Progress and Plans of National Nanotechnology Initiative (NNI) Agencies

December 2019

Department of Defense (DOD)[1]

Summary

Recognizing the revolutionary impact that nanotechnology and nanomaterials may have on our future warfighting capabilities, the Department of Defense continues to pursue foundational research in these technologies to support the modernization of the current force. Nanotechnology shows great promise to allow the ability to design unique materials to achieve improved properties and capabilities, including novel sensing capabilities/modalities, lightweight, stronger materials for protective applications, and expanded uses in medical devices, environmental remediation, and additive manufacturing. The Department is committed to maintaining a broad base of fundamental and applied nanoscience research capabilities and expertise within its laboratories, in partnership with small businesses and academia, and continues to collaborate with other Federal agencies to develop, identify, and cultivate nanotechnology-enabled materials, sensors, devices, and advanced manufacturing technologies for transition into the defense industrial base. The Department conducts these efforts through the use of broad agency announcements and funding opportunity announcements, as well as through DOD Manufacturing Technology, Defense Production Act Title III, Defense Innovation Unit, Manufacturing USA, and Small Business Innovation Research/Small Business Technology Transfer programs to build and strengthen partnerships in support of the National Defense Strategy.

Air Force

Summary

Nanoscience underpins innovations that are critical to future air, space, and cyber capabilities outlined in the Air Force (AF) 2030 Science and Technology (S&T) Strategy and the 2018 National Defense Strategy, such as universal situational awareness, the delivery of precision effects anywhere, protection of our airmen, and ability to access and survive in the battlespace. Due to extensive global investment, research in nanoscience has exploded over the past two decades, creating many new self-sustaining research communities, such as metamaterials, quantum materials, energy harvesting technologies, nanochemistry, bio-nanotechnology, nanoelectronics, etc. This profusion of nanoscience is reflected within AF S&T; nanotechnology-related

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activities or assessments of nanotechnologies span all segments of the S&T portfolio (e.g., weapons, directed energy, air vehicles, space vehicles, information technology, sensors, airman performance, materials & manufacturing). Accelerated integration of these fundamental opportunities into AF technology development, however, is challenged by excessive technical risk due to a lack of application-specific validated digital design tools, inadequate characterization techniques, unstable supply base, missing standards, and lack of application-specific manufacturing. Therefore, the Air Force Research Laboratory (AFRL) nanoscience strategy is to assess these fundamental innovations in the context of competing technology options via 6.2 and 6.3[2] investment, and leverage global innovations via 6.1 investment to address critical path challenges if appropriate. The pervasiveness and comparative nature of these activities is most efficiency executed within the context of portfolio-based research and development programs; and thus there is no longer a centrally managed AF nanoscience program. Interagency partnerships, such as with NIST, NSF, and DOE National Laboratories,[3] are being established to accelerate the creation of new nanoscale characterization techniques and standards to address requirements for in-line metrology tools and assessment of reliability. Example areas of AF nanotechnology integration that are establishing risk-reduction approaches to quantitatively assess performance enhancement opportunities include the following:

- Multifunctional structural materials to harden electronics from electromagnetic threats, maintain structural performance during hypersonic conditions, and enable the ability to manufacture components that perform multiple task via additive manufacturing.
- Materials and components to increase efficiency and reduce weight of directed energy assets.
- Lightweight and pliable electronic systems, such as antennas, batteries, and power conditioning systems that can be integrated into the surface of unmanned aerial vehicles to extend mission duration and capability.
- Physiological and biological sensors in the form of disposable patches to monitor human performance in stressful missions, improve airman-machine interface, and enable autonomy for operators such as pilots, air traffic controllers, and first responders.
- Increased security, bandwidth, data storage, and processing through miniaturized electronic and optical devices to enable encryption, as well as seamless spatial and temporal fusion of diverse sensor streams with trust.
- Agile intelligence, surveillance, and reconnaissance (ISR) components with increased broadband data transfer including radio frequency (RF) systems and hyperspectral electro-optic sensors through the use of nanostructured materials and structures to increase resolution, spectral performance, operating temperature, and autonomous distributed analysis of extremely large data sets to obtain meaningful and actionable information.

Plans and Priorities

The AFRL nanoscience strategy is to leverage global innovations via 6.1 investment, and assess these fundamental innovations in the context of competing technology options via 6.2 and 6.3 investment. The pervasiveness and comparative nature of these activities is most efficiency executed within the context of portfolio-based research and development programs; and thus the centrally managed AF nanoscience

[2] DOD budget activity codes: 6.1 (basic research), 6.2 (applied research), 6.3 (advanced technology development). See: https://crsreports.congress.gov/product/pdf/IF/IF10553.

[3] See https://www.nano.gov/partners for a list of Federal Government agencies participating in the National Nanotechnology Initiative (NNI), including their acronyms.

program has been terminated. Therefore, ongoing programs or new program priorities are not available to map against PCAs.

Example activities and associated budget estimates noted below are representative of nanotechnology-related activities within AF 6.1 investment and 6.2/6.3 research and development portfolios. These examples are not inclusive given the pervasiveness of AF nanoscience-related activities.

Key Technical Accomplishments by NNI Goal

Goal 1. Advance a World-Class Nanotechnology Research and Development Program

AFRL scientists, in collaboration with Ohio State University, the Indian Institute of Technology (Madras), and Western Digital, recently demonstrated a new method for detecting magnetic dynamics using incoherent relaxation of nitrogen vacancy centers in diamond. This technique enables high-resolution imaging of magnetic dynamics at the nanoscale, potentially uncovering new mechanisms for, and elucidating existing mysteries in, how energy moves in a ferromagnetic system. This capability will be instrumental in the improvement of technologies relying on low-damping magnetic materials, such as conventional microwave and RF components for ISR and electronic warfare (EW).

An AFRL-funded program at the University of Southern California established mechanisms that mediate energy conversion and charge transmission at the interface between living cells and synthetic surfaces. These findings have implications for cell physiology and bioelectronics, and may lead to the development of new hybrid materials and renewable energy technologies that combine the exquisite biochemical control of nature with the synthetic building blocks of nanotechnology.

An AFRL-funded program at Pennsylvania State University discovered unique, conductive edge states in a new class of two-dimensional (2D) perovskite materials. These unique properties hold promise for improving performance of solar cells, LED technology, and nanoelectronics by providing additional charge pathways within the devices. This discovery is also opening the door for the development of innovative one-dimensional electrical conduction in nanoelectronics.

An AFRL-funded international program, including activities at the University of Texas at Dallas and multiple Asian institutions, has resulted in the invention of several types of strong, powerful artificial muscles using materials ranging from high-tech carbon nanotubes (CNTs) to ordinary fishing line. Concepts such as sheath-run artificial muscles, or SRAMs, provide even greater design flexibility, allowing for the replacement of CNT yarns with less expensive yarns. These muscles are very attractive for intelligent structures, such as robotics and comfort-adjusting clothing.

Goal 2. Foster the Transfer of New Technologies into Products for Commercial and Public Benefit

AFRL's Nano-Bio Materials Consortium (NBMC), including industrial, academic, and venture capital partners, is advancing aeromedical monitoring capabilities for En Route Care and Aeromedical Evacuation missions. $5.7 million in R&D activities, and an associated $6.1 million in member cost share, will advance technologies and components that enable stress monitoring, tissue-level oxygen/biochemical monitoring, AI for multi-modal physiological monitoring, and wireless vital sign monitoring devices for ambulatory patient monitoring. These efforts focus on establishing a foundation for new dual-use products in digital health and personnel medicine that address strategic requirements within the AFRL Operational & Aeromedical Health Product Line.

AFRL, in collaboration with industry, has expanded the supplier base of Nano-Composite Optical Ceramics (NCOC) through validation of NanoSpray Combustion manufacturing. NCOC is a proprietary nanopowder composite of The Raytheon Company and is used in the manufacturing of missile radomes.

AFRL scientists, in collaboration with Purdue University, developed and tested a hyperspectral filter made from three-dimensional (3D) plasmonic nanoarrays to detect human pathogens with molecular fingerprints that are otherwise difficult to distinguish. These structured nanoscale metamaterial filters are >100x smaller than conventional optics used for hyperspectral imaging applications. These filters, used in conjunction with focal plane arrays (FPAs), are being developed for AF space and airborne applications to instantaneously identify missile threats and many other air and ground targets at much longer ranges in hidden and camouflaged environments with improved reliability. This will enable new ISR capabilities not possible today due to size, weight, and power constraints.

AFRL scientist have recently built upon their fundamental studies of the growth of colloidal gold nanorods to solve numerous production bottlenecks, including throughput, reagent waste, purification, and processability. This fabrication approach is at least 100x more efficient (time and production volume) while using 100x less toxic reagents than current state-of-the-art alternatives. Also, their fundamental investigations provided routes to enhanced nanoscale shape control, which translates into optical performance that approaches theoretical maximum, and the ability to tune absorptivity from the visible to the infrared. The combination of reduced cost, enhanced performance, and facile processability creates an enabling platform technology, with applications ranging from imaging and colorimetric biosensors, to large-area coatings, filters, and embedded reporters for *in-situ* process control. The team's patent portfolio has been licensed, with initial market transitions to bioimaging, built-environment thermal control, optical filters, optical absorbers, and specialty defense materials.

An AFRL-funded program at Harvard University demonstrated nanoscale devices for intracellular recording, the first nanotechnology developed to record electrical chatter inside a live cell. The team has recently designed a way to make thousands of these devices at once, creating a nanoscale army that could speed efforts to find out what's happening inside our cells.

An AFRL-funded program at Florida State University developed a carbon nanotube veil infused with phenol-based resin with superior heat dissipation characteristics for future hypersonic aeroshells. The composite sheets are highly anisotropic, and the CNTs have orders of magnitude higher thermal conductivity in-plane than carbon fiber. This results in the ability of the CNT composite to disperse heat at about 1/6th the thickness of conventional composites. Manufacturing innovations in recent years have brought down the cost of CNT sheets and veils, however further affordable manufacturing improvements are necessary.

AFRL is leading the development of cooperative partnerships between industry and national laboratories to establish synchrotron–based facilities to accelerate the establishment of processing-structure-property relationships for materials, including nanomaterials. For example, empirical and trial/error methods are used to obtain optimal cure cycles during processing of polymer matrix composites, which leads to high failure rates in production with minimal understanding to the primary causes. Crucial to reducing waste is to experimentally validate models with *in-operando* experiments. Collaboration under a cooperative research and development agreement (CRADA) between AFRL and Boeing and support by beamline scientists at the National Synchrotron Light Source II at Brookhaven National Laboratory led to new insights in the complex crosslink reactions of AF-relevant thermosetting resins by using nanoparticle probes in x-ray photon correlation spectroscopy experiments. Similar partnerships are being established with NIST and CHESS (Cornell High Energy Synchrotron Source) to enable complex processing and residual stress model validation, with the goal of improving mechanical properties, thermal stability, and overall life-cycle performance.

Navy

NRL Nanoscience Program

FY 2021 Plans and Priorities

Signature Initiatives and Grand Challenge (PCA 1)

In the area of nanoelectronics, NRL is developing heterostructures of 2D materials for spintronic applications. For the Sensors Nanotechnology Signature Initiative (NSI), NRL plans to investigate chemical sensor platforms for detecting the cellular signals that control wound healing. In the area of the Future Computing Grand Challenge, NRL is investigating nanophotonic approaches to quantum information processing and reservoir computing.

Foundational Research (PCA 2)

NRL anticipates continued efforts in the area of foundational research. This research includes efforts in phonon-polariton lattices, controlling magnetism in metamagnetic nanostructures, enhanced optical properties in hybrid nanostructures, and quantum-coherent networks in DNA origami structures.

Nanotechnology-Enabled Applications, Devices, and Systems (PCA 3)

NRL is developing new approaches to interface with and control biological systems. These approaches include the development of "protonic" devices for actuating cells and self-assembled nanoscale transducers that can wirelessly control living cells. Additionally, NRL is developing dimensionally-confined biological catalysts and multiscale architectures for chemical catalysts.

Key Technical Accomplishments

NRL scientists are exploring methods to exploit DNA as both a structural and informational molecule to develop modular transducers that convert enzyme activity into DNA signals, which can subsequently be amplified, combined, or processed, e.g., to reduce false positives. A new class of transducers has been devised and demonstrated based on small circular DNA oligomers (~80 bases). In operation, these assemblies undergo a rearrangement if and only if the target enzyme is present, and this has been shown to occur with high fidelity. This new approach to enzyme sensing has promise for future DNA-based "smart" sensors that can operate both *in vitro* and *in vivo*.

NRL scientists have developed a reverse epitaxial process whereby a nanocrystalline gold film becomes highly textured and porous, and supports a suspended 2D semiconductor overlayer. This porous metallic structure supports surface plasmon polaritons launched in the nanostructured gold by laser excitation and couples remotely to single-photon emitters present in the 2D semiconductor. The results suggest this new process is a versatile platform that could facilitate the use of layered materials in quantum optics systems.

NRL scientists have incorporated a pair of semiconductor quantum dots into a mechanical resonator and demonstrated that the entangled spin system can be very sensitive to motion. Each quantum dot contains one electron, and an interaction between them entangles their spin states. Motion of the mechanical resonator produces strain that changes the interaction strength and gives one of the largest spin-mechanical couplings of any solid-state system. These results may enable new techniques to control quantum bits as well as sensitive accelerometry for inertial navigation or gravitational detection of massive objects.

Photonic quantum information technologies such as computing, communication, and sensing have a critical need for integrated quantum optics platforms. A long-standing challenge in developing such platforms is integrating more than one or two solid-state quantum bits (so-called qubits). NRL scientists have developed a technique that overcomes this challenge for semiconductor quantum dots—one of the most advanced solid-state qubits—by tuning multiple quantum dots into resonance with micro-laser processing. They demonstrated photon-mediated quantum interactions between multiple dots, a critical test of an integrated quantum optics platform (Figure 1).[4]

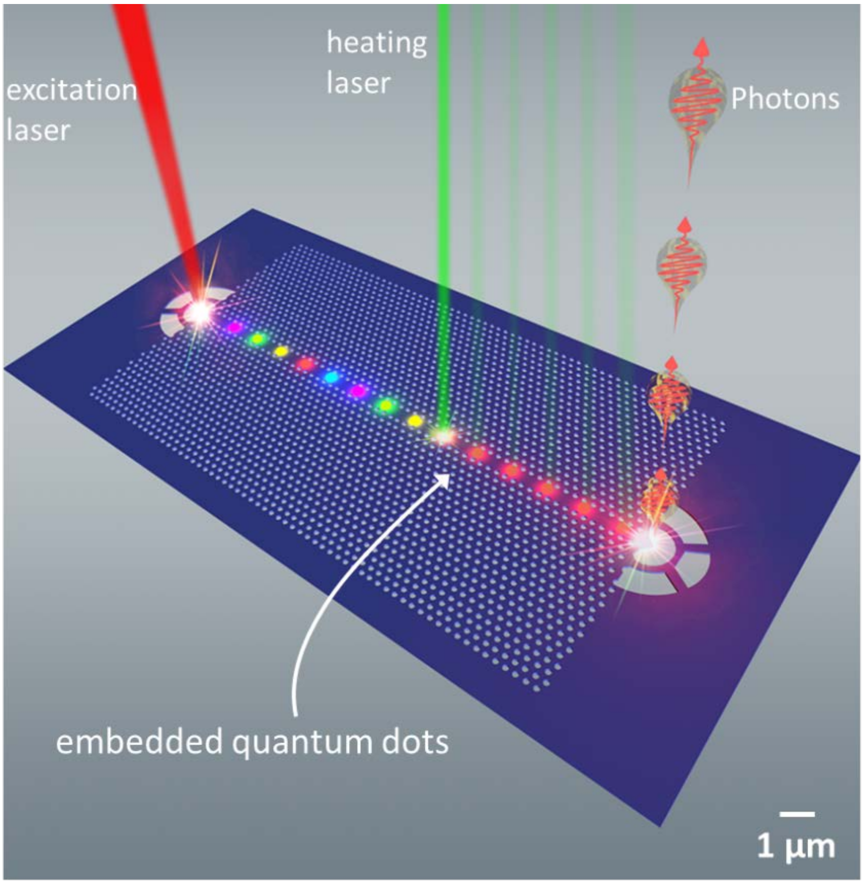

Figure 1. An integrated quantum optics device comprising semiconductor quantum dots embedded in a photonic crystal waveguide. Initially dissimilar dots are unable to interact. Using a laser-processing technique, different quantum dots can be tuned to the same emission wavelength, enabling quantum interactions, which is a critical test of an integrated quantum optics platform.
Image credits: Chul Soo Kim (image) and Joel Grim (image design), NRL.

NRL scientists have developed a way to directly write quantum light sources, or single photon emitters, into monolayer semiconductors such as tungsten diselenide (WSe_2) using an atomic force microscope. This provides deterministic creation and precise placement of these quantum emitters in a solid-state medium, a long-standing roadblock, and enables facile coupling with photonic waveguides, cavities, and plasmonic structures necessary for fabricating on-chip single photon circuitry. This quantum calligraphy also enables

[4] https://www.nature.com/articles/s41563-019-0418-0

real-time design of arbitrary patterns and arrays of such emitters. Single photon emitters are key components in a wide range of nascent quantum-based technologies, including computing, secure communications, sensing, and metrology. This work was done in collaboration with the Air Force Research Laboratory.

Scientists from three divisions at NRL have developed self-assembled nanoparticle enzyme systems that exploit channeling processes and are capable of overcoming diffusion limitations and increasing enzyme pathway activity by several orders of magnitude. This advancement paves the way for creating designer enzyme clusters that are capable of synthesizing molecules such as nutraceuticals, drugs, critical chemicals, and food from common simple molecule feedstocks and even waste at points of need such as a deployed ship, submarine, or forward operating base. Such systems are critically needed to enable Navy distributed maritime operations, increase autonomy, and reduce supply line dependency.

NRL researchers have detected laser-cooled rubidium-87 atoms in the evanescent field of a nanoscale silicon nitride optical waveguide. To do this, researchers centered a magnetic trap containing approximately 10 million atoms at temperatures of 10 microkelvin on the surface of an in-vacuum silicon chip containing the waveguide, and transmitted a picowatt-level probe beam tuned to the atomic absorption resonance at a wavelength of 780 nm through the waveguide. This demonstration is an important step towards the development of quantum sensors and quantum networks based on chip-scale laser-cooled atoms for next-generation precision navigation and timekeeping technologies.

NRL scientists have fabricated state-of-the-art biomaterials in which the chemistry and topography can be independently tuned at the nanoscale. Live cells placed on these materials exhibited enhanced adhesion and migration, which readily correlated with material design inputs. The ability to direct cell migration and adhesion is central to accelerating wound healing and regeneration, a primary objective of military medicine, and these innovative platforms now form an enabling suite of technologies for developing advanced wound pack and implant materials.

Given the significant challenge of traumatic brain injury, DOD has a continued interest in the development of new technologies (for both imaging and modulating brain activity) for new diagnostics and therapeutics. NRL materials scientists have developed small gold nanoparticles (AuNPs) that bind to the plasma membrane of neurons, harvest incident visible light, and heat the plasma membrane just enough to open ion channels and activate neurons. This is a fundamentally new application of these types of materials and demonstrates the fine degree of control that can be elicited over cells using functional nanomaterials.

NRL scientists have verified a new mechanism for modifying chemical reaction rates. Specifically, by flowing reactive chemicals through a tuned optical cavity, reaction rates could be modulated by ~80%. This capability represents a new tool for energy collection and storage (solar- or bio-fuel) and toxin remediation (for countering chemical or biological weapons).

ONR Bionanotechnology Program

FY 2021 Plans and Priorities

PCA 2. Foundational Research

The Office of Naval Research (ONR) will continue to support bionanotechnology research with emphases on fabrication techniques for hierarchical, biologically-based materials with defined properties, DNA nanotechnology and applications for functional device platforms, synthesis and patterning of materials by microorganisms, and design and fabrication of bio-inspired and biomimetic materials and devices using nature's design principles.

Key Technical Accomplishments by Goal

Goal 1. Advance a World-Class Nanotechnology Research and Development Program

Researchers supported by ONR developed and validated a new algorithmic approach for the autonomous design of all DNA staple sequences needed to fold any free-form 2D scaffolded DNA origami wireframe object from a long single strand of DNA scaffold. Such nanostructures offer the ability to organize secondary molecules, such as dyes, nucleic acids, proteins, and semiconductor nanocrystals, for applications in fields such as nanophotonics, nanoscale energy transport, and biomolecular sensing. The algorithm is available online as a stand-alone software tool, and complements recent advances in DNA scaffold generation to bring the use of scaffolded DNA origami to the wider scientific community.[5]

Researchers supported by ONR fabricated 3D self-rolled biosensor arrays of either active field-effect transistors or passive microelectrodes and used them to demonstrate, for the first time, 3D multisite and simultaneous electrophysiological recordings from a 3D multicellular system, specifically stem-cell-derived engineered cardiac spheroids. The arrays provided continuous and stable multiplexed recordings of field potentials with high sensitivity and spatiotemporal resolution, supported with simultaneous calcium imaging. Use of this approach can enhance our basic understanding of signal transduction in complex cellular assemblies, the relationship between signals and disease (e.g., arrhythmias), and tissue maturation. Additionally, the approach can be used in the development and assessment of the efficacy of drugs for disease treatment.[6]

Researchers supported by ONR engineered a microbial process to produce covalently linked repeats of mussel foot proteins (Mfp), specifically Mfp type 5, and characterized the adhesive properties of those recombinant proteins. A positive correlation between the molecular weight of the Mfp5 oligomers (i.e., longer protein chain) and underwater adhesive properties was detected. Additionally, modification of the Mfp5 oligomers with 3,4-dihydroxyphenylalanine was shown to yield comparable or higher force of adhesion and work of adhesion values for a 200 second cure time than those of previously reported Mfp-mimetic adhesives. This research demonstrates the power of synthetic biology in exploring the mechanisms that control underwater adhesion.[7]

Researchers supported by ONR fabricated activators from dormant bacterial spores suspended in water-resistant, UV-curable adhesives that achieve work densities an order of magnitude higher than synthetic humidity-responsive polymers, and respond directly to liquid water, increasing their actuation speed and power by nearly 100-fold. Potential applications of this material include humidity-driven and water-driven actuators for robotics, adaptive textiles and architectures, and energy harvesting.[8]

[5] *Science Advances* 02 Jan 2019: Vol. 5, no. 1, eaav0655. DOI: 10.1126/sciadv.aav0655

[6] *Science Advances* 23 Aug 2019: Vol. 5, no. 8, eaax0729. DOI: 10.1126/sciadv.aax0729

[7] *ACS Appl. Mater. Interfaces* 2018: Vol. 10, no. 49, 43003-43012. DOI: 10.1021/acsami.8b14890

[8] *Advanced Materials Technologies* 2019: Vol. 4, no. 8, 1800596. DOI: 10.1002/admt.201800596

Goal 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology

Funds from the Department of Defense FY 2019 Defense University Research Instrumentation Program supported the acquisition of two acoustic liquid handling robots, a bioelectronics characterization suite for biohybrid devices, a potentiostat, a super-resolution microscope, and next-generation sequencing equipment to augment the bionanotechnology research conducted by ONR-supported research teams at five academic institutions.

ONR Power Electronics Program

FY 2021 Plans and Priorities by PCA

PCA 3. Nanotechnology-Enabled Applications, Devices, and Systems

ONR plans an investment of $200,000 in FY ‘21 to continue research into nanoclay insulation materials to further develop and characterize materials and their manufacturing processes.

Key Technical Accomplishments by NNI Goal

Goal 1. Advance a World-Class Nanotechnology Research and Development Program

ONR-funded nanoclay electrical insulation materials research has resulted in a novel nanostructured insulation material that has proven the outstanding discharge resistance:

- 30X compared to neat epoxy resin.
- 15X compared to alumina nanocomposites.
- No significant erosion after a long period of testing.

Goal 2. Foster the Transfer of New Technologies into Products for Commercial and Public Benefit

ONR-funded research has direct commercial applicability to support improved power density of electrical machines that are used in numerous applications including electric vehicles (Figure 2).

Goal 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology

ONR-funded efforts supported two faculty members and four graduate students/postdocs.

ONR-funded efforts developed research/testing facilities and advanced manufacturing capabilities for nanotechnology materials.

Goal 4. Support Responsible Development of Nanotechnology

All ONR-funded nanotechnology research is conducted with high regard for environmental, health, and safety considerations.

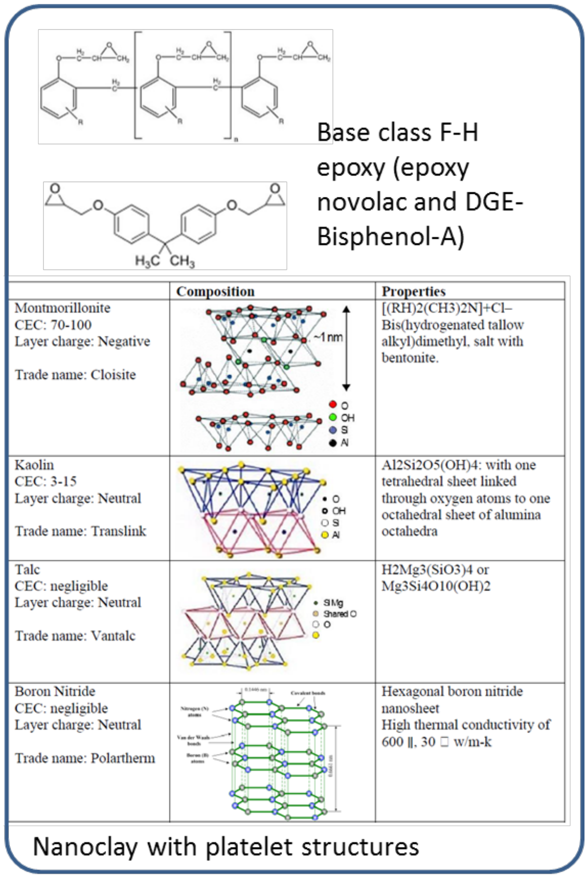

Figure 2. Improved electrical machine insulation systems can significantly improve power density to meet increasing demands for electrical energy on space- and weight-constrained Navy ships. Image credit: Yang Cao, University of Connecticut.

ONR Nano-Engineered Materials Program

FY 2021 Plans and Priorities by PCA

<u>PCA 2. Foundational Research</u>

The Office of Naval Research will continue to support programs on understanding the scientific phenomena that define the unique properties of structural and multifunctional nanomaterials. A special emphasis is on identifying material systems and processes enabling the assembly of these materials at mesoscale and beyond while preserving and potentially enhancing the material properties, initially defined at the nanoscale. There is a specific interest in understanding the limits imposed by the physical and chemical characteristics of a material in creating these nanomaterial ensembles with desired properties.

Key Technical Accomplishments by Goal

<u>Goal 1. Advance a World-Class Nanotechnology Research and Development Program</u>

An ONR-supported Rice University team, together with an Oak Ridge National Laboratory group, discovered that by patterning nanoscale donut shapes into a two-dimensional crystal, they can achieve a new level of control over the material's electrical and optical properties. The resulting localized strain could enable the tuning of the 2D material properties for applications like quantum information systems.[9]

A new study from ONR-supported Northwestern University researchers shows that better graphene oxide (GO) "paper" can be made by mixing strong, solid GO flakes with weak, porous GO flakes. The finding will aid the production of higher-quality GO materials, and it sheds light on a general problem in materials engineering: how to build a nanoscale material into a macroscopic material without losing its desirable properties.[10]

A new study from ONR-supported University of Pennsylvania researchers found that Weyl semimetals (WSMs), a class of quantum materials, have bulk quantum states whose electrical properties can be controlled using light. The University of Pennsylvania team showed, through combined theoretical modelling and experimental measurements of a spatially dispersive circular photogalvanic effect (s-CPGE), that WSMs can support a circulating photocurrent when illuminated by circularly polarized light at normal incidence. This work allows researchers to not only better observe quantum phenomena, but it provides a way to engineer and control unique quantum properties simply by changing light-beam patterns. Modulating the transport mode of an electrical charge by light's polarization and intensity could translate into a powerful design idea for devices.[11]

An ONR-supported Purdue University team has developed a new process to help overcome the brittle nature of ceramics and make them more ductile and durable. The Purdue team calls the process "flash sintering," which adds an electric field to the conventional sintering process used to form bulk components from ceramics. The team has been able to show that even at room temperatures, ceramics sintered with the electric field surprisingly deform plastically before fracture when compressed at high strain. A study published in *Science Advances* demonstrates that applying an electric field to the formation of ceramics makes the material almost as easily reshaped as metal at room temperature. The Purdue team specifically applied its technique to titanium dioxide, a widely used white pigment.[12]

ONR Nanoelectronics Program

FY 2021 Plans and Priorities by PCA

<u>PCA 2. Foundational Research</u>

The ONR Nanoelectronics program will continue to foster and encourage high-risk innovative research in nanoscience that will enable revolutionary new electronic devices to achieve their ultimate limits of high speed, light weight, and low power consumption, and that interactively combine sensing, processing, computation, and communications functions. The research challenges the program seeks to address are: the fundamental building block of information handling beyond transistors; novel computing architectures that are suited for the new paradigm after Moore's law complementary metal oxide semiconductor (CMOS) scaling has ceased; and reliable and cost-effective means to synthesize and fabricate electronic circuitry at atomic resolution. In FY '20, ONR plans to start a major initiative focused on molecular quantum technology built on a bottom-up synthesis electronics platform.

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[9] *Sci Adv* 5 (5), eaav4028; DOI: 10.1126/sciadv.aav4028

[10] *Nat. Comm.* 2019, 10:3677; DOI: 10.1038/s41467-019-11609-8

[11] *Nat. Mater.* 18, 955–962 (2019) doi:10.1038/s41563-019-0421-5

[12] *Sci Adv* 5 (9), eaaw5519; DOI: 10.1126/sciadv.aaw5519

Key Technical Accomplishment by NNI Goal

GOAL 1. Advance a World-Class Nanotechnology Research and Development Program

Top Physics Honors: A former ONR principle investigator (PI) and ONR Young Investigator Award (YIP) winner, Prof. Pablo Jarillo-Herrero of MIT, was selected as the sole winner of the American Physical Society (APS) Oliver E. Buckley Condensed Matter Physics Prize, "for the discovery of superconductivity in twisted bilayer graphene."

DOD Vannevar Bush Faculty Fellowship: Two ONR Nanoelectronics PIs, Prof. Dimitri Basov of Columbia University and Prof. Jack Harris of Yale University, were among 10 winners of the 2019 DOD Vannevar Bush Faculty Fellowship.

Coherent Manipulation of Single Atom Spin States: In a landmark experiment, ONR PI and IBM scientist Chris Lutz and his group, in collaboration with the group of Andreas Heinrich of the Institute of Basic Science in Korea (former ONR PI), succeeded in coherently controlling and manipulating the spin state a single titanium atom, using the scanning-tunneling microscope-based electron spin resonance (ESR) technique. The coherent control of spins arranged with atomic precision provides a solid-state platform for quantum-state engineering and simulation of many-body systems.[13]

Army

CCDC Army Research Laboratory

Summary

The Combat Capabilities Development Center Army Research Laboratory (CCDC ARL) prioritizes warfighter-need-inspired nanotechnology solutions for Army problems. High-performance sensors and electronic materials, optical materials, and ballistic materials all benefit from the utilization of nanotechnology, but require significant research into both fundamental science and the implementation of these materials—with questions ranging from selection of optimal molecular structures to development of synthetic pathways, to methodology for templating and/or dispersion in composite systems. Use-inspired research allows ARL to maintain focus on the development of nanotechnology-driven systems.

Plans and Priorities

ARL is collaborating with Polymer Plus, Case Western Reserve University (CWRU), and the New Jersey Institute of Technology (NJIT) to develop high-performance composites. The research exploits multi-layer film processing to manufacture polymeric tapes with highly oriented and organized nanostructure, enabling films with high tenacity and toughness. These tapes can be consolidated into macroscale multi-layer composite structures with potential applications for next-generation protection systems and weapons.

ARL is exploring the role of nanoscale void initiation, growth, and relaxation on the deformation processes of polymer glasses. Deformation initiates in local nanoscale soft zones in the glass, and ARL has developed novel resins and adhesives that exhibit high ballistic impact resistance by controlling the dynamic heterogeneity in the glass. In a collaboration between ARL, NIST, and the University of Chicago, future work is focused on introducing responsive bonds and shape-changing molecules into the resins to control

[13] K. Yang et al., *Science* 366, 509 (2019).

nanostructural heterogeneity to facilitate the voiding processes and develop structural polymer glasses with externally triggered ductility. The technology has potential applications for armor and weapons.

Key Technical Accomplishments

The quest for new protection technology and to push the limits of materials for energy absorption to protect the soldier has continued under the two-dimensional polymer (2DP) fundamental research effort at the Army Research Laboratory. Three critical thrusts were advanced in FY ’19: (1) theoretical simulations and molecular design, (2) fundamental synthesis and scale-up of molecular structures, and (3) characterization and validation of formed products. Each of these efforts and the expansion of the mission need resulted in both research and expanded technical partnerships in FY ‘19. Accomplished theoretical simulations resulted in identification of critical covalent and non-covalent interactions that can lead to flaw-tolerant materials. Subsequently, the team initiated synthetic advancements to achieve manufacturing of predicted molecular constructs. Significant challenges existed in synthesizing 2DPs of high quality with minimal flaws and processing them into useful forms. The ARL team partnered with a world leader in 2DP synthesis and processing at Northwestern University and exploited advanced processing methods to accelerate product fabrication and quality improvement. The new processing capability resulted in fabrication of more than a dozen new 2DP molecules and the development of methods to transfer and measure the properties. Efforts then shifted to measuring and characterizing performance elements related to the manufactured products. ARL demonstrated that the synthesized 2DP polycrystalline powders can be cast into films of uniform thickness, ranging from 50–200 nm to 20 μm with Brunauer–Emmett–Teller (BET) surface areas over 300 m^2/g and highly ordered by x-ray diffraction. Mechanical tests validate that the 2DP products are robust and meet the Army intent to fabrication of structural 2DPs. Formed 2DP films have measured stiffness and strength values of 25 GPa and 1.5 GPa, respectively, matching closely to theoretical predictions. In future work ARL and partners in academia will continue to advance the number of 2DP materials available and standardize testing methods for cross-organizational comparisons of properties. Such efforts will enable effective advancements in the field to be measured against a common standard and ultimately enable commercialization of capable solutions in the near future for soldier protection outcomes.

Engineer Research and Development Center (ERDC)

Plans and Priorities

Efforts will continue under many Army applied research programs focused on the use of advanced materials, including materials that incorporate aspects of nanotechnology in materials, modeling, and characterization, to support requirements for advanced force protection systems. This work now includes the use of nanoscale graphene, carbon nanofibers, and other additives for modification of resins in composites; nanoceramic additives for hardening of metals; and nano-modification of concrete materials.

Collaborations are continuing between ERDC and the University of Southern Mississippi, including research activities that leverage nanotechnology. These include focus areas on nanomaterial additions to construction materials, including graphene and nanoclay in systems such as asphalt and composites to improve mechanical properties and durability, as well as controlled optoelectronic properties for a variety of future sensing and coating applications. These efforts utilize advanced modeling and synthesis approaches to produce prototype materials for ERDC evaluation and transitions to support Army applied research programs.

Advanced materials for force protection are under development as part of collaborative research with the University of Mississippi. These will utilize combinations of nanomaterials including nanocellulose and carbon nanotube forests in multilayered composite assemblies. Computational modeling will be used to optimize the design of prototype composites for ERDC evaluation and potential transitions to support Army applied research programs. The technology utilizes commercial products integrated into optimized systems.

ERDC is continuing to work with Texas A&M University to validate a novel microwave detection method for determining presence of free nanotubes in paints, and will publish a framework for selecting different analytical methods for measuring carbon nanomaterial release from complex matrices. Another collaboration with Texas A&M University has also been developed to utilize a novel means for dispersion and incorporation of carbon nanofibers into concrete composites. These materials, at the lab scale, have shown much promise for improved performance for military and infrastructure applications.

ERDC, in collaboration with Missouri State University and Brewer Science, is investigating new methods for integrating 2D printed nanotechnology-enabled sensors into 3D printed parts (including drones) for detection of environmental conditions (temperature, humidity); this will enable flexibility and gas detection for greater deployability of low-cost environmental sensing in remote locations. These technologies have resulted in improvements in manufacturing processes, reduced cost associated with managing waste materials, and reduced environmental risk associated with nanomaterial manufacturing.

Two new projects have been developed through the Small Business Technology Transfer (STTR) program focused on nanocrystalline metal coatings with applications for improved hardness and force protection applications. These projects with high-quality industry and academic partners are using novel fabrication means such as additive friction stir welding to deposit nanocrystalline coatings of targeted material compositions that have the potential to achieve a unique combination of high strength, hardness, and ductility that cannot be achieved through conventional manufacturing methods.

ERDC has been collaborating closely with the National Graphene Association and its industry and academic members, including supporting of technology roadmapping as well as key engagements such as the American Graphene Summit in Washington, DC. These initiatives are aligned with ERDC's research on the use of graphene for applications in water treatment, multi-functional materials and sensors, durable coating systems, and for improved performance of infrastructure materials such as asphalt concrete for pavements.

A new in-house basic research project was initiated in FY '19 focused on graphene applications to Army Corps of Engineers installations and military engineering core competency areas. This work focuses on development of internal technical competencies in graphene science and on industry and academic partnerships that are aligned with targeted integration of graphene in various applications.

New capabilities for electrospinning were developed in FY '19, focused on producing nanoscale fiber materials for use in composites as well as membranes. This work under Army basic research is utilizing novel polymer nanocomposite formulations with multiple functionalities for combined strength, chemical/biological degradation, or self-sensing properties that cannot be achieved using conventional manufacturing approaches.

New Army basic research was initiated in FY '19 focused on high-entropy alloys with nanocrystalline grain structure for use in metallic material systems for force protection and projection. These materials offer much promise, with a unique combination of high strength and ductility that cannot be achieved through other alloy compositions or manufacturing approaches. The work utilizes a solid solution strengthening approach of four to five alloying elements at roughly equal composition produced using high-plasticity manufacturing methods that lead to bi-modal grain size distributions that infer high strength due to nanocrystalline grains and high ductility beyond the yield point due to activation of dislocation nucleation and motion initially within micrometer-scale grains followed by motion across grain boundaries and nanoscale grains.

New Army basic research was initiated in FY ‘19 focused on using nanoscale seeding of concrete hydration reactions with targeted minerals and nanoparticle morphologies. This approach promotes targeted crystal structure formation with a hypothetical improvement in mechanical properties and durability of concrete materials. The work is initially focused on developing and understanding the nanoscale seeding effects on crystal nucleation and will later examine composites produced using this approach to compare with conventionally produced materials and compositions.

Continuing Army basic research is examining the development of ice-based nanocomposites for arctic engineering applications. These nanocomposite materials use water-dispersible forms of nanocellulose and various functionalized nanoclays that exfoliate and disperse in the liquid state and then template ice crystal nucleation and growth, resulting in improved crystal structure via grain alignment as well as nanoscale reinforcement. Studies are currently being conducted in cold-room conditions to measure the mechanical properties of these materials, as well as other applications such as thermal energy storage.

Key Technical Accomplishments

Multifunctional materials were developed under Army basic research using paramagnetic and ferromagnetic nanomaterials incorporated into elastomers. These materials have been studied in fluids for rheological property control, but also for structural joints and panels where properties can be directly controlled by externally applied magnetic fields. This work, concluded in FY ‘19, focused on upscaling of the nanocomposite materials to fabricate various prototypes for testing, determining that trace additions of ferromagnetic fillers are effective in modifying elastic and rheological properties by orders of magnitude under moderate applied magnetic fields.

Nanosilica morphology, molecular structure, and defect chemistries have been characterized for the first time under Army basic research. This effort is focused on developing advanced nanomaterials and modeling capabilities for use in high-performance concrete materials for expedient protection and structural hardening. This effort is the first of its kind to fully characterize these complex and highly variable materials produced by industrial partners. This work, which concluded in FY ’19, has led to numerous models that capture the impact of nanomaterial composite, morphology, and molecular structure on rheology, kinetics, and mechanical properties of concrete materials, and are now being utilized in applied materials-by-design research.

Nanoceramic particles were incorporated into metal matrix composites using a novel additive manufacturing process. These materials are being studied for high hardness coatings for metals as part of Army applied research on advanced force protection systems. The work couples novel materials, synthesis approaches, and modeling. The developed materials show significant improvements in performance compared with conventional metals used for force protection. Systems incorporating these advanced materials are now being optimized for functional gradations in properties and being studied using quasi-static and ballistic experiments coupled with modeling and simulation.

The use of nanocellulose additives for concrete and polymer composites was studied as part of Army applied research with collaborators at the University of Maine. This work focused on functionalization approaches and composite synthesis methods to generate improvements in mechanical properties. Upscaling of these materials has occurred, including pilot-scale manufacturing of thermoplastics that incorporate nanocellulose reinforcements.

Institute for Soldier Nanotechnologies (ISN)

Plans and Priorities

The Army's Institute for Soldier Nanotechnologies at MIT, in collaboration with the Army Research Laboratory and other Army engineering and research centers, will continue to perform basic research to help the Army enable high-impact and potentially game-changing protection and other capabilities for the soldier and the soldier's platforms and systems. The planned ISN research emphasizes exploration of novel phenomena associated with fundamental processes (physical, chemical, biological) at the nanoscale or arising from nanostructural features in materials and devices, recognizing that nanotechnology entails much more than making materials that are very small and have very low weight. The intrinsic properties of matter (e.g., dielectric, chemical, mechanical, transport, etc.) become size-dependent below a critical length scale of a few hundred nanometers. Thus, these properties can change each time the material is made smaller. This provides opportunities for the discovery of new effective materials and phenomena that are otherwise unattainable in nature.

Research at the ISN comprises three strategic areas: Soldier Protection, Battlefield Care, and Sensing (SRA-1); Augmenting Situational Awareness (SRA-2); and Transformational Nano-Optoelectronic Soldier Capabilities (SRA-3). SRA-1 focuses on studies to develop lighter-weight, stronger materials to protect the soldier and soldier-augmenting platforms and systems from mechanical damage owing to blast waves, ballistic impacts, and mechanical vibrations, using various mechanisms of energy absorption including phase transitions and materials deformation. Specific materials to be studied include molecular composites, organic polymers, superelastic metal alloys and ultrahigh-strength ceramic formulations. SRA-2 concentrates on providing the soldier and soldier platforms with the next level of capabilities for secure communications, multi-faceted situational cognition and visualization, and invulnerability to enemy detection and, potentially for some cases, immunity to enemy electromagnetic pulse and spoofing technologies. The approach is a full frontal attack on diverse segments of the electromagnetic spectrum currently under-exploited owing to inadequate scientific understanding of the basic physics of novel electronic, optical, and electromagnetic phenomena or the unavailability of efficacious materials and devices to capitalize on recent progress in this understanding. SRA-3 primarily focuses on understanding fundament optical, electronic, and transport/reaction phenomena in nanostructured materials and learning how to apply these phenomena to enable major advances in portable power, communications, signal processing, and detection.

Key Technical Accomplishments

Highly Ordered 2D MoS_2 Archimedean Scroll Bragg Reflectors as Chromatically Adaptive Fibers

Nanostructured fibers provide a basis for a unique class of multifunctional textiles, composites and membrane applications, including those capable of chromatic modulation because of their high aspect ratio, surface area, and processing capability. This research utilized 2D materials including molybdenum disulfide (MoS_2) and hexagonal boron nitride (hBN) to generate single layer Archimedean scroll fibers, possessing cross sections formed from a single 2D molecular layer. Chemical vapor deposited (CVD) monolayer MoS_2 (0.29-0.33% in volume) and 217-245 nm-thick poly (methyl methacrylate) (PMMA) were used to create Bragg reflector fibers, exploiting the anisotropic function, exhibiting reflection at 630-709 nm and verifying the highly ordered nano-inclusions. The Bragg reflectors show memory response to heating and cooling, which switches the reflection wavelength from 630 to 699 nm. The reflectance and transmittance spectra of MoS_2/PMMA and MoS_2/polydimethylsiloxane (PDMS) layered composites were simulated to provide the design of scroll fiber composites using the transfer matrix methods. Moreover, the project demonstrated the incorporation of a few-layer CVD hBN into the scroll fiber composite emitting photons at 576 nm. The highly oriented layered structures extend the capability of the fiber nanocomposites to take advantage of anisotropic optical, electrical, and thermal properties unique to the 2D materials. Figure 3 illustrates some representative results.

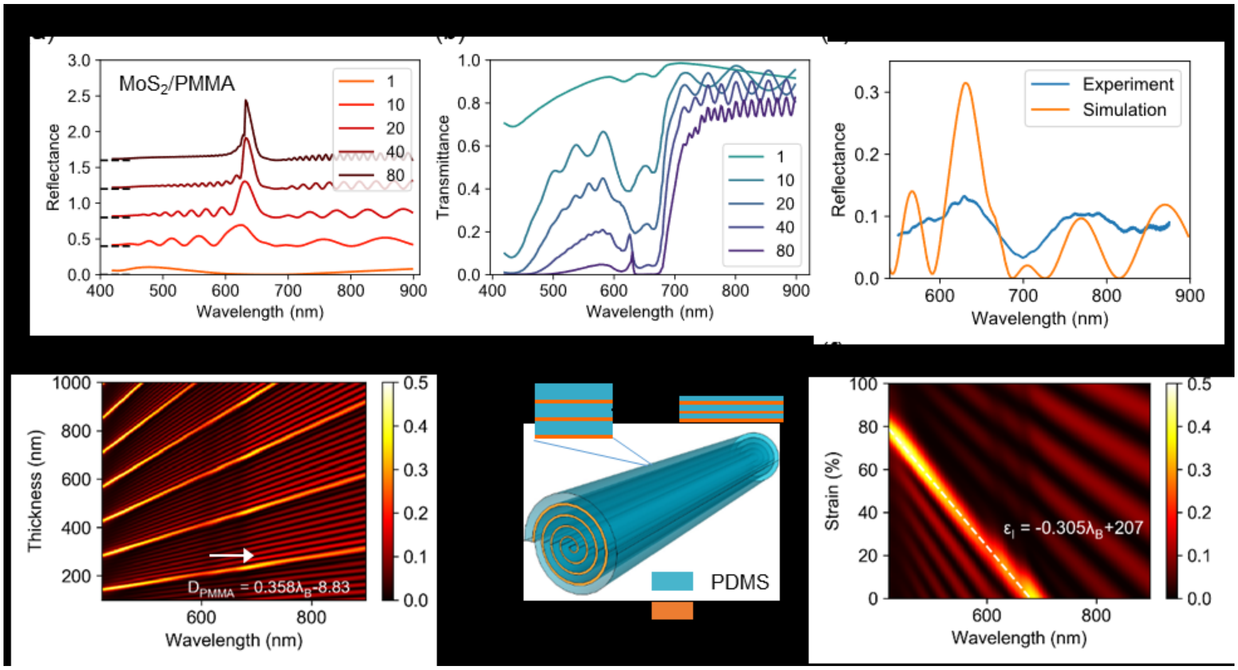

Figure 3. Mathematically simulated reflectance and transmittance spectra of MoS_2/217 nm-thick PMMA 1D Bragg reflector using the transfer matrix method. Image credits: Michael Strano, MIT.[14]

<u>Empowering Future Vaccines and Immunotherapies with Nanotechnology-Based Adjuvants</u>

Vaccines are a powerful defense against infectious diseases, and the advent of successful vaccines against diverse pathogens has saved millions of lives to date. However, a number of diseases relevant to the military have remained unsolved challenges for vaccine development, including malaria, tuberculosis, HIV, and Ebola. Protein vaccines do not typically elicit an immune response on their own, and must combined with adjuvants, compounds that provide inflammatory cues or promote the immune response to a co-administered antigen. Adjuvant design is challenging because of the need to strongly drive specific aspects of the immune response while maintaining a rigorous safety profile for administration to healthy recipients. Nanotechnology-based approaches that target vaccine adjuvants or immunomodulators to lymph nodes have the capacity to enhance both the potency and safety of vaccines, by focusing adjuvant activity in tissues where immune responses are initiated and avoiding systemic exposure. ISN is developing two distinct nano-adjuvant strategies to augment these vaccines, using self-assembling stimulator of interferon gene (STING) agonist amphiphile-adjuvants and saponin nanoparticles (see Figure 4 below).

[14] Reprinted with permission from *Nano Lett.* 2020, 20, 5, 3067–3078, https://doi.org/10.1021/acs.nanolett.9b05004, Copyright 2020 American Chemical Society.

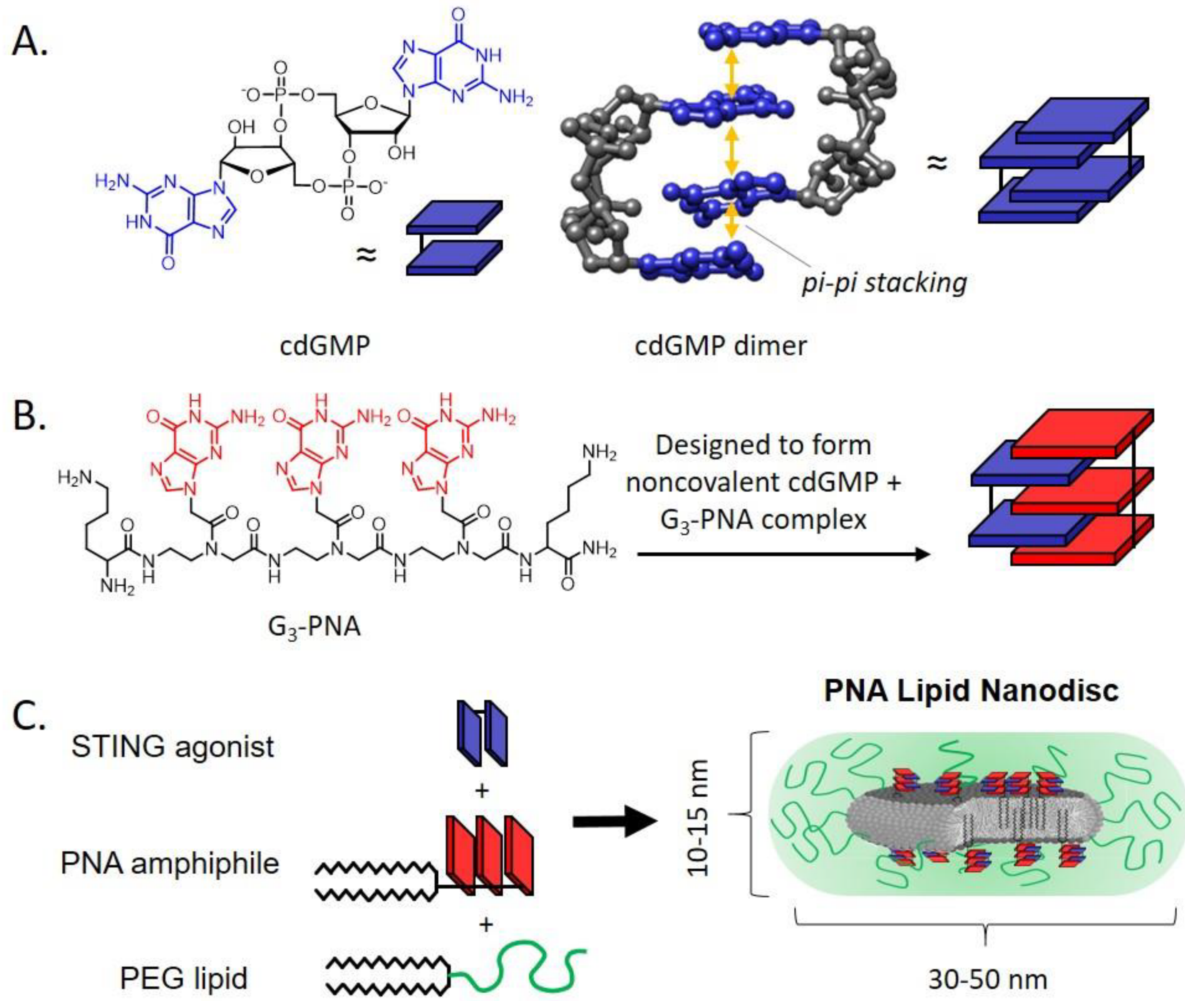

Figure 4. Design of self-assembling peptide nucleic acid (PNA) amphiphiles and PNA lipid nanodiscs (PNA-LNDs) for cyclic dinucleotide targeting to lymphoid tissues. Image credits: Eric Dane, MIT.

Mid- & Long-Wave Infrared Detector Arrays on Flexible Substrates

This project focuses on the development of a new generation of compact, low-power hyperspectral imagers operating in the thermal and mid-infrared spectral regions. For this, ISN researchers are working on spectrally tunable graphene-based filters and detector arrays that promise unprecedented performance for uncooled imagers. Some of the target applications that this technology can enable include night vision, remote material/threat identification, hazardous gas imaging, automated vehicles and aircraft, and point-to-point infrared (IR) communication. In 2019, researchers continued the development of mid- to long-wave infrared detector arrays. Studies included growth and characterization of high-quality graphene and hBN, which were then used for the fabrication of ultrasensitive thermo-mechanical bolometers (Figure 5). In parallel, researchers are developing new slot antennas to enable a graphene multispectral detector.

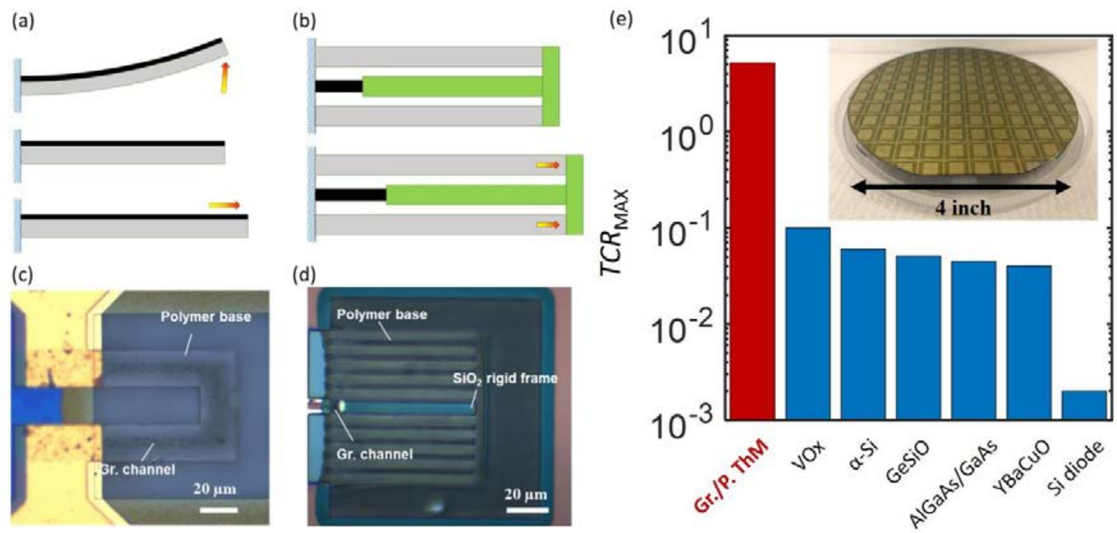

Figure 5. Graphene/polymer thermomechanical bolometer.
Image credits: Tomás Palacios, Dirk Englund, Jing Kong, MIT.

Solid State Power Generation at Millimeter Scales

This project aims to expand the frontiers of high-temperature nanophotonics, explore new physical phenomena that enable unprecedented control of thermal radiation and radiative heat transfer at the nanoscale and at very high temperatures (>800^{0}C), and demonstrate novel materials, devices, and system-level applications ranging from mesoscale thermophotovoltaics (TPV), small-scale radioisotope power sources, all the way to non-conventional IR light sources and room-temperature IR detectors. The overall project is structured around two synergistic lines of investigation: (1) development of high-temperature nanophotonic materials for shaping thermal radiation, and (2) development and demonstration of high energy density millimeter-scale hydrocarbon TPV generators.

Recent significant progress on both includes the following:

1. Fabricated the first hafnia-filled (HfO_2) 2D photonic crystal (PhC) selective emitters on 4-inch tantalum (Ta) wafers. The filled cavity photonic crystal offers much higher in-band emission by radiating into all possible channels (not just around normal incidence), paving the way towards record system efficiencies and record power density (Figure 6).
2. Developed a fabricated swirl-stabilized microcombustor (flame) to replace the existing catalytic (flameless) microcombustor. The swirl-stabilization is easy to ignite and does not suffer from the degradation mechanisms that the catalyst did. This novel microcombustor is a critical component of the next-generation mesoscale TPV generator demonstration ISN is building. This microcombustor is 4x4 cm in size and operates at 400 W—four times larger than the previous system demonstration; the new 20 W design will be more relevant for the dismounted soldier's power requirements. The larger

size has enabled the use of a swirl-stabilized design because it is not possible to have a combustion chamber large enough to avoid quenching.

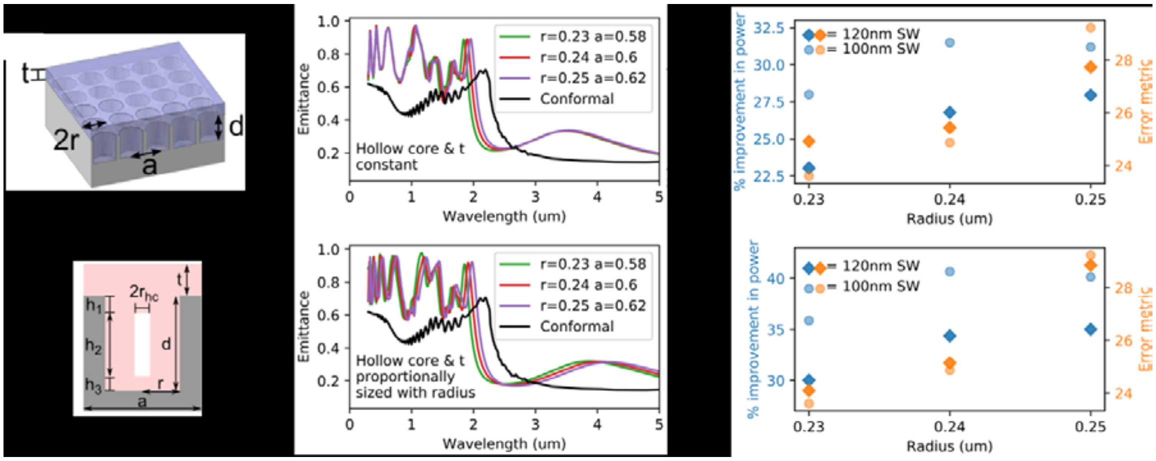

Figure 6. Simulated realistic filled PhCs with depths 1.5 2 µm, radii 0.23 0.25 µm, and period such that the sidewalls are 120 nm. Image credits: Ivan Čelanović, Marin Soljačić, Peter Fisher, MIT.

<u>Nanophotonics-Enhanced Systems for the Soldier</u>

ISN researchers developed a computational framework[15] for efficient optimization-based "inverse design" of large-area metasurfaces for applications such as broadband/angle-insensitive metalenses and demultiplexers. In particular, to optimize surfaces that can be thousands of wavelengths in diameter, the research team employed a "locally periodic" approximation in which the scattering problem is approximated by a composition of periodic scattering problems from each unit cell of the surface. At the analytical level, a precise theory of metasurface approximation was developed[16] that not only proves an adiabatic theorem for the convergence of the "zeroth-order locally uniform" approximation but also provides higher-order corrections that would allow rapidly varying surfaces to be modeled with arbitrary accuracy. Furthermore, the team extended its computational framework to large-scale "topology optimization,"[17] which vastly expands the design space by considering every pixel/voxel in the device region as a degree of freedom. In the forward direction, this approach exploits the locally periodic approximation combined with massively parallel computations of the unit cells of a large-area metasurface while, in the inverse direction, the method employs a powerful adjoint sensitivity analysis to rapidly obtain the gradients and efficiently explore the enormous design space, typically ~105-106 degrees of freedom. As a demonstration of the versatility and power of this approach, the team designed a high numerical aperture (NA) multi-layered metalens concentrator (1000λ in width) that can focus light coming from multiple incident angles to a single focus (Figure 7).

[15] *Optics Express*, vol. 26, p. 33732, 2018: https://doi.org/10.1364/OE.26.033732

[16] *Optics Express*, vol. 26, p. 30202, 2018: https://doi.org/10.1364/OE.26.030202

[17] *Optics Express*, vol. 27, pp. 15765, 2019: https://doi.org/10.1364/OE.27.015765

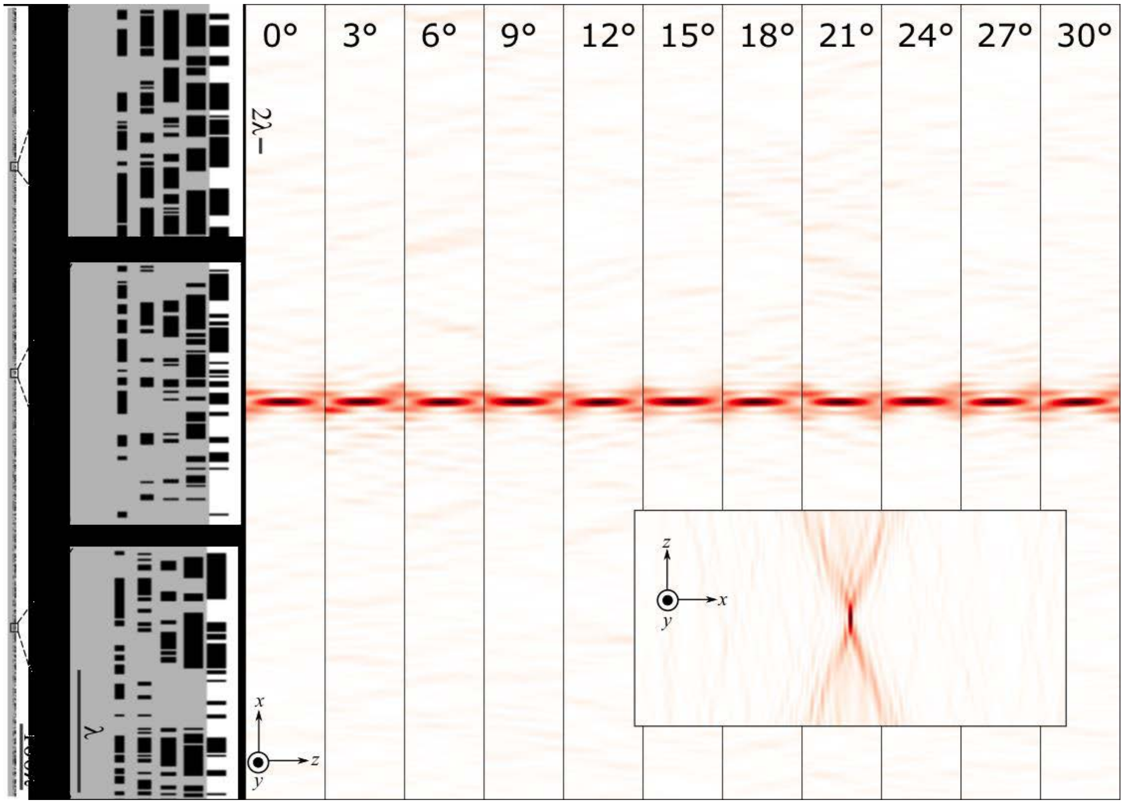

Figure 7. Multi-layered high-NA large-diameter metalens concentrator designed by topology optimization. Image Credit: Steven Johnson, Marin Soljačić, John Joannopoulos, MIT.[18]

Defense Advanced Research Projects Agency (DARPA)

Summary

DARPA is focused on developing advanced technologies to underpin decisive national security capabilities in the years to come. In January 2018, DARPA, along with companies from the semiconductor and defense industries, announced six new research centers under the agency's Joint University Microelectronics Program (JUMP) to undertake high-risk, high-payoff research focused on driving long-term research in microelectronics. JUMP is pushing fundamental technology research and establishing long-range microelectronic research themes that include foundational development for energy-efficient integrated nanotechnologies and major advances in cognitive computing. JUMP consists of a half-dozen university-based research centers, each dedicated to a different technology theme and collectively supporting fundamental microelectronics research conducted by hundreds of professional scientists and their students. In particular, the Applications and Systems-driven Center for Energy-Efficient Integrated Nanotechnologies (ASCENT) focuses on material and device innovations for breakthrough advances in integrated nanoelectronics that will allow the United States to transcend the anticipated limits of CMOS technology and increase the performance and efficiency of future computing systems. The Center for Brain-inspired Computing Enabling Autonomous Intelligence (C-BRIC) aims to deliver major advances in cognitive computing, with the goal of enabling a new generation of autonomous intelligent systems. The overall goal

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[18] Reprinted with permission from *Opt. Express* 27, 15765-15775 (2019), https://doi.org/10.1364/OE.27.015765, © The Optical Society.

of the centers is to catalyze innovations for increasing the performance, efficiency, and overall capabilities of broad classes of electronics systems for both commercial and military applications.

Plans and Priorities by PCA

1b. Nanoelectronics NSI

In FY ‘21, the centers in JUMP will fabricate emerging novel materials, vertical CMOS transistors for novel memory-logic co-integration circuits, beyond-CMOS spintronics for brain-inspired computing, in/near-memory hardware demonstrations for machine-learning workloads, advanced compound semiconductor transistors, and advanced packaging to demonstrate power efficient digital, storage, and RF/Terahertz device prototypes.

1f. Future Computing Grand Challenge

In FY ‘21, the centers in JUMP will demonstrate next-generation distributed and centralized computing architectures and subsystems to enhance efficiency of information extraction, processing, and autonomous control.

Key Technical Accomplishments by Goal

Goal 1. Advance a World-Class Nanotechnology Research and Development Program

Centers in JUMP identified emerging materials; power-efficient RF, terahertz, digital, and storage device prototypes and designed architectures for three-dimensional integration of device technologies; heterogeneous integration of functionally diverse components; and new types of spin-based memory and logic devices. Centers have identified novel distributed and centralized computing architectures and subsystems for efficient information extraction, processing, and autonomous control applications to narrow the orders-of-magnitude computing efficiency gap between current computing systems and the brain. Application drivers for new computer architectures and algorithms developed under the JUMP centers include autonomous drones and personal robotic assistants.

Goal 2. Foster the Transfer of New Technologies into Products for Commercial and Public Benefit

In collaboration with the non-profit Semiconductor Research Corporation (SRC), DARPA recruited a consortium of cost-sharing industry partners to fund and oversee JUMP. Major semiconductor and defense companies involved in JUMP include Intel, IBM, Micron, Analog Devices, EMD Performance Materials, ARM, Samsung, TSMC, Raytheon, Northrop Grumman, and Lockheed Martin. In FY ‘19, industry partners provided critical technical guidance to university research teams for future long-term impact on commercialization of developed technology.

Goal 3. Develop and Sustain Educational Resources, a Skilled Workforce, and a Dynamic Infrastructure and Toolset to Advance Nanotechnology

Major technical accomplishments from JUMP in FY ‘19 include the development of university research teams with application-oriented technical projects to conduct breakthrough research. The highly-skilled students working on and being trained within these multidisciplinary research teams will ultimately become the workforce of tomorrow that will implement these technologies into commercial solutions.