U.S. DEPARTMENT OF
ENERGY

Microelectronics at the Department of Energy:

Capabilities and Opportunities for Driving U.S. Competitiveness

Advanced Light Source, LBNL

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INTRODUCTION

Microelectronics are everywhere—embedded in our consumer products; underlying our power, transportation, and information infrastructure; and fortifying our national security. These and other microelectronics applications are also intricately linked with America's energy and decarbonization goals. For instance, advanced power electronics are critical to our transition to renewable power and electric transport, and more energy-efficient computing and consumer devices are needed as energy consumption grows rapidly. Meanwhile, global supply chain disruptions beginning in 2020 and the ensuing chip shortage caused by the COVID-19 pandemic highlight the vulnerability of microelectronics supply chains. The globally distributed manufacturing base can be disrupted in unexpected ways, and there is no single solution to these challenges given the range of applications and technologies within the microelectronics industry—from ever-smaller, nanoscale feature sizes to large-scale commodity use cases to specialized functionalities. Rather, solutions will require the private sector, federal agencies, and research and development (R&D) organizations such as labs and universities to act in concert beyond their individual missions.

The Biden-Harris Administration has articulated clear priorities that apply to the microelectronics industry. In February 2021, the administration released Executive Order 14017 on America's Supply Chains. This order directs the U.S. Department of Energy (DOE) to analyze supply chains for the Energy Sector Industrial Base, including those for microelectronics and semiconductors, and to provide recommendations for addressing key vulnerabilities, securing stable raw material sources and domestic manufacturing capacity, and strengthening U.S. competitiveness. In response, DOE published America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition, the first comprehensive U.S. government plan to build an Energy Sector Industrial Base, along with a deep dive assessment of the semiconductor supply chain. The recommendations in these reports focused on strengthening the U.S. position in energy-efficient semiconductor design, fabrication, and advanced packaging, as well as in advanced power electronics. These priorities are also reflected in administration-supported legislation, such as the Infrastructure Investment and Jobs Act (IIJA) and the pending America COMPETES Act of 2022, which includes authorization for up to four DOE Microelectronics Science Research Centers, similar to the department's National Quantum Information Science Research Centers initiated in 2020.

DOE is well positioned to support these administration priorities. However, sector competitiveness will ultimately be driven by the vitality of the semiconductor industry in the United States. Close interaction between DOE programs and the private sector across the Research, Development, Demonstration, and Deployment (RDD&D) continuum is critical. To bolster coordination, this paper outlines DOE's current, broad-ranging capabilities in microelectronics, future opportunities, and role in interfacing with industry to drive U.S. competitiveness.

Throughout this paper, as is common in industry, we will use the terms "microelectronics" and "semiconductors" interchangeably to refer to: semiconductors and related materials, processing chemistries, design, fabrication, lithography, packaging, sensors, devices, integrated circuits, processors, computing architectures, modeling and simulation, software tools, and related technologies.

For more information, contact microelectronics@science.doe.gov.

Center for Nanophase Materials Sciences at DOE's Oak Ridge National Laboratory

[1] DOE, ***America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition*** (2022), https://www.energy.gov/policy/articles/americas-strategy-secure-supply-chain-robust-clean-energy-transition.

[2] DOE, ***Semiconductor***: ***Supply Chain Deep Dive Assessment*** (2022), https://www.energy.gov/sites/default/files/2022-02/Semiconductor%20Supply%20Chain%20Report%20-%20Final.pdf.

DOE CAPABILITIES AND OPPORTUNITIES IN MICROELECTRONICS

DOE is one of several federal departments that plays a substantial role in fostering the growth of the microelectronics industry. DOE's microelectronics efforts include multidisciplinary R&D activities that advance technologies for future sensors, detectors, wired or wireless communications, control, and computing technologies that are critical for national priorities in energy efficiency, clean energy, and national security. DOE's activities also extend across the RDD&D continuum—from the development of novel materials and technologies to prototyping and commercialization of these technologies. DOE's 17 national laboratories offer facilities, capabilities, intellectual property, and expertise in microelectronics. These assets, along with an increased focus on DOE programs driving demonstration, deployment, and manufacturing scale-up, will be key to building greater U.S. competitiveness in the sector.

Ames Laboratory (Ames)
Argonne National Laboratory (ANL)
Brookhaven National Laboratory (BNL)
Fermi National Accelerator Laboratory (Fermilab)
Idaho National Laboratory (INL)
Lawrence Berkeley National Laboratory (LBNL)
Lawrence Livermore National Laboratory (LLNL)
Los Alamos National Laboratory (LANL)
National Energy Technology Laboratory (NETL)
National Renewable Energy Laboratory (NREL)
Oak Ridge National Laboratory (ORNL)
Pacific Northwest National Laboratory (PNNL)
Princeton Plasma Physics Laboratory (PPPL)
Sandia National Laboratories (Sandia)
Savannah River National Laboratory (SRNL)
SLAC National Accelerator Laboratory (SLAC)
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

Table 1. DOE National Laboratories

SLAC National Accelerator Laboratory, one of 17 DOE national laboratories with resources applicable to microelectronics RDD&D

While much of DOE's work, across all facilities and programs, has applications in microelectronics, Table 2 identifies facilities and programs of particular relevance to U.S. competitiveness in microelectronics.

DOE SCIENTIFIC FACILITIES & PROGRAMS / MICROELECTRONICS CAPABILITIES	Materials & Processing	Fabrication & Prototyping	Devices, Circuits, & System Integration	Charaterization & Testing	Computing & Algorithms	Manufacturing	Commercial Deployment
NATIONAL USER FACILITIES							
Light Sources (5)	✓	✓		✓			
Neutron Sources (2)	✓			✓			
Nano Centers (5)	✓	✓	✓	✓	✓		
Leadership Computing Centers (3)					✓		
NATIONAL NUCLEAR SECURITY ADMINISTRATION FACILITIES							
Microsystems Engineering, Science and Applications (MESA) Facilities	✓	✓	✓	✓			
Leadership Computing Facilities (4)					✓		
ADVANCED MANUFACTURING PROGRAMS							
Power America Institute		✓	✓	✓		✓	
ISO50001 Ready Programs		✓	✓			✓	✓
Industrial Assessment Centers	✓	✓				✓	
LOAN PROGRAMS							
Advanced Technology Vehicle Manufacturing						✓	✓
Title 17 Innovative Energy Loan Guarantee Program						✓	✓

Table 2. DOE Microelectronics Capabilities[3]

For R&D, DOE Office of Science user facilities and National Nuclear Security Administration (NNSA) facilities provide the most advanced tools of modern science for scientific research. For demonstration and deployment, DOE's manufacturing, commercialization, and loan programs connect the private sector with DOE scientific resources and resulting technologies. These facilities and programs have core capabilities spanning the following seven areas:

[3]See Appendix for links to specific facilities and programs.

1 MATERIALS & PROCESSING

Future processes for microelectronic devices and systems depend on experimental, theoretical, and computational research to illuminate underlying chemical transformations and energy flows. Such fundamental research can enable the use of new materials, generate new concepts for data storage and memory and create new architectures, such as 3D assemblies or flexible soft interfaces. In turn, these innovations can enable future logic, memory, sensing, power, and communications devices, as well as systems with transformative functionality and enhanced energy efficiency.

Our five **Nanoscale Science Research Centers** have leading-edge capabilities for materials synthesis and chemical processing, as well as broad suites of leading-edge characterization tools. These centers are continually upgrading infrastructure to stay at the leading edge, thereby allowing users to rapidly synthesize and characterize new materials and processing chemistries. Resulting R&D that leverages unexploited physical phenomena can enable far more efficient computation, communication, and sensing than today's technologies allow.

2 FABRICATION & PROTOTYPING

For decades, continued improvements in lithography, the process by which smaller and smaller devices are patterned onto silicon wafers, drove advances in microelectronic technologies. Future advances using novel materials, processes, and structures will require access to leading-edge prototyping facilities where proof-of-concept fabrication can be carried out and new devices and capabilities demonstrated.

LBNL CXRO extreme UV lithography facility

For example, the **Center for X-ray Optics** (CXRO) at the **Advanced Light Source** at LBNL has worked closely with other national labs and industry partners over decades to develop extreme UV lithography. Continued advances in both light sources and optics, as well as materials and chemistries for patterning of nanoscale features onto wafers, will allow for increasingly dense and energy-efficient devices. Close collaboration with industry can rapidly transition advanced capabilities from the lab into commercial applications.

3 DEVICES, CIRCUITS, & SYSTEM INTEGRATION

New opportunities in computing, communication, and sensing require innovative devices that can be connected into circuits and integrated into systems in novel ways to enable transformational advancements in energy efficiency and functionality. These advances will enable the development of edge computing, advanced wireless networks, and innovative computing architectures such as brain-inspired neuromorphic computing.

For example, the **Center for 3D Ferroelectric Microelectronics**, a DOE Office of Science Energy Frontier Research Center (EFRC) led by Penn State University in partnership with other universities, ORNL, and Sandia, is working to exploit the third dimension in microelectronics for functions beyond interconnects. Specifically, researchers are establishing the foundational knowledge that will allow them to incorporate non-volatile ferroelectric memory densely interconnected with logic to create low-power, 3D, non-von Neumann computation. Similarly, the **Quantum Materials for Energy Efficient Neuromorphic Computing** EFRC, led by UC San Diego, aims to lay down the quantum-materials–based foundation for the development of an energy-efficient, fault-tolerant computer that is inspired by and works like the brain (neuromorphic computing).

4 CHARACTERIZATION & TESTING

To build the information processing engines of the future, we not only need new materials and devices, but we also need new ways of characterizing and testing at length scales below 10 nanometers, approaching atomic scales.

ANL Center for Nanoscale Materials

Existing DOE user facilities, including the **Nanoscale Science Research Centers** and **x-ray and neutron scattering facilities**, are uniquely positioned to address this challenge through instrumentation and capabilities targeted at future microelectronics devices and systems. In the near term, advanced accelerator-based **light source** technologies providing intense sources of extreme UV radiation could enable higher resolution optical metrology tools. In addition, DOE **leadership computing facilities** offer opportunities for computation and modeling that complement experimental synthesis, processing, fabrication, and characterization.

5 COMPUTING & ALGORITHMS

Harnessing the properties of emerging devices will create innovation opportunities for future computing and algorithms. For example, computing R&D may accelerate the performance of artificial intelligence and machine learning algorithms with superior energy efficiency. To pursue this area of research, DOE supports collaborations between Office of Science programs, national laboratories, academia, and industry to design, model, simulate, and prototype intelligent integrated circuits that demonstrate electronic properties for next-generation computing and sensing.

For example, since 2011, DOE has partnered with industry to accelerate the transition of innovative ideas from processor and memory architecture research into future products in a series of *Fast Forward* and *Design Forward* R&D projects that has included American companies AMD, Cray, IBM, Intel, and Nvidia. The projects aim to evaluate advanced research concepts, critical node technologies, and designs for high-performance computing relevant to DOE applications.

[4] Ang, James A., Hammond, Simon David, Hemmert, Karl Scott, and Laros, James H., "DOE's Fast Forward and Design Forward R&D Projects: Influence Exascale Hardware" (2015), https://www.osti.gov/servlets/purl/1513941.

6 MANUFACTURING

Semiconductor technologies should not only be invented in the United States but also made here. Manufacturing of advanced microelectronics products can create good jobs and drive critical supply chain resiliency. In addition to basic and applied R&D, DOE promotes a competitive domestic semiconductor industry through a comprehensive program of manufacturing R&D, technical assistance for industrial energy efficiency and cost savings, and workforce development support.

DOE supports advanced wide bandgap (WBG) power electronics, essential to the transition to renewables and electrification, from basic R&D of next-generation materials at national user facilities to manufacturing. Since its creation in 2009, the Advanced Research Project Agency for Energy (ARPA-E) has launched programs that have enabled innovations throughout the WBG power electronics value chain, from materials and devices to modules and circuits to application-ready systems integration. **PowerAmerica**, a Manufacturing USA Institute, works with industrial members to reduce cost and de-risk new technologies, providing a strategic advantage for U.S. electric equipment manufacturers through integration with a domestic supply chain. For example, the development of thick silicon-carbide power electronics for applications up to 10 kilovolts is a focus of PowerAmerica and the DOE Advanced Manufacturing Office's semiconductor R&D goals.

DOE's **Industrial Assessment Centers** (IACs) provide no-cost technical assessments to small- and medium-sized U.S. manufacturers, including semiconductor manufacturers, to help improve their competitiveness through energy savings, improved productivity, and waste reduction. The IIJA expands the scope of this program to include smart manufacturing and provides for Implementation Grants to help manufacturers carry out the recommendations. DOE also offers multiday In-Plant Trainings that give participants unbiased and technology-neutral knowledge and tools to improve energy efficiency and productivity in their plants through the Better Buildings, Better Plants program. DOE further provides assistance to boost the cost-competitiveness of U.S. businesses through the 50001 Ready and Superior Energy Performance 50001 (SEP 50001) programs.

7 COMMERCIAL DEPLOYMENT

Beyond research, development, and demonstration, DOE also supports the commercial deployment of microelectronics technologies in critical energy applications.

The DOE **Loan Programs Office** (LPO) can support domestic semiconductor manufacturing through two programs. The **Advanced Technology Vehicle Manufacturing** program provides direct loans—an attractive form of cheap capital—to support manufacturers of light-duty vehicles and vehicle components, which includes microelectronics components. Through authorities granted (but not yet funded) through the IIJA, this program can be extended to medium- and heavy-duty vehicles, as well as maritime transport and aviation applications. LPO's **Title 17 Innovative Energy Loan Guarantee Program** supports early deployment of new technologies, including microelectronics, that support renewable energy and energy-efficiency applications that mitigate greenhouse gas emissions. This program supports the construction of early post-pilot commercial plants.

DOE OPPORTUNITIES TO DRIVE U.S. MICROELECTRONICS COMPETITIVENESS

DOE is positioned to play a leading role in driving U.S. microelectronics competitiveness, not only because of its extensive RDD&D capabilities in microelectronics, but also because the clean energy and national security goals central to the department's mission provide opportunities to apply and scale the use of innovative microelectronics technologies.

For clean energy and decarbonization

The Biden-Harris Administration has set ambitious climate goals, including decarbonizing the electric grid by 2035. The nation needs greatly improved microelectronics to ensure this new grid is energy-efficient, resilient to natural phenomena and intentional attack, and adaptive to fluctuations in demand and renewable power generation. This critical upgrade requires rapid, sustained progress in microelectronics science and technology innovations from millivolt to megavolt scales. Driven by DOE programs, R&D at the national labs and rapid commercialization and scaling of existing technologies present an opportunity for the United States to achieve both technological and manufacturing competitiveness in domestic and export markets.

Beyond the electric grid, there are many opportunities to increase DOE's support for microelectronics technologies at the demonstration and deployment phase in clean energy applications. For example, advanced packaging is a growing, innovative area that depends heavily on design capabilities in which the United States excels. In addition, advanced manufacturing in microelectronics—including additive, field-assisted assembly, self-assembly, and hybrid manufacturing modes—is a rising area and presents opportunities for transformative advances. However, U.S. industry still needs to build domestic manufacturing facilities or risk being left behind. Similarly, developers at the forefront of the renewable energy and electrified mobility transitions are calling for new, higher voltage power electronic devices, modules, and materials. A critical gap also exists at the pilot-plant phase. Yet, there are few funding programs and a significant need for DOE to offset the remaining technology risk. Supporting smaller manufacturers of advanced chips that enable electrification and automation is another opportunity.

Big automakers have substantial market power and may make it difficult for smaller manufacturers that cannot compete without access to vertically integrated supply chains. To move innovations to the marketplace and accomplish the administration's decarbonization goals, the nation will need sustained investment in semiconductor device R&D and manufacturing at the device, chip, and system levels.

For national security

Beyond the administration's climate goals and the needs of the energy sector, NNSA also requires a trusted supply of radiation-hardened microelectronics to support the deployment of nuclear weapons. As operational environments evolve and new requirements emerge, allocation of NNSA R&D resources must be evaluated and aligned to support the safety, security, and effectiveness of the nation's nuclear deterrent. Production of NNSA resources must also keep pace with evolving trends in microelectronics production to maintain a trusted supply of hardened microelectronics for nuclear weapon applications. The trustworthiness of the nuclear weapons supply chain must be sustained to protect against potential counterfeit and sabotage.

An interdisciplinary approach

Building the U.S. semiconductor industry of the future will require an interdisciplinary approach to R&D, manufacturing, and commercial deployment, involving communication between disparate parts of the value chain. For example, to develop standards and more easily design multichip systems incorporating different technologies, experts in complementary metal-oxide semiconductors and interconnects must work with experts from many other fields, such as photonics and microelectromechanical systems. Likewise, as WBG devices are increasingly incorporated into systems with electronics controls, a multidisciplinary research ecosystem must evolve to ensure performance, reliability, and safety. DOE has a strong role to play at this nexus.

With the broad range of capabilities and opportunities that DOE brings to the microelectronics space, we expect the department to remain a hub within U.S. government for realizing the nation's microelectronics competitiveness in the years to come.

APPENDIX

The table below provides links to specific DOE user facilities and programs for reference. For more information, please contact microelectronics@science.doe.gov.

NATIONAL USER FACILITIES - LIGHT SOURCES

Advanced Light Source (ALS), Lawrence Berkeley National Laboratory (LBNL)
- https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/ALS

Advanced Photon Source (APS), Argonne National Laboratory (ANL)
- https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/APS

National Synchrotron Light Source II (NSLS-II), Brookhaven National Laboratory (BNL)
- https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/NSLS-II

Stanford Synchrotron Radiation Light Source, SLAC
- https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/SSRL

Linac Coherent Light Source (LCLS), SLAC
- https://science.osti.gov/bes/suf/User-Facilities/X-Ray-Light-Sources/LCLS

NATIONAL USER FACILITIES - NEUTRON SOURCES

High Flux Isotope Reactor (HFIR), Oak Ridge National Laboratory (ORNL)
- https://science.osti.gov/bes/suf/User-Facilities/Neutron-Scattering-Facilities/HFIR

Spallation Neutron Source (SNS), ORNL
- https://science.osti.gov/bes/suf/User-Facilities/Neutron-Scattering-Facilities/SNS

NATIONAL USER FACILITIES - NANOSCALE SCIENCE RESEARCH CENTERS

Center for Nanoscale Materials (CNM), ANL
- https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CNM

Center for Functional Nanomaterials (CFN), BNL
- https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CFN

The Molecular Foundry (TMF), LBNL
- https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/TMF

Center for Nanophase Materials Sciences (CNMS), ORNL
- https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CNMS

Center for Integrated Nanotechnologies (CINT), Los Alamos and Sandia National Laboratories
- https://science.osti.gov/bes/suf/User-Facilities/Nanoscale-Science-Research-Centers/CINT

NATIONAL USER FACILITIES - LEADERSHIP COMPUTING CENTERS

Argonne Leadership Computing Facility (ALCF), ANL
- https://science.osti.gov/ascr/Facilities/User-Facilities/ALCF

National Energy Research Scientific Computing Center (NERSC), LBNL
- https://science.osti.gov/ascr/Facilities/User-Facilities/NERSC

Oak Ridge Leadership Computing Facility (OLCF), ORNL
- https://science.osti.gov/ascr/Facilities/User-Facilities/OLCF

NNSA FACILITIES

MESA, Sandia National Laboratories
- https://www.sandia.gov/mesa/?msclkid=0bb2ba2ab4ec11ec8f5fdb36bee7882a

Building 654, Lawrence Livermore National Laboratory (LLNL)
- https://asc.llnl.gov/facilities

Livermore Computing Complex (LCC) Building 453, LLNL
- https://asc.llnl.gov/facilities

The Strategic Computing Complex (SCC), Los Alamos National Laboratory
- https://www.lanl.gov/projects/advanced-simulation-computing/_assets/docs/

The 725E data center, Sandia
- https://www.sandia.gov/labnews/2020/06/19/leedv4-gold/

ADVANCED MANUFACTURING PROGRAMS

Power America
- https://poweramericainstitute.org/

Industrial Assessment Centers
- https://www.energy.gov/eere/amo/industrial-assessment-centers-iacs

LOAN PROGRAMS

Advanced Technology Vehicle Manufacturing
- https://www.energy.gov/lpo/products-services/advanced-technology-vehicles-manufacturing-loan-program

Title 17 Innovative Energy Loan Guarantee Program
- https://www.energy.gov/lpo/renewable-energy-efficient-energy-projects-loan-guarantees

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