Microsystems Exploration Topic (μE)
DARPA-PA-19-04-06
Heterogeneous Heterostructures (H2)

I. Topic Description

The Defense Advanced Research Projects Agency (DARPA) is issuing a Microsystems Exploration topic (μE) inviting submissions of innovative basic or applied research concepts in the technical domain of next-generation electromagnetic components and technologies. This μE is issued under the Program Announcement for Microsystems Exploration, DARPA-PA-19-04. All proposals in response to the technical area(s) described herein will be submitted to DARPA-PA-19-04 and if selected, will result in an award of an Other Transaction (OT) for a prototype project not to exceed $1,000,000.

A. Introduction

Today's state of the art (SoA) microwave and millimeter wave power amplifiers have been made possible by the creation of lateral and vertical heterojunction semiconductor devices, such as high electron mobility transistors (HEMTs) and heterojunction bipolar transistors (HBTs), respectively. To meet future mission requirements for longer range operation, wider bandwidth, and link robustness, power amplifiers with higher output power than can be achieved with today's SoA are needed. This in turn will demand radio frequency (RF) device structures that simultaneously exhibit higher charge density, higher breakdown field, good carrier transport properties, and high thermal conductivity – a combination of materials properties that does not exist today in any single material system. Researchers have theorized that potentially game changing device structures can be formed by integrating dissimilar materials to solve current device performance limitations, but have not succeeded in realizing these devices, primarily due to poor interface quality between dissimilar materials, which degrades the electronic properties.

B. Objective/Scope

The Heterogeneous Heterostructures (H2) program will create a new path for realizing high-power density, microwave and millimeter wave devices by demonstrating heterogeneous heterojunctions. In particular, the H2 program will explore and develop approaches to create low defect density interfaces between dissimilar (e.g., non-lattice matched) materials. These approaches will be used to create heterojunctions with low defect density ($< 3x10^{11}/cm^2$) and heterostructures which simultaneously exhibit high charge density, high breakdown field, good carrier transport properties, and high thermal conductivity to support the creation of RF transistors with a 10X increase in power density compared with today's SoA.

As an example, recent developments have shown that electrically clean interfaces between dissimilar materials could be achieved by a technique called "grafting."[1] Grafting involves joining two dissimilar materials with a uniform, thin, chemically active "glue layer," such as oxides or nitrides, to create a low defect density stable junction. Grafting has recently been used

[1] Lattice-mismatched semiconductor heterostructures" arXiv:1812.10225v1 **[physics.app-ph]**

to successfully join lattice mismatched semiconductor materials and to create nearly ideal diode junctions that closely match the ideal diode equation, demonstrating low-defect density, and therefore minimal carrier recombination, at the interface. Exploration of this technique with a wide variety of dissimilar materials is one approach that could be used to create a new set of candidate heterogeneous heterojunctions for the creation of high-power RF devices.

Electronic properties of heterostructures are extremely sensitive to changes in heterojunction structure, chemical composition, defectivity, etc. It is expected that the interfacial or "glue" layer may alter the band bending of dissimilar materials. Therefore, design of heterogeneous heterostructures will require refinement of models and simulations to account for heterojunction band alignments/offsets in the presence of interfacial layers. Models must also account for crystallographic orientation, thin film properties, and the impact of carrier density on transport properties and breakdown fields. These models will then be used to guide the design of heterogeneous heterostructures that meet the performance requirements of high-power RF devices.

The H2 program will demonstrate innovative new approaches for developing heterostructures and serve as a potential pathfinder for a future high-power density RF device program. Realistic device simulations developed within the program are expected to demonstrate a 10X increase in power density at microwave and millimeter-wave frequencies to enable wider spectral coverage, so that future radar, communications, and electronic warfare (EW) systems can deliver 3X longer range operation and support more complex wideband waveforms with 10X higher data rates. These devices will impact a broad array of microwave and millimeter wave applications including high-power solid-state sources, high-power per element phased arrays, and power amplifiers for size, weight, and power (SWAP) constrained applications.

C. Structure

Proposals submitted to DARPA-PA-19-04 in response to the technical areas of this μE topic must be UNCLASSIFIED and must address two independent and sequential project phases: a Phase 1 Feasibility Study (base) and a Phase 2 Proof of Concept (option). The periods of performance for these phases are 12 months for the Phase 1 base effort and 6 months for the Phase 2 option effort. Combined Phase 1 base and Phase 2 option efforts for this μE topic should not exceed 18 months. The Phase 1 (base) award value should not exceed $700,000. The Phase 2 (option) award value should not exceed $300,000. The total award value for the combined Phase 1 and Phase 2 is limited to $1,000,000. Phase 1 studies will be evaluated to determine the feasibility of the approach and whether to exercise the Phase 2 option. The program will support fundamental research.

The H2 program will consist of two technical areas (TAs): TA1 – Vertical Transport Devices and TA2 – Lateral Transport devices. Proposals are limited to a single TA and representative device. However, proposers may submit multiple standalone proposals to TA1 and TA2. Each proposal must be submitted as a separate proposal with no duplication of tasks.

D. Technical Area Descriptions

As stated above, the H2 program consists of two technical areas: TA1 – Vertical Transport Devices and TA2 – Lateral Transport devices. For both technical areas, proposers must define a specific lateral or vertical heterogeneous heterostructure microwave or millimeter wave device and the associated material/junction properties required to realize a 10X improvement in RF power density over SoA. Both technical areas will follow the same general program plan.

Phase 1: Develop new processes to form low defect density heterogeneous heterojunctions

Proposers will develop approaches to create heterogeneous heterojunctions and demonstrate low defect density interfaces and the presence of high carrier density, for example, a 2D electron or hole gas (for lateral devices), or near ideal p-n, p-p, or n-n junctions (for vertical devices) as required by the proposed high-power density device. Proposers will develop accurate physics-based models for heterojunctions including detailed layer diagrams, band bending, and electronic properties such as carrier concentration and defect density necessary to achieve the device goal. Proposals should describe their approach to assessing heterointerface structural quality, defect density, and electrical properties by physical interrogation and electronic methods. Proposers may plan to use TEM, AFM or other high-resolution microscopy to structurally characterize the heterogeneous heterointerfaces. Proposers may wish to fabricate Schottky diodes, p-n junctions, Hall structures or other heterojunction test structures and characterize them using Hall, C-V, I-V, DLOS and DLTS or similar techniques to determine the junction quality, interface state density, band offsets (ΔE_c or ΔE_v), interface charge, carrier mobility, mean free path, the presence of Shubnikov de Hass oscillation (in the case of lateral devices), etc. Proposers should also describe their approach for characterizing other test structures necessary to complete Phase 2 device modeling such as tunneling contacts.

Phase 2: Design novel heterogeneous heterostructures guided by accurate physics-based modeling and simulation.

Proposers will utilize the Phase 1 integration techniques in conjunction with physics-based modeling to design and demonstrate heterogeneous heterostructures that simultaneously meet or exceed the Phase 2 metrics. Proposers will implement a final device model that will be validated, and the properties of the resulting high carrier density, high breakdown voltage heterogeneous heterostructures will be assessed through transport, or other measurements, to confirm that the predicted band bending and electronic properties are achieved.

Program Metrics:

The following nominal metrics are included as a guidepost. By the end of Phase 1, high quality, low defect density heterogeneous heterojunctions will be developed. By the end of Phase 2, it is expected that heterogeneous heterostructures will be demonstrated that simultaneously meet or exceed the proposer-defined transport properties and device metrics. Proposers are required to meet the 10x SoA power density simulation and 100:1 carrier to heterojunction defect density metrics by the end of Phase 2.

H2	Frequency (GHz)	RF Power Density (W/mm)	Junction Defect Density (/cm^2)	Carrier Density (/cm^2)*	Mobility (cm^2/V-s)*	Vsat* (cm/s)	Breakdown Field (V/cm)*	Thermal Conductivity (W/m*K)*
Phase 1	Proposer Defined	N/A	50x < Carrier Density	1 X 10^{13}	N/A			
Phase 2		10x SOA (Simulated)	100x < Carrier Density	3 X 10^{13}	850	2 x 10^7	8 x 10^6	500

***** Nominal values and should be refined by proposer based on proposer-defined device requirements and must be achieved simultaneously.

In addition to the plan provided above, proposals should clearly detail:

- The proposed materials, heterojunction formation techniques, final heterostructure, and simulated high power density device concept, including any initial theory, simulations, or measured data to support performance claims required to meet the proposer-defined device metrics.
- The proposed device test bench and characterization method(s) to demonstrate successful attainment of performance goals at the end of Phase 1 and Phase 2.
- Phase 1 and Phase 2 measurable milestones, the expected deliverables at the end of each phase, and schedule.
- Risks and risk mitigation strategies.

E. Schedule/Milestones

Proposers must address the Research Project Objectives, metrics, and deliverables, along with fixed payable milestones in their proposals. The task structure must be consistent across the proposed schedule, Task Description Document (TDD), and the Vol. 2 - Price Volume. If selected for award negotiation, the fixed payable milestones will be directly incorporated into Attachment 3 of the OT agreement ("Schedule of Milestones and Payments") with milestone amounts calculated based on the proposed accumulation of monthly amounts up to each milestone date. Please see the sample OT for Prototype provided as an attachment to DARPA-PA-19-04.

Fixed milestones for the program must include:

Milestone #	Milestone	Exit Citeria /Deliverable	Due Date
Phase 1			
1	Report on junction fabrication approaches and completion of test measurement setup.	Milestone Report	Month 2
2	Report on baseline heterogeneous heterojunction defect density and future defect mitigation plans. Baseline 2D electron or hole gas properties (for lateral devices) or p-n junctions ideality factor (for vertical devices)	Milestone Report	Month 4
3	Report on reduced heterogeneous heterojunction defect density and revised defect mitigation plan; improve junction defect density and 2D electron or hole gas properties (for lateral devices) or p-n junctions ideality factor (for vertical devices), targeting carrier densities of proposer defined device.	Milestone Report	Month 6
4	Report on reduced heterogeneous heterojunction defect density and revised defect mitigation plan; improve junction defect density and 2D electron or hole gas properties (for lateral devices) or p-n junctions ideality factor (for vertical devices), targeting carrier densities of proposer defined device.	Milestone Report	Month 9
5	Improve junction defect density and 2D electron or hole gas properties (for lateral devices) or p-n junctions ideality factor (for vertical devices). Demonstrate heterogeneous heterojunctions with 50:1 carrier to defect concentration ratio and carrier concentrations or ideality factors required by phase 2 device. Improve Updated physics and device models. Report detailing program plan for Phase 2.	Milestone Report / Measurable Structures for IV&V	Month 12
Phase 2			
6	Baseline transport properties of the heterogeneous heterostructure. Compare against phase 2 metrics. Initial report on heterogeneous heterosturctures, integration and transport measurements. Heterostructure optimization plan.	Milestone Report	Month 13
7	Midphase report on heterogeneous heterosturctures, integration and transport measurements	Milestone Report/ In Person PI Review	Month 15
8	In person demonstration of final heterostructure characteristics demonstrating simultaneous exhibition of phase two metrics.	Milestone Report/ Live Demo	Month 17
9	Final Report on heterostructure measurements and device models projecting 100:1 carrier/defect ratio and device simulation showing 10x power density over state of the art.	Milestone Report / Measurable Structures for IV&V	Month 18

For planning and budgetary purposes, proposers should assume a program start date of July 7, 2021. Schedules will be synchronized across performers, as required, and monitored/revised as necessary throughout the program.

All proposals must include the following meetings and travel in the proposed schedule and costs:

- To foster collaboration between teams and disseminate program developments, a one-day virtual kickoff, and virtual Principal Investigator (PI) meetings will be held approximately every six months due to the current difficulties traveling due to COVID19. In addition, for budgeting purposes, plan for one two-day meeting to potentially be held in Phase 2, in the Washington, D.C. or San Francisco, CA area.
- Regular teleconference meetings will be scheduled with the Government team for progress reporting of each milestone, as well as problem identification and mitigation. Proposers should also anticipate at least one site visit in Phase 2 by the DARPA Program Manager, during which they will have the opportunity to demonstrate progress towards agreed-upon milestones.

F. Deliverables

Phase 1 and 2 deliverables will be reports detailing the results of the Phase 1 and 2 milestones as indicated in Sections D and E. This includes the submission of written reports and supporting PowerPoint presentations via teleconference or in person for each milestone. In addition, at least two samples of measurable heterojunctions and heterostructures will be delivered to the government team for independent verification and validation in each phase as specified in the milestone chart.

II. Award Information

Selected proposals that are successfully negotiated will result in the award of an OT for a prototype project. See Section 3 of DARPA-PA-19-04 for information on awards that may result from proposals submitted in response to this notice.

Proposers must review the model OT for Prototype provided as an attachment to DARPA-PA-19-04 prior to submitting a proposal. DARPA has provided the model OT in order to expedite the negotiation and award process and ensure DARPA achieves the goal of Microsystems Exploration, which is to enable DARPA to initiate a new investment in less than 90 days from each μE topic announcement. The model OT is representative of the terms and conditions that DARPA intends to award for all Microsystems Exploration Awards. The task description document, schedule of milestones and payments, and data rights assertions requested under Volumes 1, 2, and 3 will be included as attachments to the OT agreement upon negotiation and award.

As discussed in DARPA-PA-19-04, Section 5, "Application and Submission Information," proposers may suggest edits to the model OT for consideration by DARPA and provide a copy of the model OT with track changes as part of their proposal package. It is strongly encouraged that proposers include comments providing the rationale for any suggested edits of a non-administrative nature. Suggested edits may be rejected at DARPA's discretion. In order to ensure that DARPA achieves the Microsystem Exploration goal of award within 90 days from the posting date of the μE topic announcement, DARPA reserves the right to cease negotiations if the parties fail to reach an agreement on OT award terms and conditions within this time period. If edits to the model OT are not provided as part of the proposal package, DARPA assumes that the proposer has reviewed and accepted the award terms and conditions to which they may have to adhere and the sample OT agreement provided as an attachment, indicating agreement with the listed terms and conditions applicable to the specific award instrument.

III. Eligibility

See Section 4 of DARPA-PA-19-04 for information on who may be eligible to respond to this notice.

IV. μE Topic Responses

Responses to this μE topic must be submitted as full proposals to DARPA-PA-19-04 as described therein. All proposals must be unclassified.

A. Proposal Content and Format

All proposals submitted in response to this notice must comply with the content and format instructions in Section 5 of DARPA-PA-19-04. All proposals must use the templates provided as Attachments to the PA and follow the instructions therein.

Information not explicitly requested in DARPA-PA-19-04, its Attachments, or this notice may not be evaluated.

B. Proposal Submission Instructions

See Section 5 of DARPA-PA-19-04 for proposal submission instructions.

C. Proposal Due Date and Time

Proposals in response to this notice are due no later than 4:00 PM on May 6, 2021. Full proposal packages as described in Section 5 of DARPA-PA-19-04 must be submitted per the instructions outlined therein *and received by DARPA* no later than the above time and date. Proposals received after this time and date may not be reviewed.

Proposers are warned that the proposal deadline outlined herein is in Eastern Time and will be strictly enforced. When planning a response to this notice, proposers should take into account that some parts of the submission process may take from one business day to one month to complete.

V. Proposal Evaluation and Selection

Proposals will be evaluated and selected in accordance with Section 6 of DARPA-PA-19-04. Proposers will be notified of the results of this process as described in Section 7.1 of DARPA-PA-19-04.

VI. Administrative and National Policy Requirements

Section 7.2 of DARPA-PA-19-04 provides information on Administrative and National Policy Requirements that may be applicable for proposal submission as well as performance under an award.

VII. Point of Contact Information

Thomas Kazior, Program Manager, DARPA/Microsystems Technology Office, H2@darpa.mil

VIII. Frequently Asked Questions (FAQs)

All technical, contractual, and administrative questions regarding this notice must be emailed to H2@darpa.mil. Emails sent directly to the Program Manager or any other address may result in delayed or no response.

All questions must be in English and must include name, email address, and the telephone number of a point of contact. DARPA will attempt to answer questions publically in a timely manner; however, questions submitted within 7 days of the proposal due date listed herein may not be answered.

DARPA will post an FAQ list under the μE topic on the DARPA/MTO Opportunities page at (http://www.darpa.mil/work-with-us/opportunities) The list will be updated on an ongoing basis until one week prior to the proposal due date. In addition to the FAQ specific to this notice, proposers should also review the Program Announcement for Microsystems Exploration General FAQ list on the DARPA/MTO Opportunities page under the Program Announcement (DARPA-PA-19-04).

To aid in the proposal preparation process, a Proposal Preparation Checklist and Tips document has been provided with the μE topic announcement on beta.sam.gov. This document can also be found along with the FAQ posted on the DARPA/MTO Opportunities page at (http://www.darpa.mil/work-with-us/opportunities).