF: EXPECTED OUTCOMES AND PAYOFF

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Goal: Develop UWBG materials/devices to enable next generation Army RF electronic systems

If successful, what difference will it make?

- Higher RF power systems – longer range; more data; less jamming
- Reduced SWaP

Who cares?

Networks, PNT, All Army/DoD radio/antenna/wireless systems users

How will progress be measured?

- Device physics and design: high-field, non-equilibrium carrier transport; electrical and thermal co-simulation; device processing techniques and contact engineering
- Materials: Large-area, low-defect density, single-crystal substrates; demonstrate hetero-epitaxial growth; develop doping techniques; transition wafers to ARL/SEDD
- Final metric: Demonstrate TRL4 RF power devices with significantly enhanced power density (10x greater than SoA GaN)

Maintain electromagnetic supremacy in congested, harsh environments.

UWBG RF ELECTRONICS CENTER

Ultra-wide Bandgap RF Electronics Center:

- Basic research program initiated by Combat Capabilities Development Command/Army Research Laboratory/Army Research Office (ARO)
- Focused on an area of strategic importance to U.S. national security
- Increase the Army's intellectual capital in UWBG materials/RF electronics & improve its ability to address future challenges to spectral dominance
- Bring together universities, research institutions, companies, and individual scholars to support multidisciplinary and cross-institutional projects addressing these topic areas
- Promote research in specific areas of UWBG materials and devices, promote a candid and constructive relationship between DA and UWBG research community
- US Institutions ONLY

Technical topics:

- UWBG semiconductor devices & physics
- UWBG materials
- Physics-driven AI/ML

Teaming and funding:

- Self-organized teams can propose to any combination of (sub)topics; budget commensurate with scope
- Funding levels range from ~$150k/yr (single sub-topic) to $4.5M/yr (full scope of center)
- 3 year base period, 2 year option

TOPIC 1: UWBG SEMICONDUCTOR PHYSICS AND DEVICES

- Progress in UWBG materials synthesis has enabled fundamental research into new device structures and physics underlying device performance
- Ultimate goal is to create RF electronic device structures that break power density limit of GaN, maintain at least 10 dB gain, and demonstrate an order of magnitude improvement in power density (W/mm) over current SoA WBG RF devices

1.1 UWBG Semiconductor Physics: understand how extreme high-power and high-frequency fields in UWBG devices affect charge carrier dynamics, lattice dynamics, thermal and electronic transport, interfacial behavior, etc

1.2 UWBG Semiconductor Devices: enable high-voltage bias in small device structures at very high frequencies (90+ GHz). Requires basic research in: 1) Scaling of device and contact resistances; 2) Scaling of gate length to realize high effective velocity; 3) Field management to realize fields at or near theoretical material breakdown strength; 4) Coupling of electrical and thermal transport with full-wave electromagnetics.

1.3 Novel Approaches to Integration of WBG/UWBG semiconductors: Proper integration (contacts, passivation, thermal management, gate insulators, etc.) is crucial to current RF electronics technology and next generation technology based on UWBG

Integration can be limiting factor in performance of many or most RF devices. Integration breakthroughs may also enable unprecedented RF performance from existing WBG materials like GaN, or allow UWBG materials to overcome critical shortcomings (e.g., Ga_2O_3 with poor thermal conductivity)

TOPIC 2: UWBG MATERIALS

- Goal is electronic-grade UWBG semiconductor materials that surpass GaN
- Specific success metrics are: a) $E_g \geq 4$ eV; b) Epi films and/or single xtals 4+ inches; c) *n* and *p* of $10^{10} – 10^{20}$ cm^{-3} with μ of 100 – 1000 $cm^2/V \cdot s$; d) Electron damage threshold ≥ 500 keV, atom displacement energy ≥ 20 eV, electric breakdown strength ≥ 10 MV/cm, thermal conductivity ≥ 300 W/m·K

2.1 Novel approaches to large area, uniform UWBG growth: novel growth methods for electronic-grade, wafer-scale growth of diamond, c-BN, AlGaN, or related UWBG single crystals as bulk substrates and/or epi films. Uniform and controlled thickness, composition, planarity, and defects. (Example: conversion of graphene/h-BN to diamond/c-BN)

2.2 UWBG growth processes, defects, and doping: integrated theory and experimental approaches to model, characterize, and control thermodynamic and kinetic factors in UWBG crystallization and epitaxy

2.3 Discovery of new UWBG semiconductors and alternative materials for RF electronics: alternative and innovative approaches that yield new UWBG semiconductors that can achieve all goals for Topic 1, and/or exotic materials approaches (e.g., 2D materials, twistronics, topological materials, ferroelectrics, etc.) that reveal alternate, unexpected routes suitable for high frequency electronic devices

TOPIC 3: PHYSICS-DRIVEN AI/ML FOR UWBG MATERIALS AND DEVICE DISCOVERY

- Goal to develop AI & ML methodologies for more efficient sampling of materials phase space, thermodynamic energy landscapes, and RF device design
- Reduce Center's reliance on empirical & Edisonian approaches to discovery and design
- Fundamental new approaches that are **physics**-driven, as opposed to data-driven

Research challenges poorly suited for current ML or AI approaches because data in short supply and expensive to obtain

Successful approaches will likely fuse ML, materials physics, and device/RF physics in novel ways to create models that guide researchers more efficiently towards discovering what is not known or easily intuited, but physically sound

Leverage the relative strengths of humans (fundamental physical understanding of "ground truths") and machines (the ability to make high-dimensional, non-intuitive inferences)

Uncertainty quantification (UQ) is expected to be a critical aspect in development cycle of new UWBG materials and devices that behave as one expects. Given paucity of data, new UQ methods likely needed for experiment, simulation, and physics-driven AI/ML models

FUNDING OVERVIEW

Funding:

- **$4.5M/year available (anticipated)**
- **Proposal scope can range from ~$150k/yr (i.e., single sub-topic) to $4.5M/yr (covering full center scope)**
- **Awards made at funding levels commensurate with proposed research, scope, PI/team type, and funding availability.**
- **Awarded proposals will have a 36-month base period and 24-month option period (pending performance & availability of funds)**

i. Awards will be in the form of contracts, grants, and cooperative agreements. ***Strong preference for cooperative agreements*** to allow for maximum interaction, cooperation, and collaboration between government and awardees

ii. ALL awardees expected to collaborate and cooperate with and among each other as well as with DEVCOM-ARL researchers (there will be annual Center reviews)

iii. Awards will be made at funding levels commensurate with proposed research, investigator/team type, as well as availability of funding

iv. Government may award some, all, or none of submitted proposals

v. Applicants are required to submit whitepaper to be considered for proposal

vi. Only INVITED proposals based on submitted whitepapers will be considered for selection

vii. Teams encouraged to self-organize at any scale to create a white paper/proposal that addresses one, several, or all topics/subtopics as they see fit

SUBMISSION PROCESS, SUBMISSION DATES, ANTICIPATED AWARD TIMELINE

FOLLOW THE INSTRUCTIONS IN THE BAA

The BAA supersedes any information presented today (in the event of any conflict or confusion)

Timeline

i. **Whitepapers (8 pg. max for technical content) due NLT 1600 ET 15 Feb 2021**
ii. **Notification of selection for full proposal 22 Mar 2021 – selected whitepapers will receive feedback**
iii. **Proposals due NLT 1600 ET 1 Jun 2021**
iv. **Only INVITED proposals based on submitted whitepapers will be considered for selection**
v. **Late whitepapers or proposals will not be considered**
vi. **Applicants may target any combination of (sub)topics. Multiple whitepapers and proposals from a single institute may be submitted, e.g., addressing separate areas**
vii. **Proposal selection anticipated 2 August 2021; award anticipated after 1 Oct 2021 pending FY22 Federal Budget**

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND –
ARMY RESEARCH LABORATORY

Advanced Electronics Device Technologies

Dr. Romeo del Rosario, Chief – Electromagnetic Spectrum Sciences (EMSS) Division

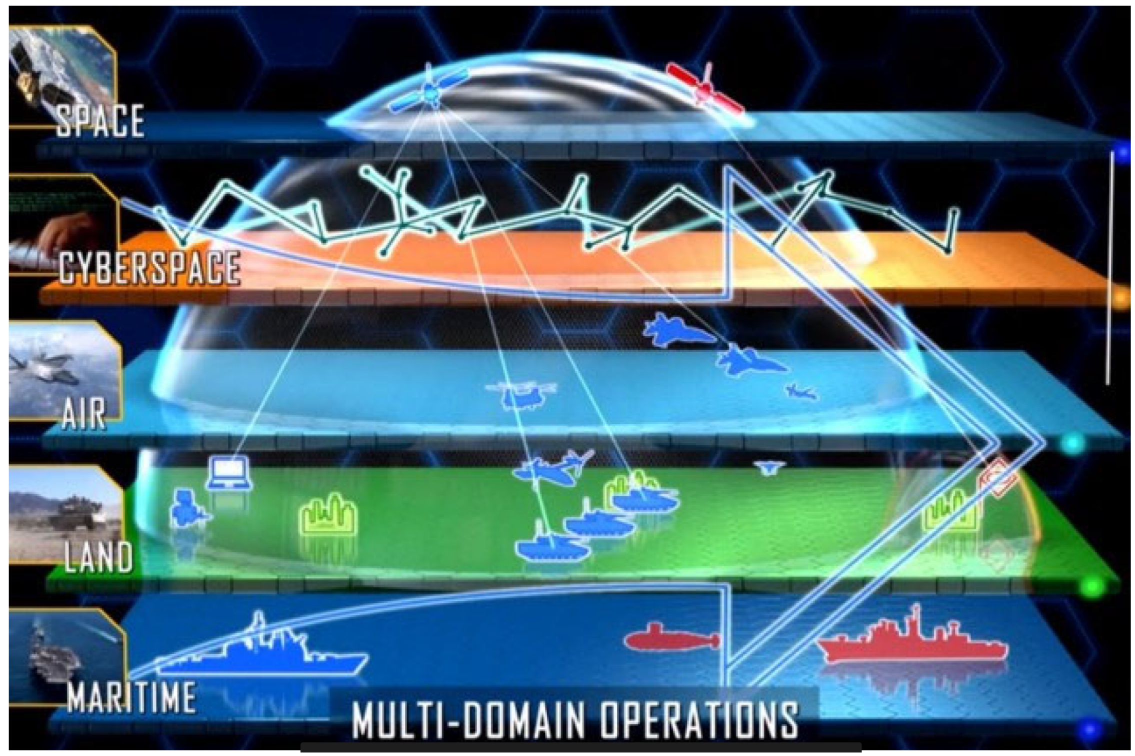
POC: **romeo.d.delrosario.civ@mail.mil**
romeo.d.delrosario.civ@cvr.mil

OVERVIEW

Army Challenges
- Intro: Soldier & platform missions constrained by energy supply, demand, payload impact
- Motivations: Longer mission duration | increased functionality | distinct use cases

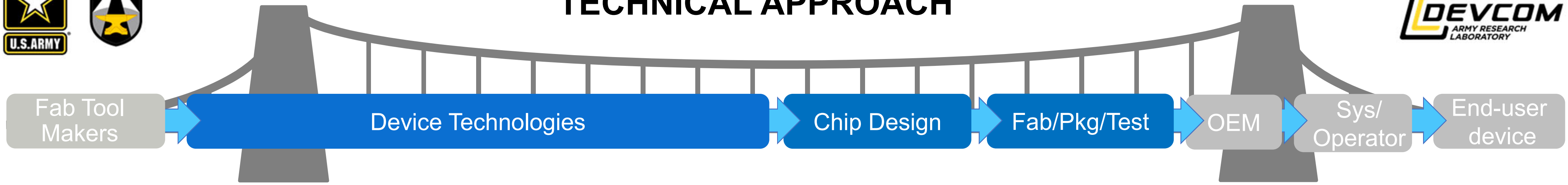
Key Technical Challenges
- Distributed Sensing
- Electronic Warfare (EW)
  - Small platform proliferation
  - Communicate in contested environment
- Assured Communications
  - Communicate in congested environment
- Computing at the edge
- Army mission constraints
  - Size, Weight, Power, Cost, Time (SWAP-CT)
  - Competition

Community Context
- DoD/Tri-Service
- Revisiting chipmaker business models
- Leveraged investment
- Evolving academic/industrial engagement



RF Electronic Materials is an AFC *Priority Research Area*

TECHNICAL APPROACH



Functionalities / Outcomes

- RF
- Digital
- Optoelectronic
- Sensing

Division Device Technologies

Growing

RF-DSFETs
TEDs
Neuromorphic Devices

55 nm LPX CMOS
Nanoporous Si
AM Packaging
PZT MEMS

AlGaN UV Emitters
SiC APD
EO III-V

Transitioning

GaN HEMT
~~SiC MOSFETs~~

→ UWGB Power Devices

Key Technical Challenges

- Distributed Sensing
- Electronic Warfare (EW): Small platform proliferation, Communicate in contested environment
- Assured Communications: Communicate in congested environment
- Computing at the edge
- Army mission constraints
  - Size, Weight, Power, Cost, Time (SWAP-CT)
  - Competition

Community Context

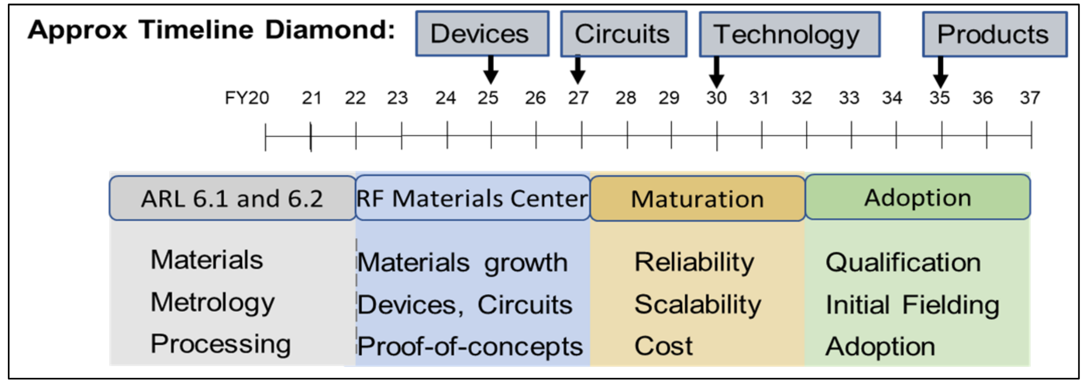
- DoD/Tri-Service
- Leveraged investment
  Evolving academic/industrial engagement

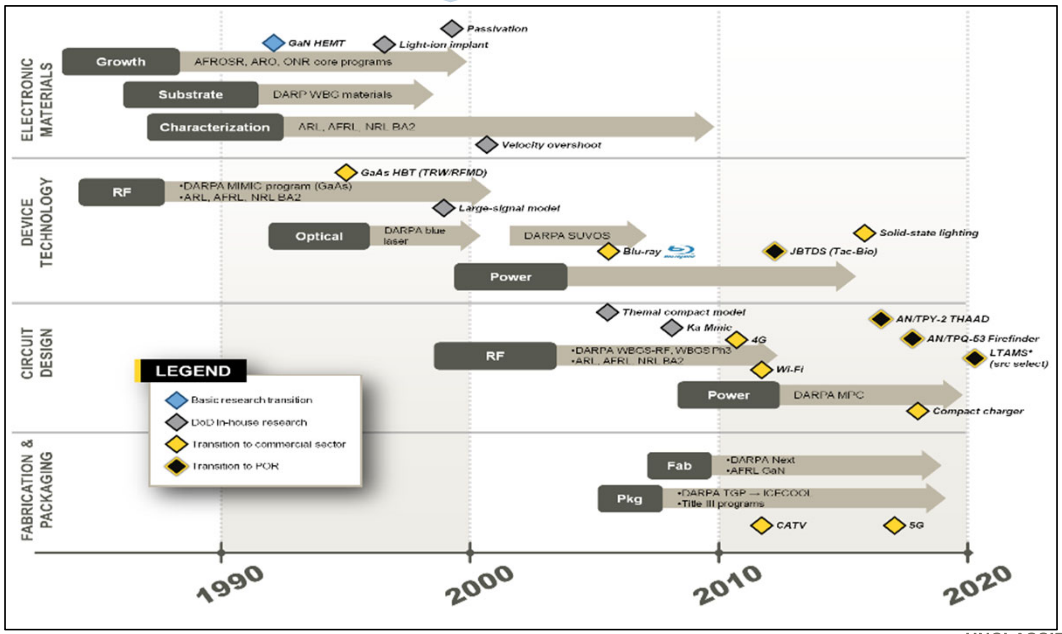
*Device Technology ≡ circuit fab capability comprising: semiconducting **material(s), substrate, interconnect** and their requisite fabrication process and design rules*

The Long Game: Materials → Devices → Systems

GaN Development timeline:

- 30 years to fielded systems
- $1B investment
- 13 PoR’s





ARL Diamond Initiative:

- Foundational research to precipitate DoD investment in next-generation device technology
- $10.2M, 5 years

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Diamond Electronics Research at ARL

Tony Ivanov

15 Dec 2020

tony.g.Ivanov.civ@mail.mil

ARL DIAMOND ELECTRONICS RESEARCH GROUP

Tony Ivanov
BC, Technology Integration

Glen Birdwell
TL, Material Metrology

Sergey Rudin
Theory

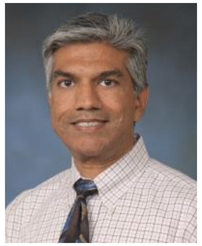
Mahesh Neupane
DFT Modeling

Dima Ruzmetov
Substrate Engineering

James Weil
Processing Lead

Stephen Kelly
Processing

Derwin Washington
Processing

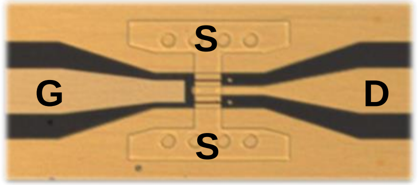


Pankaj Shah
Compact Modeling

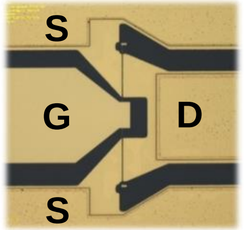
Leo De La Cruz
TCAD, RF Test

TECHNOLOGY ROADMAP

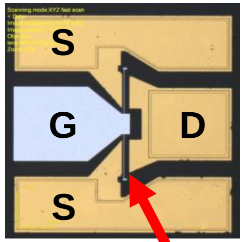
GEN1
Air Doping



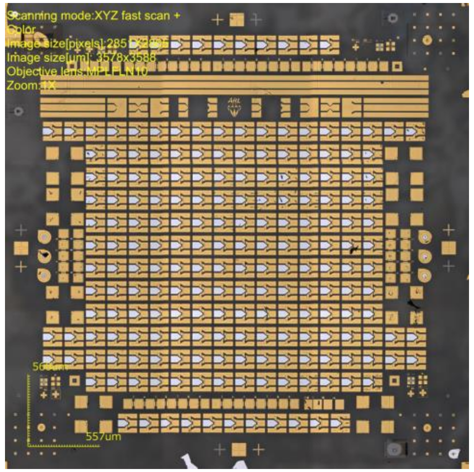
GEN2
Oxide Acceptor



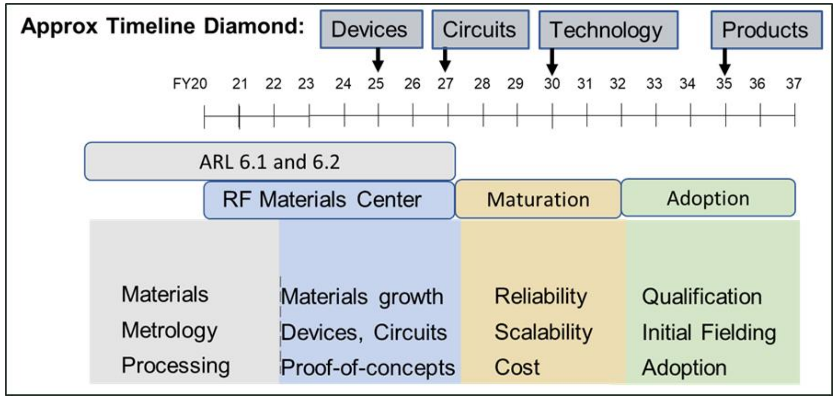
GEN3
RF Power Features



GEN4
Diamond/BN hetero-structures?



Typical Gen3 Substrate
3.5x3.5 mm
~200 FETs
Lg=50, 100, 200, 400, 800 nm



GEN1 RESULTS

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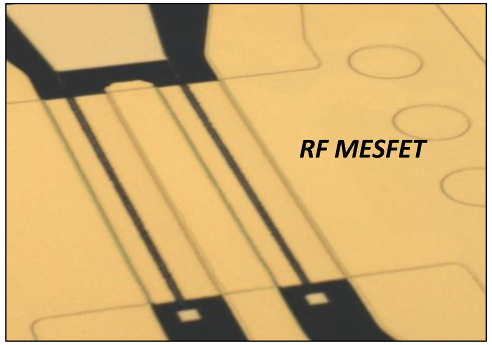
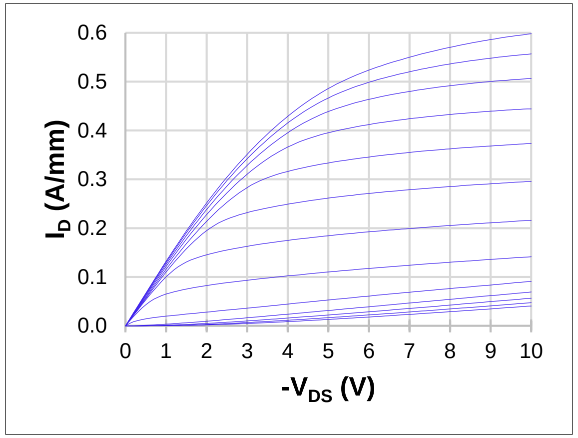
Diamond MESFET

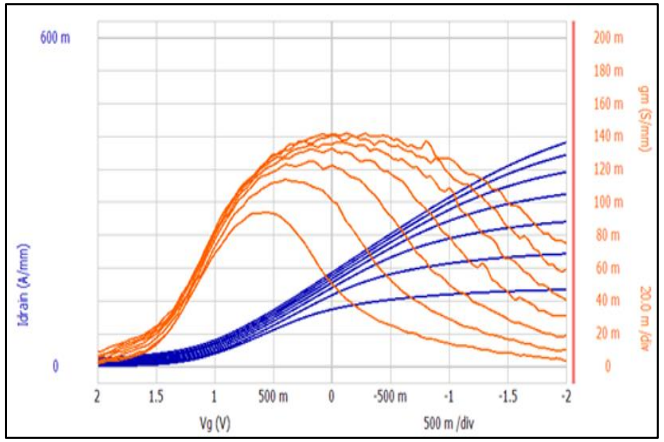
L_g = 0.10 um, W_g = 40 um



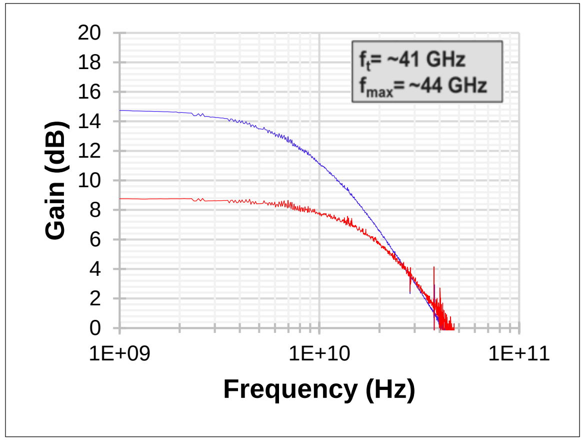
I_{DS} = 600 mA/mm



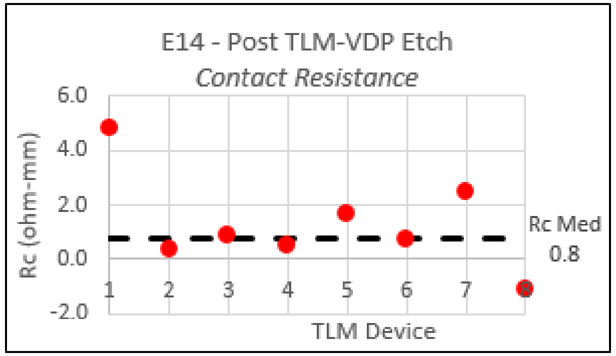
g_m = 140 mS/mm



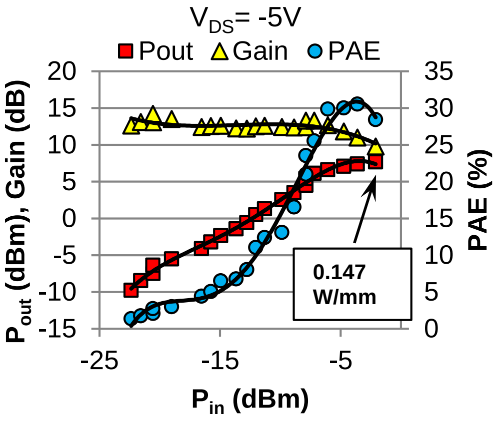
f_T = 41 GHz; f_{max} = 44 GHz



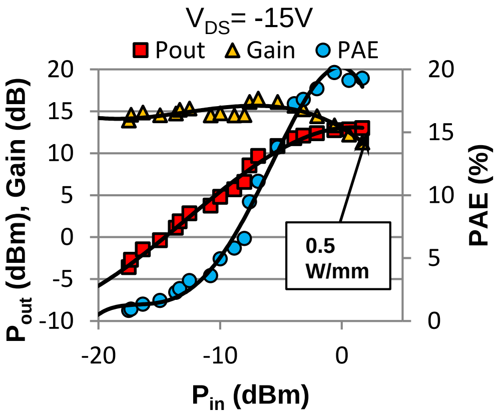
R_C = 0.8 Ω-mm



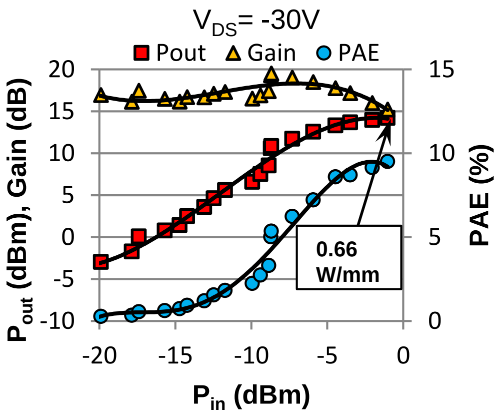
PAE = 30%



Gain = 15 dB



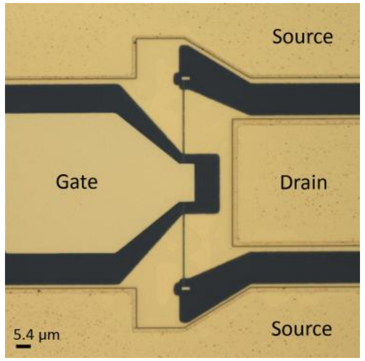
P_{OUT} = 0.66 W/mm



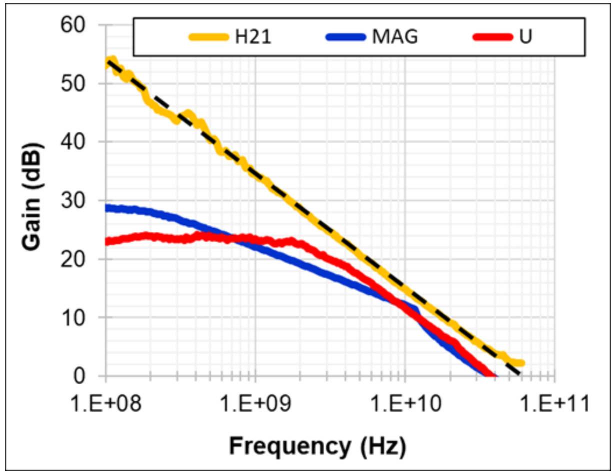
GEN2 RESULTS

Diamond MESFET

L_g = 0.10 um, W_g = 50 um

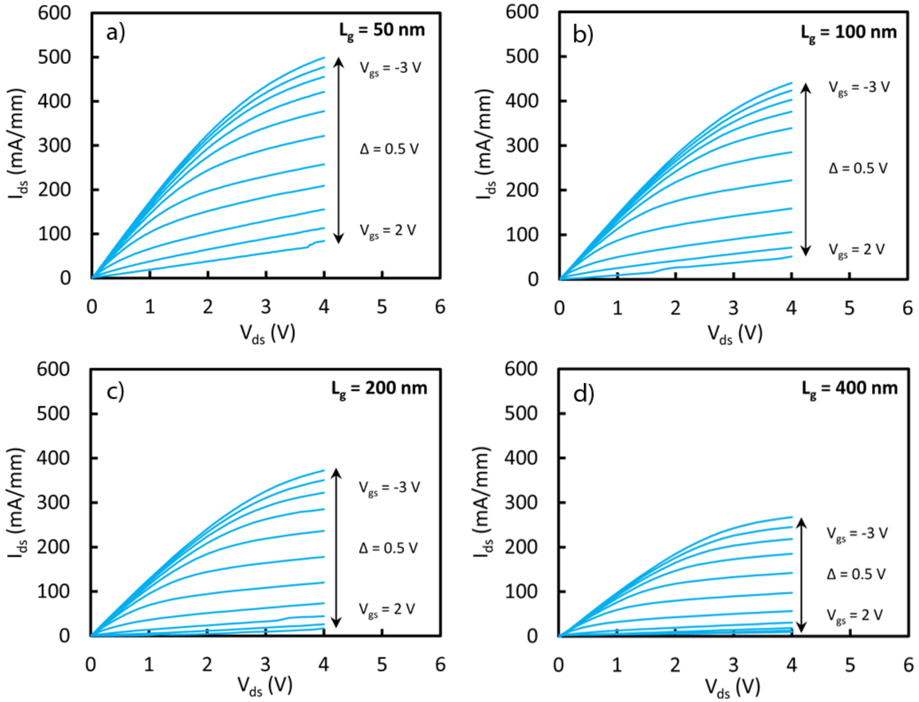


f_T = 62 GHz; f_{max} = 38 GHz



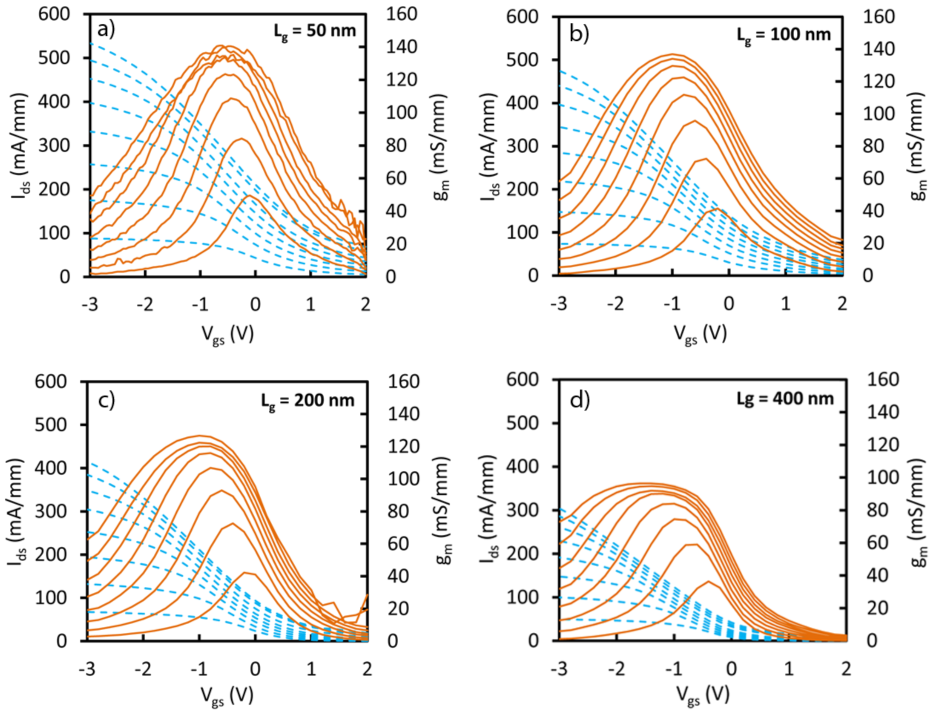
I_{DS} = 700 mA/mm

Gate scaling



g_m = 150 mS/mm

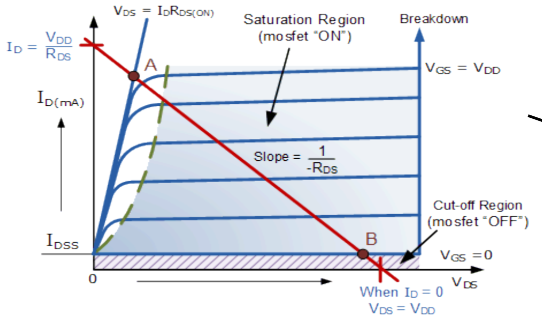
Gate scaling



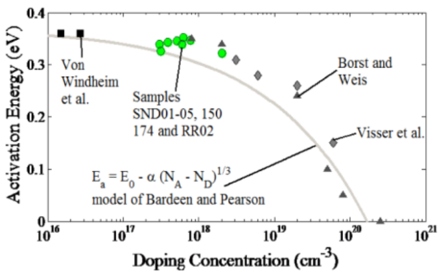
Devices stable for > 6 months

GEN3 DEVICE IMPROVEMENT OPTIONS

Goal – $R_{ON}\downarrow$; $V_{knee}\downarrow$; $I_D\uparrow$; $V_{BR}\uparrow$

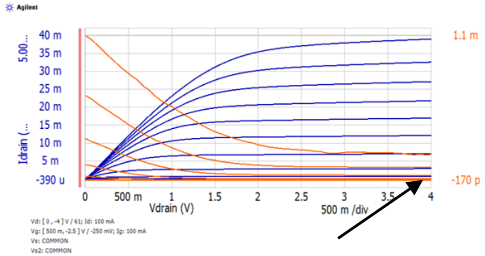


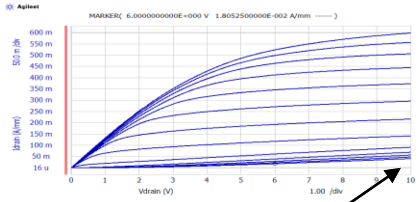
Re-grown p+ contacts



Boron Activation Energy Reduction with Doping (**Low Resistance Contacts**)

Leakage current reduction by substrate engineering

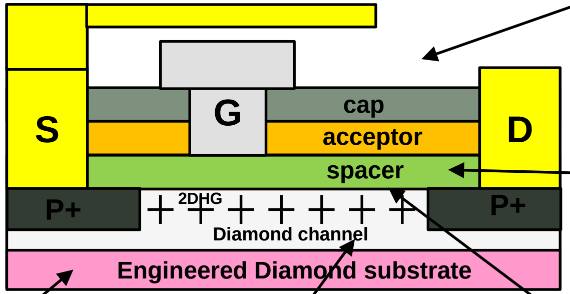




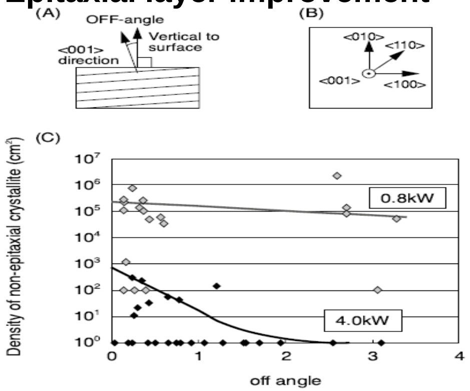
Conventional RF Power Device techniques applied to Diamond

Carbide contacts, $L_{GD}>L_{GS}$, T-gate, UHV metal deposition, $L_G\leq100$nm, $L_{SG}\leq100$nm, 2DHG concentration grading, RESURF, super junction, field plates; hermetic passivation, etc.

ARL's Gen3 Device

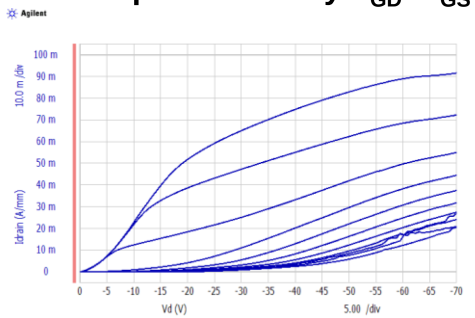


Epitaxial layer improvement

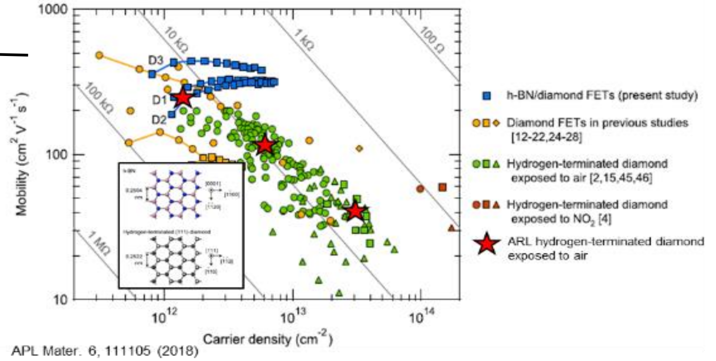


Surface roughness and defect density improvement by diamond epitaxy off angle control.

BV improvement by $L_{GD}>L_{GS}$



Mobility improvement



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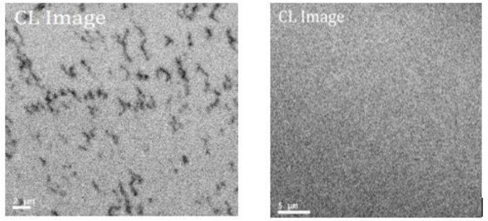
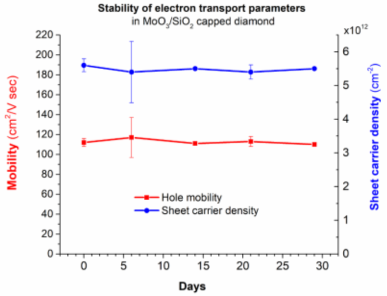
CMP for R_a=2.0 Å



Cathodoluminescence images of sub-surface damage before and after diamond CMP.

Hermetic passivation



PATH FORWARD

- Use fundamental science as enabler for UWBG technology development
- Develop UWBG HEMT (or similar performance device)
- Reduce thermal management burden
- Achieve RF power density of 10x GaN
- Develop next generation Army RF technology (<90 GHz)
- Explore generation-after-next possibilities (>90 GHz)
- Validate all research outcomes with ARL testing

U.S. ARMY COMBAT CAPABILITIES DEVELOPMENT COMMAND – ARMY RESEARCH LABORATORY

Transformational Materials Science – RF Electronics Center

Cynthia Bedell, SES

Director

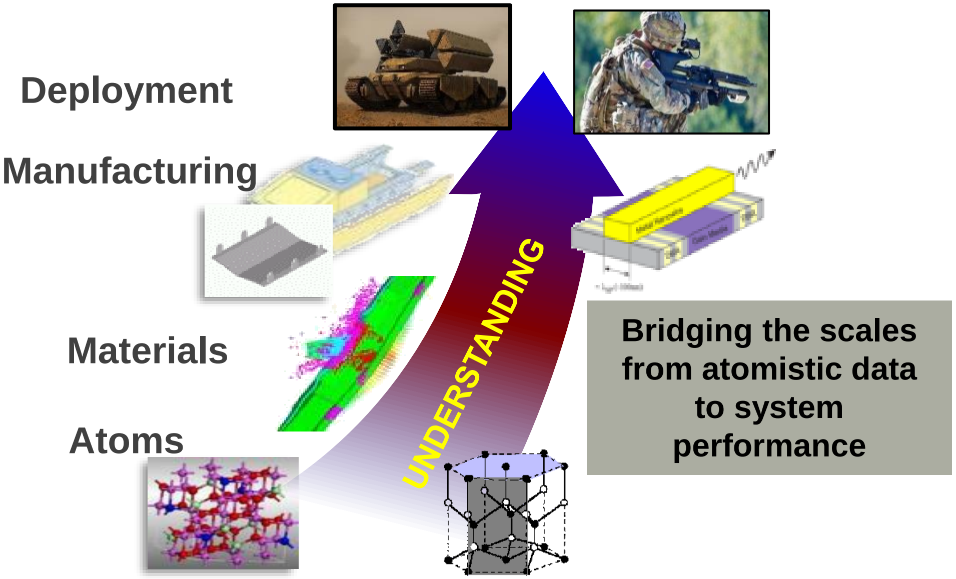
Computational and Information Sciences Directorate

Distribution A

13 Dec 2020

TRANSFORMATIONAL MATERIALS SCIENCE

Goal: Reduce the time and cost to design new materials with desired performance under even the most extreme conditions. Enable rapid adaptability to emerging threats that is not possible with existing methods.



<u>Current approaches:</u>

- Combination of computation and experimentation
- Separate macroscopic material behavior into individual unit phenomena, usually by scale
- Construct a model of unit phenomena incorporating experimental data
- Combine unit models into a single multiscale model of the macroscopic behavior and utilize it to design a new material

<u>Questions:</u>

- New experimental techniques may significantly increase available data. Can existing data science methods be applied to materials design?
- Existing material models often capture years or even decades of development. Can we fuse physics-based and data-science driven material models?

<u>Future approaches:</u>

- Data-science methods that directly incorporate existing knowledge/physics, i.e., physics-informed machine learning
- Physics-informed machine learning with quantifiable uncertainty of model predictions
- Methods for automated construction of multiscale models of materials, e.g. multiscale machine learning
- Machine-learning design and optimization of materials

COLLABORATION OPPORTUNITIES

- Many models of physical systems (e.g. materials) often capture years or even decades of research
- Need to enable fusion of physics-based models of complex physical systems with data-science/machine-learning approaches–physics-informed machine learning (PIML)

Physics-informed machine learning

- Multiscale modeling provides a fundamental framework for development of predictive models of complex physical systems
- ARL is interested in:
    - Development of PIML methods to facilitate rapid construction of multiscale and multi-physics models of complex physical systems:
        - Automatic creation of surrogate models for at-scale/unit models in multiscale and multi-physics model assemblies
        - Scale-bridging/data transfer between at-scale/unit models in multiscale and multi-physics model assemblies
        - Construction of multiscale and multi-physics PIML model assemblies
    - PIML methods allowing to directly incorporate invariants/constraints present in many physical systems (e.g. mass or energy conservation)

COLLABORATION OPPORTUNITIES

Uncertainty quantification for machine learning

- Assessment of predictive capabilities of computer models is crucial
- ARL is interested in:
  - Uncertainty quantification (UQ) analysis of data-science and machine-learning
    - Assessment of uncertainty in predictions of PIML models of physical systems
    - UQ of multiscale and multi-physics PIML models of physical systems
    - PIML for non-deterministic (stochastic) models of physical systems (e.g. materials with random microstructure)

Machine learning for physical systems based on small data

- For many complex physical systems experimental data availability is very low
- ARL is interested in:
  - Enabling use of data from multiple sources, with possibly different fidelities, to train PIML models of physical systems
  - Methods for assessment of predictive capabilities of PIML models trained on sparse data
  - Strategies for systematic improvement of PIML models by judicious selection of auxiliary data points for experimental data acquisition

COLLABORATION OPPORTUNITIES

Machine-learning design of physical systems

- ARL is interested in:
  - Methods for machine learning to facilitate design and control of physical systems
  - Machine learning approaches to enable reliable design of physical systems
  - Machine learning techniques to allow purposeful decision making on the basis of computer models of physical systems

U.S. Army Contracting Command

Business Briefing

Ultra-wide Bandgap RF Electronics Center 2022

BAA W911NF-21-S-0003

Kevin Bassler
ACC-APG RTP Division
15 December 2020

Opportunity Day

Please note that nothing discussed today should be construed as intent to change the BAA.

Unless a change is made to the BAA, all proposers should propose only to what is discussed in the BAA and not to these slides or information conveyed today.

Award Instruments (Preferred)

Cooperative Agreement (CA) under the authority of 31 U.S. Code § 6305 .

An executive agency shall use a cooperative agreement as the legal instrument reflecting a relationship between the United States Government and a State, a local government, or other recipient when—

(1) the principal purpose of the relationship is to transfer a thing of value to the State, local government, or other recipient to carry out a public purpose of support or stimulation authorized by a law of the United States instead of acquiring (by purchase, lease, or barter) property or services for the direct benefit or use of the United States Government; and

(2) substantial involvement is expected between the executive agency and the State, local government, or other recipient when carrying out the activity contemplated in the agreement.

Award Instruments

Grant - A legal instrument that, consistent with 31 U.S.C. 6304, is used to enter into a relationship:

(1) The principal purpose of which is to transfer a thing of value to the recipient to carry out a public purpose of support or stimulation authorized by a law or the United States, rather than to acquire property or services for the Federal Government's direct benefit or use.

(2) In which substantial involvement is not expected between the Federal Government and the recipient when carrying out the activity contemplated by the grant.

(3) No fee or profit is allowed.

Award Instruments

Procurement Contract - A legal instrument, consistent with 31 U.S.C. 6303, which reflects a relationship between the Federal Government and a state government, a local government, or other entity/contractor when the principal purpose of the instrument is to acquire property or services for the direct benefit or use of the Federal Government.

Contracts are primarily governed by the following regulations:

a. **Federal Acquisition Regulation (FAR)**
b. **Defense Federal Acquisition Regulation Supplement (DFARS)**
c. **Army Federal Acquisition Regulation Supplement (AFARS)**

Funding Levels

- **The awards will be made at funding levels commensurate with the proposed research, scope, investigator/team type, as well as availability of funding.**

- **It is anticipated that approximately $4.5M in total of annual funding will be available for award for all the teams/components of the Center. Depending on the scope of a proposal, whether addressing only a single sub-topic at one extreme, to potentially covering the full scope of the Center at the other extreme, it can request funds in the range from ~$150K all the way to the full $4.5M. Each increment or option will be subject to the availability of out-year appropriations.**

ELIGIBILITY INFORMATION

Institutions of higher education, nonprofit organizations, state and local governments, and for-profit organizations (i.e. large and small businesses) in the United States or its territories.

FFRDC's may propose as allowed by their sponsoring agency and in accordance with their sponsoring agency policy

Not Allowed- ARL/DoD laboratories or other government labs

ELIGIBILITY INFORMATION

Two-step submission process for ALL applicants.

- **Must submit a timely and compliant whitepaper or NOT eligible to submit a Proposal for consideration for funding.**
- **Must receive an invitation from the Government to submit a Proposal based on the whitepaper or else NOT eligible to submit a Proposal.**

Whitepaper Submission

- **Whitepapers must be emailed to the following email address: usarmy.rtp.rdecom-aro.mbx.baa3@mail.mil**
- **Whitepapers – 15 February 2021 no later than 4:00 PM Eastern Time**
- **Email subject line must include the phrase "Whitepaper Submission UWBG RF Electronics"**
- **Must follow the formatting and page limitations of BAA**

Full Proposal Submission Process (Assistance Instruments)

- All proposers for a grant or cooperative agreement *MUST* submit through grants.gov if seeking a grant or cooperative agreement (preferred).

- At grants.gov you can search by the funding opportunity number, W911NF-21-S-0003 or search by the CFDA Number 12.431

- Grants.gov recommends submitting your proposal package ***at least 24-48*** hours prior to the close date to provide you with time to correct any potential technical issues that may disrupt the proposal submission.

Full Proposal Submission Process (Contracts)

- **All proposers seeking a contract can submit through grants.gov or email directly to usarmy.rtp.rdecom-aro.mbx.baa3@mail.mil.**

- **At grants.gov you can search by the funding opportunity number, W911NF-21-S-0003 or search by the CFDA Number 12.431**

- **Grants.gov recommends submitting your proposal package *at least 24-48* hours prior to the close date to provide you with time to correct any potential technical issues that may disrupt the proposal submission.**

Submission Date

- **Proposals are due 1 June 2021 no later than 4:00 PM Eastern Time. Proposals submitted after the closing date will not be considered or evaluated by the Government.**

Evaluation Process

- Preliminary review for proposal completeness, eligibility requirements, conformance with BAA requirements
- Individual proposals will be evaluated against the evaluation criteria – not against each other
- Proposals received under this BAA will be evaluated using merit based, competitive procedures based on the Evaluation Factors in Section II. G. of the BAA.
- All information necessary for the review and evaluation of a proposal must be contained in the proposal itself. No other material will be provided to the panel. Proposals should contain sufficient technical detail to allow for in-depth technical assessment.

Proposal Evaluation Criteria

Factors- descending area of importance

i. Scientific merit, soundness, and programmatic strategy of the proposed.

ii. Relevance and potential contributions of the proposed research to one or more of the topic areas.

iii. Qualifications and availability of the Principal Investigators and key co-investigators

iv. Rigor and completeness of the teaming plan. This will be considered as of equal importance as criteria iii. (Qualifications) above.

v. Applicants record of past performance.

vi. Realism and reasonableness of cost

Key Dates

EVENT	DATE
Whitepapers Due	15 February 2021
Selection of Whitepapers	22 March 2021
Full Proposals Due (Invite Only)	1 June 2021
Selection of Proposals	2 August 2021
Award	Est- late October 2021

* Please pay close attention to closing dates and times. Proposals submitted after the closing date will not be considered or evaluated by the Government.