INTEL REQUEST FOR PROPOSALS (RFP)

2D PMOS Intel Strategic Research Area (ISRA)

SUBJECT

Intel's University Research & Collaboration Office (URC) requests proposals for a center focused on 2D PMOS transistors.

Beyond Intel's announced nanoribbon GAAFET, few transistor scaling options exist. 2D transition-metal-dichalcogenide (TMD)-based CMOS will theoretically outperform Si GAAFET at short gate lengths. Experimentally, however, most of the research community is focused on NMOS improvements, whereas CMOS needs both PMOS and NMOS to function. This center is a focused effort to reach FEOL PMOS performance targets. Improvements are needed in 2D PMOS material quality, 2D PMOS contact and doping schemes, and basic 2D defect meteorology that is predictive of device performance.

KEY DATES

- **Information session for proposers:**
  Intel's research staff will be available for a conference call on **March 29th and April 4th** at **2PM PST** (conference call details to be shared upon request) to answer questions and provide additional clarifying information regarding the RFP**.** Additional information sessions (up to two more, dates TBD) will be scheduled based on requests

- **Proposal Submission Deadline: May 4th, 2022 at 5:00pm PST**.
  All materials must be submitted to roman.caudillo@intel.com, kevin.p.obrien@intel.com, and carl.naylor@intel.com no later than the deadline above to be eligible for review and selection. Please include "RFP 2D PMOS ISRA" in the Subject of your email.

- **Planned Award Notification: June 15th, 2022.**

- **Planned Projected Research Start: September, 2022.**

OVERVIEW

2D transition-metal dichalcogenides (TMD) have been identified as a promising replacement for Silicon transistors at future scaling nodes. 2D TMDs enable gate scaling down to 5nm channel length, theoretically without subthreshold swing deterioration. Much progress in the community has been made in understanding 2D NMOS TMD devices, but very little work has been completed on PMOS devices. CMOS needs both NMOS and PMOS to function. This request for proposals is seeking to generate academic interest in solving the other half of the CMOS scaling issue.

Intel invites innovative research proposals under the research vectors listed below; we strongly encourage collaborative proposals. We intend to encourage collaboration between PIs throughout the 2D center, with regular engagements.

The overarching goals or research vectors (RVs) of the center are the following:

RV1. Prototype a PMOS 2D device hitting key performance targets: > 600uA/um Ion, low contact resistance (Rc) <= 200 Ohm-um with electrostatic gating and subthreshold slope (SS) < 100 mV/decade, proof of principle.

RV2. Low PMOS contact resistance without electrostatic gating; solutions need an integration path to 300mm.

RV3. High-throughput, non-destructive and predictive metrology of 2D PMOS mobility and/or defect density and type.

PROGRAM SCOPE AND FUNDING

This program contemplates funding a small center of 3-year funded research proposals that are renewable annually, contingent on measurable and tangible satisfactory progress and continued promise in the research direction of the proposal. The 3 research vectors (RVs) in this center should include a comprehensive scope of research across materials, devices, and metrology. We suggest that each submitting PI submit a proposal centered around 1 RV, identifying their expertise, experience, and tangible expected results. However, we encourage multiple PIs with coordinated proposals that combine multiple research vectors to address the broader technical objectives through a small team of graduate students and post docs. Salient aspects of the center are as follows:

(1) There is a material, device, and knowledge exchange between the performing PIs, students, and postdocs in the center.

(2) Periodically, materials, devices, and metrology evaluated at Intel, towards development of 2D CMOS FEOL technology.

(3) PIs are expected to be able to transfer the 2D material growth technology, device physics, and modeling know-how to Intel within the framework of the center.

(4) There will be monthly review meetings with Intel and each PI's group to review progress, staggered weekly across the PIs

(5) There will be an initial kickoff meeting with all participants present (in-person, if possible, virtual if pandemic still preventing in-person). At the end of the 1st year, there will be another in-person meeting, COVID willing, with all center members. After the first year, we will have biannual center meetings (one in-person and one virtual).

TECHNICAL OBJECTIVES

The core of this proposal is to accelerate development and scientific understanding of 2D p-type transistors, in furtherance of Moore's law scaling. In 2D transistors, contact resistance, doping and defect densities are clear roadblocks.

This center will be a collaborative center with 3 research vectors (RVs) in order to have a comprehensive study and improvements to 2D TMD p-type deposited transistors that demonstrate viability of manufacturable 2D CMOS. The following sections describe the detailed research vectors (RVs) and possible associated research tasks that are expected to achieve the desired research outcome:

RV1 – Demonstration of a PMOS 2D device that simultaneously hits all performance targets.

This research vector will provide a comprehensive study and optimization of 2D TMD material growth technology, device structure, channel engineering, and device contact properties for 2D PMOS transistors. Two or three PIs are expected in this research vector. The goal is both a scientific and engineering objective. We hope to demonstrate a path forward for 2D PMOS that is competitive with silicon transistors. This requires fundamental improvements which allows simultaneously hitting the top 3 PMOS transistor performance metrics, the ultimate 2D challenge. Simultaneously prototype an Ion > 600uA/um with contact resistance (Rc) <= 200 Ohm-um at a sub 100 mV/dec subthreshold swing. Electrostatically doping of the contacts is acceptable for this RV. The devices cannot be from exfoliated bulk PMOS material or "random" monolayer grown PMOS flakes, but rather from monolayer grown films on either the as grown substrate and/or transferred. To achieve these results, we strongly believe improvements are needed in fundamental materials, doping, passivation and contact innovations. The final result will be the following: (1) fabricated single-layer device hitting *all* PMOS preliminary targets and (2) recommended growth method/material and contact method for tech transfer to Intel.

RV2 – Realistic 2D doping strategy

Modern transistors need atomic doping in the contact regions to lower contact resistance. Currently, there are a handful of academic studies on PMOS doping methods. This RV will focus on finding the correct doping strategy; either replacing the metal or the chalcogenide atom in TMD or a new option only available to 2D monolayer materials (e.g., remote surface doping). The PI will be responsible for demonstrating doping control of a monolayer PMOS grown film and not using exfoliated material. We strongly recommend the PI leading RV2 collaborate with the PI yielding the films in RV1. This research will facilitate new doping ideas available to 2D transistors to accelerate the technology interception timeline. The final result will be a 2D transistor with an Ion/Ioff ratio > 10^5 without electrostatic doping of the contact region.

RV3 – Predictive metrology on 2D materials

We believe 2D transistor mobility is currently limited by point defects and there is no accepted non-destructive metrology technique to quantify point defect levels; therefore, there is no precise predictive metrology for device performance. We recognize the contributions of both TEM and STM to quantify and characterize defects, but these are of limited values as a predictive metrology in an industrial setting. RV3 will be focused on developing a predictive metrology and thus give real time feedback to both RV1 and RV2 to accelerate PMOS development. We highly encourage the PI leading RV3 to continuously work with the PIs in RV1 and RV2 and utilize the same as-grown material, not exfoliated material. We envision a team where the metrology predicts the device level performance. A predictive metrology is a game changer.

Addendum on multi-PI co-ordination: PIs are expected to submit individual, single PI proposals with an addendum section showing the integration with the multi-PI effort. Proposals that show a clear vision supported by strong theoretical understanding, clear materials track record and analytical framework showing the ability to meet the figures of merit will be prioritized. Universities and research centers in Europe and Asia are also encouraged to apply.

PIs must submit separate whitepaper per technical task (at the granularity of 1-2 PhD students or 1 postdoc). This is to allow the flexibility for the advisory panel to select the best PI for each category. Leveraging the funding with regional government funds, research center grants and/or national institutes is highly encouraged wherever possible but is not considered a requirement.

PROPOSAL FORMAT

Please note that Intel is unable to receive proposals under an obligation of confidentiality. All proposals submitted should therefore include only public information.

Proposals should be 3-6 pages, not including citations or cost volume. Slight preference will be given to proposals that aim at defining a project for one Principal Investigator (PI) for up to three years. Researchers can be part of only one proposal. Each proposal should comprise the following sections:

• **Proposal cover page (max 1 page)**

- Organization
- List of PIs and the main contact person
- List one research vector or at most 2 targeted research vectors
- List intended close collaboration PI submitting to other research vectors
- Executive summary including intended outcomes. Summarize the key elements of the proposal.

• **High-level motivation, preliminary results, approach, and proposed goals for the research questions (<= 3 pages).** Briefly describe the motivation for the proposed project, preliminary results, techniques (especially novel ones) that underpin the approach, and the plan of tackling the proposed research questions. Summarize what will have been accomplished after 3 years if all goes according to plan. Be sure to detail the current state-of-the-art for the proposed technology (or nearest related technologies). This section must also include an explicit statement of the Intellectual Property (IP) status for all background IP related to this technology (i.e., are the property rights to this technology protected, and if so, who owns those rights).

• **Statement of work, schedule, milestones, success criteria and deliverables (<=3/4 page).** For each of the goals addressed, outline the 3-year scope of the effort, including tasks to be performed, schedule, milestones, deliverables, and success criteria. It is understood that aspects of this research effort may be exploratory in nature and schedules/deliverables reflect intentions rather than a firm commitment.

• **Personnel plan and expertise statement (max. 1/4 page per Researcher).** Include a list of key personnel (at most 6) plus a statement on each person's role and time commitment. For each person, please add a brief bio or web page link and list their 6 most relevant prior publications (within the last 8 years) for the selected research questions.

• **Student plan (<1 page).** In light of Intel's strong commitment to diversity and creating an inclusive environment, please address: (a) your organization's commitment to diversity and inclusion with respect to race, national origin, gender, veterans, individuals with diverse

abilities and LGBTQ, (b) a summary of your performance in this area and any initiatives you are pursuing, and (c) the diverse team you propose for this project, and information about the PhD students and postdocs you envision to assign to this project (if known). Outline the approach and plan whereby PhD students will be recruited and incorporated into the team, and any plans for encouraging/supporting those students in collaborations with Intel (e.g., availability for Internships should a mutually interesting opportunity arise). If the PIs have a pre-existing relationship and history of student hiring by Intel please discuss issues/plans/ideas to continue or strengthen that connection.

- **Prior Intel Collaborations (max 1/3 page per project).** If you collaborated with Intel in the past, please list the project/institute, the year, and the main contact(s) at Intel. Furthermore, add a short abstract outlining the scope.

- **Past Successful Technology Transfers (<=1 page).** Evidence of past successful industry collaborations and technology transfers. Examples include startups, products, and other evidence of tangible business impact of the involved academics.

- **Budget and Financials (1/3 page).** Typical grants are USD $150K per year for three years. We plan to work under an Open Intellectual Property model (results are published, code is open sourced). Our goal is to maximize the available research ideas for our fixed amount of total funding. Universities may propose how to achieve this. Please also indicate how many researchers (FTE) can contribute their research for the proposed funding.

- **IP-compatible funds amplification (no limit).** If the team can obtain funding for related work from other sources (including the University) and the sponsor commits to follow a public dedication approach for that project or provide Intel with non-exclusive, royalty-free **research and commercial** licenses to any IP, the team may list funding that would be considered to amplify the proposed project.

- **Citations (unlimited).**

- **Cost volume (unlimited)**. Cost proposal in Excel or another format as appropriate

EVALUATION CRITERIA

In order of importance, the evaluation criteria for this solicitation are as follows:

1. **Potential contribution and relevance to Intel and the broader industry:** The proposed research should directly support a technology solution that addresses the RVs outlined above, leading to technological advances with the potential for ongoing technology transfer in collaboration with Intel and the broader industry.

2. **Technical innovation:** Proposed solutions of interest should clearly push the boundaries of technical innovation and advancement. Research that is not of interest in this program include incremental advancements to state-of-the-art and current design practices. Feasibility of new algorithms/techniques should be demonstrated through SW/HW implementations.

3. **Clarity of overall objectives, intermediate milestones, and success criteria:** The proposed Research Plan should clearly convey that the PIs have the knowledge and capability to achieve the stated research goals. It is understood that any research program will have uncertainties and

unanswered questions at the proposal stage, but a clear path forward in key challenge areas must be identified and justified. Teams are expected to demonstrate progress toward project goals at quarterly milestones and monthly project status updates. As detailed in the "Program Scope and Funding" section, the proposal should explicitly point out which RV is being addressed, the synergy among them if more than one RV, the plan and milestones towards building research prototypes, plan for ongoing technology transfers, and the anticipated proof of concept outcome. Strength of project management will also be considered.

4. **Qualification of participating researchers:** The extent to which expertise and prior experience bear on the problem at hand. Please elaborate on track records of building research prototypes (e.g., open-source research code/collaterals on GitHub) and resulting publications from past relevant projects.

5. **Cost effectiveness and cost realism:** The extent to which the proposed work is both feasible and impactful within the proposed resource levels will be examined.

6. **Potential for co-funding:** Opportunity for closely synergistic matching grants and co-funding with other funding entities, such as SRC, NSF, DARPA, NSERC, etc., will be given significant consideration.

7. **Potential for broader impact:** As an industry leader, Intel pushes the boundaries of technology to make amazing experiences possible for every person on earth. From powering the latest devices and the cloud you depend on to driving policy, diversity, sustainability, and education, we create value for our stockholders, customers, and society. Intel expects the academic community to be strong partners in making Intel successful through support of Intel's goals and commitments to diversity, sustainability, and education. Intel supports the advancement of computing education and diverse participation in STEM. Significant consideration will be given to proposals in which the outcome of the research can influence the development of new curriculum initiatives impacting undergraduate or graduate education at the respective universities (e.g., exposure to latest industry technologies/tools in classroom setting). Proposals are encouraged to elaborate on how the proposed work is anticipated to impact student education on campus and/or the broader academic community.

PI MEETINGS AND COLLABORATION STRUCTURE

Intel will be deeply engaged with the center and will assign partner technologists/collaborators across RVs to interact with the academic community to produce a stream of innovation proof points, publications, demonstrations, and technology transfers into Intel and the broader industry throughout the duration of the program. We aim for the interaction to be bi-directional where Intel collaborators are part of the research team. Not only will they provide research feedback, but they will also actively contribute and co-develop the research to amplify the center outcome and enable continuous technology transfers into Intel and the broader industry.

It is expected the PI and student researchers will collaborate on a daily or weekly basis. PIs and their groups are expected to report out to Intel on a monthly cadence, virtually, on progress and help needed. PI, student and Intel collaborator meetings will be used to review research results, present significant updates, and provide feedback.

Semi-annual face-to-face or virtual meetings will be held to facilitate center-wide information exchange, review, and discussion of research. Researchers should anticipate one annual face-to-face meeting to be held at an Intel site in the US or Europe and one annual face-to-face meeting to be held at a university associated with this center. Associated travel costs for two annual meetings should be considered and included in the proposed budget. In the event unexpected travel restrictions prohibit a face-to-face meeting, a virtual meeting will be held.

To aid in collaboration across projects within the center and communication of research findings to the public, it is anticipated that a center website will be established, hosted, and maintained. Intel requests the right to host the associated website link on their respective university program websites.

Intel will offer free access to Intel's Academic Compute Environment, a resource for academia researchers in the center to exercise their workloads on Intel's latest hardware.

For those researchers who are already funded and seek collaboration opportunities with Intel and other researchers in the area of this RFP, please let us know. One option is to participate in center activities (e.g., seminars, workshops, and hardware access) without Intel funding.

ELIGIBILITY

This RFP is open only to academic researchers and institutions that have been specifically invited to participate in the proposal process. However, invitees may freely select additional academic collaborators. Any questions regarding eligibility should be directed to Roman Caudillo.

INTELLECTUAL PROPERTY

This solicitation affords proposers the choice of submitting complete program proposals for the award of a gift, grant, a Sponsored Research Agreement, or other agreement as appropriate. Intel reserves the right to negotiate the final choice of agreement.

INTEL TEAM CONTACT INFO

The following individuals from Intel are actively involved with the creation of this center:

Roman Caudillo: roman.caudillo@intel.com

Kevin O'Brien: kevin.p.obrien@intel.com

Carl Hugo Naylor: carl.naylor@intel.com

Please send proposal submissions and related inquiries to the above contacts; and please include "RFP 2D PMOS ISRA" in the Subject of your email.

FAQ

1. What is the typical grant and proposal team size?
Proposals generally request grants of approximately $150K per year. This would typically support 1 or 2 graduate students advised by 1 or 2 PIs. We expect to receive roughly 20 proposals and award 3-4 grants.

2. What is the envisaged project duration?
Three years (there is a renewal process each year, but proposals should outline all 3 years).

3. Do you consider proposals primarily concentrating on theory/simulations?
Proposals should be more experimental centered but theory submissions are still welcome.

4. Can you specify which researchers have been invited to this RFP?
We don't release the names of invited researchers. Keep in mind that if you are seeking to partner with a specific academic PI, your partners do not have to be invited; you can choose to partner with any PI and share the RFP with them.

5. Are we encouraged to seek co-funding opportunities?
While co-funding is not required, a proposal with co-funding or matching funding would be a strong plus.