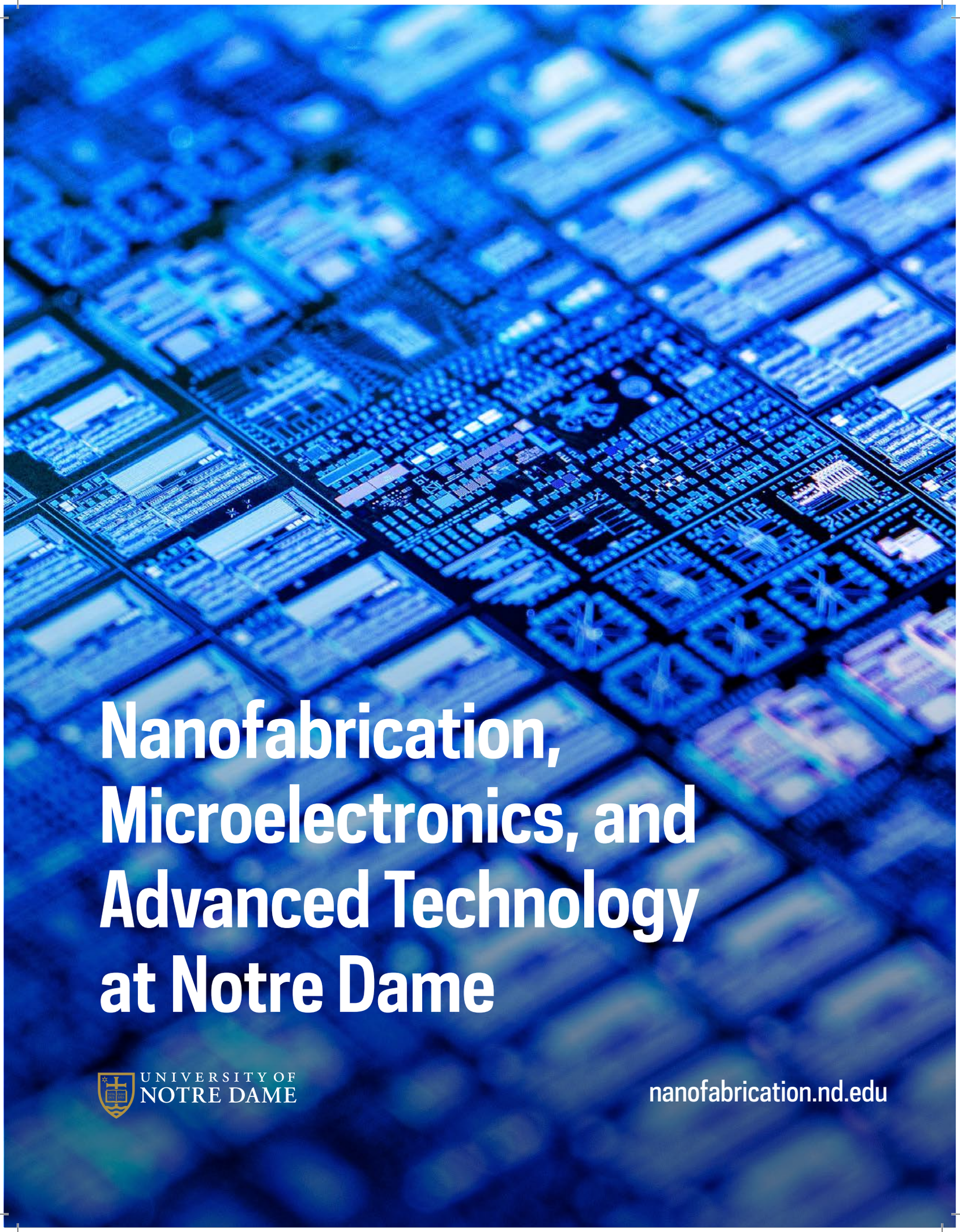


Nanofabrication, Microelectronics, and Advanced Technology at Notre Dame

UNIVERSITY OF NOTRE DAME

nanofabrication.nd.edu



INTRODUCTION

Nanotechnology at the University of Notre Dame

Founded in 1895, the University of Notre Dame's Department of Electrical Engineering is one of the oldest in the nation. Its researchers are leading advances in wireless communication, robotics, photonics, and bioelectronics. Over the past four decades, work on semiconductors and microelectronics has emerged as a key research strength of the University, enabling high speed and low power transistors, memory, computing, and artificial intelligence.

Notre Dame has close ties to the semiconductor industry, including the Semiconductor Research Corporation (SRC), a not-for-profit research and development consortium consisting of leading semiconductor companies. Notre Dame faculty have made significant contributions over a fifteen-year span with the leadership of and technical engagement in three SRC-funded research centers, including:

- Midwest Institute for Nanoelectronics Discovery (2008–2013)
- Center for Low Energy Systems Technology (2013–2018)
- Applications and Systems-Driven Center for Energy-Efficient Integrated Nanotechnologies (2018–2023)

Notre Dame has a long history of collaboration with the Department of Defense dating from World War II to the present. Notre Dame values close ties with the State of Indiana, regional universities, and the Midwest Semiconductor Network (MSN). The MSN is a network of universities and community colleges across Indiana, Illinois, Kentucky, Michigan, and Ohio formed in 2022 to support the development of semiconductor manufacturing in the Midwest.

The following pages highlight Notre Dame's core facilities and capabilities that support the education of innovators and leaders in advanced technology research and development.

Providing a Collaborative Environment for Microelectronics Research

FACILITIES



Notre Dame core facilities support research and advanced prototyping to promote U.S. leadership in semiconductors and microelectronics.

Notre Dame facilities that enable and enhance microelectronics research:

Notre Dame Nanofabrication Facility
The Notre Dame Nanofabrication Facility (NDNF) is a world-class teaching and research clean room located in the Stinson-Remick Hall of Engineering at the University of Notre Dame.

Learn more at: nanofabrication.nd.edu

Notre Dame Integrated Imaging Facility
The Notre Dame Integrated Imaging Facility (NDIIF) provides an integrated suite of microscopes and imaging systems that enable users to address the most complex modern research problems and expert staff to guide users.

Learn more at: imaging.nd.edu

Notre Dame Materials Characterization Facility
The Materials Characterization Facility (MCF) delivers state-of-the-art analytical services, expertise, and instrumentation to address complex materials problems.

Learn more at: mcf.nd.edu

iNDustry Labs at Notre Dame
As the University of Notre Dame's platform for collaboration with local industry, iNDustry Labs is uniquely positioned to unlock investments in technology, talent, and skills in the South Bend-Elkhart Region.

Learn more at: industrylabs.nd.edu

Notre Dame Engineering Innovation Hub
The Engineering Innovation Hub offers students, faculty, and industry partners resources for collaboration, fabrication, automation, robotics and modeling.

Learn more at: engineering.nd.edu

University of Notre Dame IDEA Center
Standing for Innovation, De-Risking, and Enterprise Acceleration, the IDEA Center is the fundamental resource for commercialization and entrepreneurial activities at Notre Dame.

Learn more at: ideacenter.nd.edu

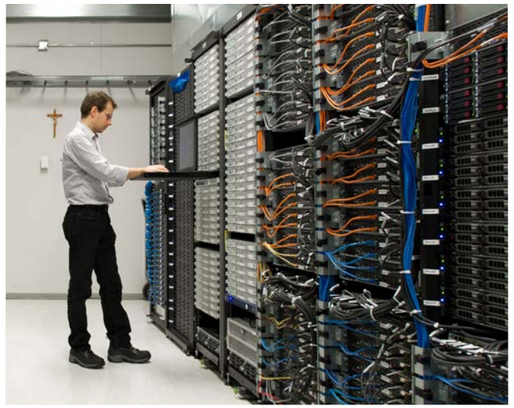


Notre Dame Nanoscience and Technology
Notre Dame Nanoscience and Technology (NDnano) promotes collaborative research in engineering and science to address unsolved scientific and technical questions with an aim to promote the greater good.

Learn more at: nano.nd.edu

Notre Dame Materials Science and Engineering
The Materials Science and Engineering program promotes the interdisciplinary understanding of materials through collaborative research to advance knowledge and new applications.

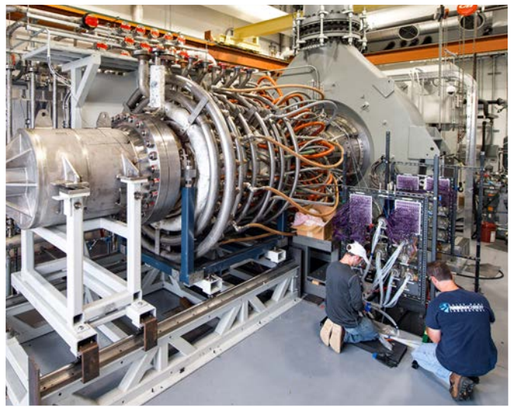
Learn more at: mse.nd.edu

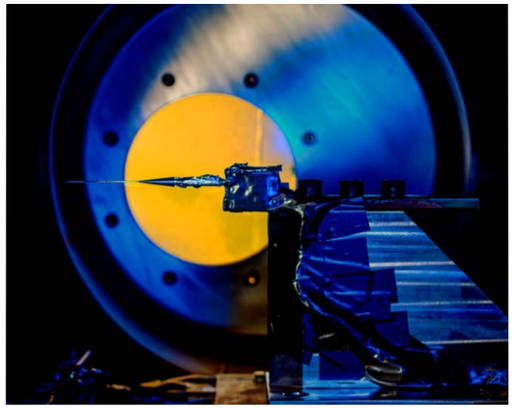


Center for Research Computing
The Center for Research Computing facilitates multidisciplinary discoveries through advanced computation, software engineering, artificial intelligence, and digital research tools.
Learn more at: crc.nd.edu

Notre Dame Power & Propulsion
Notre Dame Power & Propulsion is a research and development organization focused on the execution of large-scale, high-energy, high-complexity testing supported by leading-edge computational and analysis capabilities.

Learn more at: powerpropulsion.nd.edu





Hessert Laboratory for Aerospace Research
The Hessert Laboratory for Aerospace Research features 19 high-speed wind tunnels that generate near-flight conditions for Notre Dame's groundbreaking work in aerospace engineering.

Learn more at: engineering.nd.edu

Notre Dame Hypersonic Systems Initiative
The Notre Dame Hypersonic Systems Initiative engages the University's broad expertise in engineering and science to address the technical challenges of developing efficient, hypersonic flight vehicles.

Learn more at: hypersonics.nd.edu

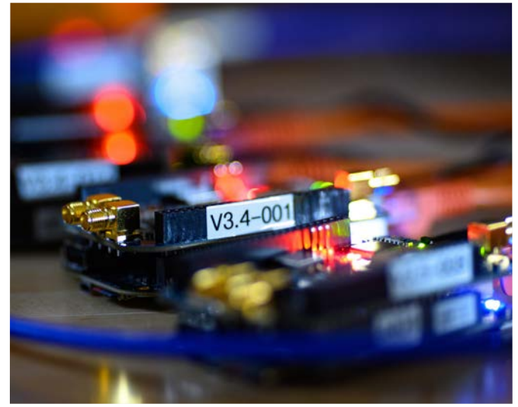


ND Energy
ND Energy researchers make new discoveries, scientific advancements, and technological breakthroughs that empower students and faculty to innovate, educate, and influence the world toward a more sustainable energy future.

Learn more at: energy.nd.edu

LIFT Network
The LIFT Network enchances skill attainment, research, commercialization, and entrepreneurship across the South Bend – Elkhart Region.

Learn more at: liftsbe.org



Wireless Institute
The Wireless Institute (WI) is a research center within the College of Engineering established to leverage Notre Dame's expertise to tackle interdisciplinary problems involving radio technologies and spectrum policy. In 2021, the WI became the lead institute for the U.S. National Science Foundation (NSF) SpectrumX center, the world's largest academic hub for radio spectrum stakeholders to innovate, collaborate, and contribute to maximizing the social welfare of the spectrum.

Learn more at: wireless.nd.edu



Nanofabrication, Characterization, and Research Facilities

CLEAN ROOM



The Notre Dame Nanofabrication Facility (NDNF) is the equipment set and supporting 9,000 square foot clean room environment for research and teaching in nanoelectronics, optoelectronics, microfluidics, nanofabrication, and related disciplines.

NDNF users explore a wide range of materials and processes, including silicon-related electronic devices, compound semiconductors, nanowires, carbon nanotubes, graphene, and organic polymer-based materials. In addition, the NDNF facilitates the study of microfluidic technologies for medical applications and micron-scale mechanical device fabrication.

The NDNF makes possible a wide range of cutting-edge research in fields that include high performance electronic devices, optical electronic processes, microelectromechanical systems, nanomagnetics, microfluidics, and bioengineering.

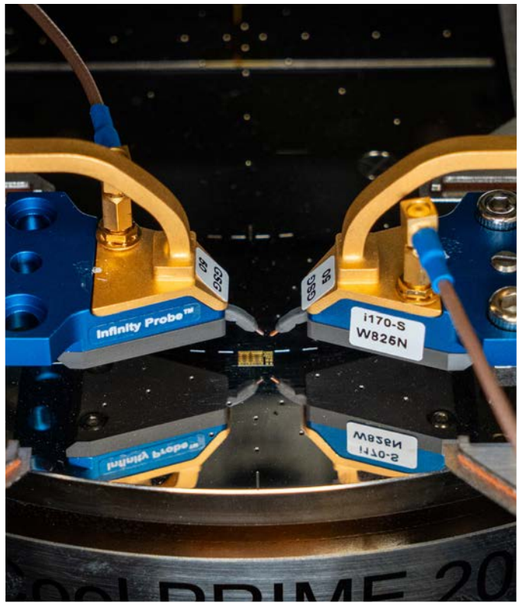
The NDNF staff are a highly skilled team of equipment experts available every weekday to train users, convey safety best practices, and ensure sustainable equipment operation. Specifically, the team creates operating procedures, trains and assists users on equipment operation, maintains, troubleshoots and repairs equipment, and provides advice to users on processing options available within the facility to achieve the research objectives.

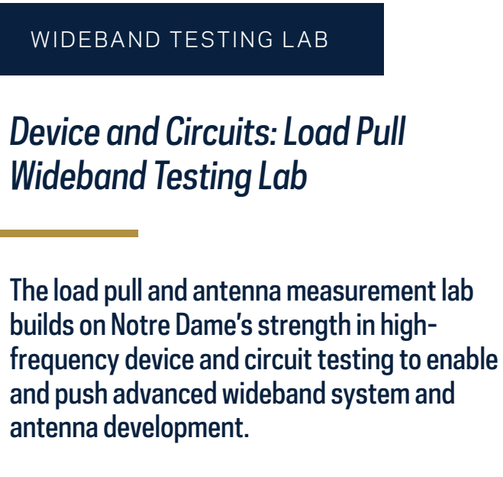
WIDEBAND TESTING LAB

Device and Circuits: Load Pull Wideband Testing Lab

The load pull and antenna measurement lab builds on Notre Dame's strength in high-frequency device and circuit testing to enable and push advanced wideband system and antenna development.

Notre Dame's testing capabilities include on-wafer linear network analysis from DC through 220 GHz and passive and hybrid-active load-pull for large-signal device characterization and modeling covering Ka-band (18-40 GHz) and W-band (94 GHz), as well as intermodulation measurements and full noise characterization through these same bands. This facility also provides full-band noise parameter, intermodulation, and load-pull capabilities covering D-and G-bands (110-170 GHz, 140-220 GHz) for beyond-state-of-the-art wide band gap and ultra-wide band gap transistors, monolithic microwave integrated circuits (MMICs), and systems. Extension to in-fixture and module-level test is also available.





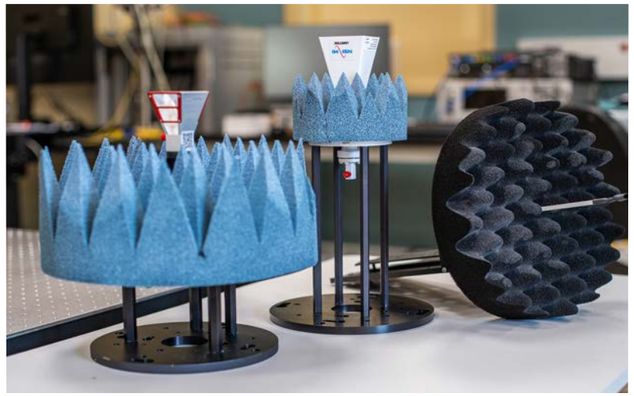


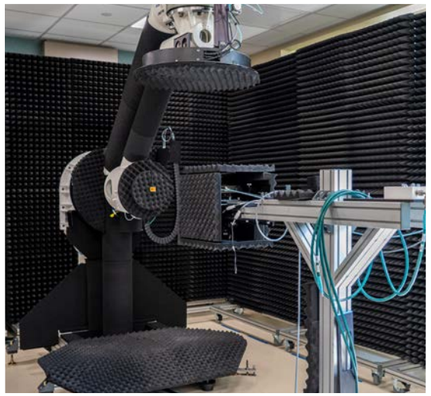


Wideband Antenna Measurement Lab

The wideband antenna measurement lab can cover frequencies from 4 to 220 GHz with a spherical near- field antenna range with probes and gain standards for C-, X-, Ku/K/Ka-, V-, W-, D-, and G- bands. There is an anechoic chamber with reconfigurable wall sections. Both frequency domain and time domain measurements can be performed. The frequency domain includes radiation patterns, effective isotropic radiated power (EIRP), and frequency converters (IF-to-RF, RF-to-RF).

The time domain includes error-vector magnitude (EVM), coexistence including 5G NR, 6G-candidate, radar, and SATCOM waveforms. The system consists of two operational modes. First is the "all around" spherical scan mode for mounted antennas. Second is the hemispherical scan mode on a custom open-top probe station for on-chip/on-wafer antennas.







Nanofabrication Equipment at the University of Notre Dame

LITHOGRAPHY

Formation of patterns in polymers using lasers, lamps, and electron beams

GCA AutoStepper System
5x reduction, production-grade i-stepper with repeat exposure capabilities as large as 17mm x 17mm.

MJB3 Mask Aligner, MJB4 Backside Aligner
A 200 W mercury short-arc lamp housed in a high resolution optical system. The MJB4 has g-line and i-line LED sources, topside alignment resolution <0.8µm, and <5µm backside alignment resolution.

OAI Deep-UV Light Source
High-performance light collimated illumination system intended for UV flood exposure.

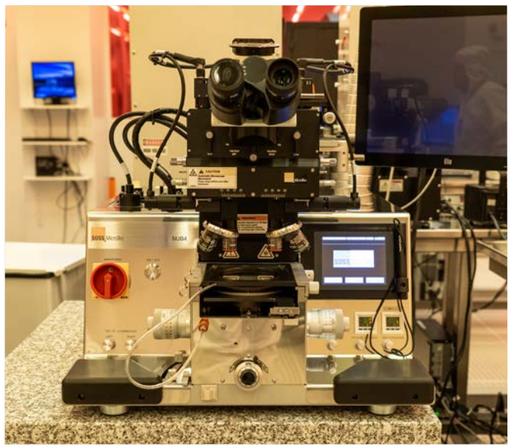
Raith EBL
Electron beam lithography system that can write to <8µm in size on 50-200 µm diameter wafers as well as arbitrary pieces at the cm scale.

Heidelberg Maskless Aligner
Equipped with UV laser sources (375 and 405nm) with write speeds of 1100mm^2/min.



DEPOSITION

Versatile suite of tools to deposit thin films of metal, dielectrics, and semiconductors



Denton Evaporator
The Denton Explorer® 14 e-beam evaporator is a six-pocket hearth deposition system.

Angstrom Engineering Evaporator
Six pocket e-beam source plus ion source and substroke heating from ambient to 500°C.

Oerlikon Evaporator
An electron beam vacuum deposition system.

Varian Thermal Evaporation System
A thermal vacuum deposition system.

Veeco Evaporator
Used for thermal vacuum deposition of Al or Cr on substrates situated 30 cm above the evaporation sources.



FC1800
Electron beam vacuum deposition systems.

Lesker Atomic Layer Deposition
The atomic layer deposition system is designed for R&D applications using their patented precursor focusing technology.

Angstrom Engineering Sputtering System
Six magnetron sources, O_2, Ar, N_2, ambient, 100 mm diameter wafers. In situ ellipsometer substrate temperature control 300-500°C.

Dual-Chamber Sputtering System
A three-chamber, 16-target ultra-high vacuum sputtering system used to deposit magnetic materials.

Emitech Sputter Coater
Employs a magnetron target assembly that enhances the efficiency of the sputtering process using low voltages, giving a thin and fine-grain coating.

Oerlikon 450B Single-Chamber Sputtering System
Equipped with three DC magnetron-enhanced sputtering guns (800 W) and two RF sputtering guns (300 W) for the deposition of metals and dielectrics.

Oxford ALD
An atomic layer deposition system is a plasma-enhanced ALD system for the monolayer growth of thin films.

Savannah ALD
An atomic later deposition tool.

First Nano LPCVD
A horizontal-tube furnace system, capable of low pressure chemical vapor deposition of polysilicon on 100 mm diameter wafers.

SMI MOCVD
Metalorganic chemical vapor deposition of high purity crystalline GaN compound semiconductor thin films.

Unaxis PECVD
For the plasma enhanced chemical vapor deposition of SiO_2 and silicon nitride on silicon and compound conductor wafers.

Scioto Omicron MBE
Molecular beam epitaxy to grow high-purity, single-crystal epitaxial (chalcogenide amloxide semiconductors) films in cluster tool arrangement with ALD, XPS, UPS, and Auger characterization.

ETCHING

Plasma reactive ion etching tools for subtractive removal of materials

Oerlikon ICP-RIE
An inductively coupled plasma reactor for independent control of plasma density.

Oxford ICP-RIE
The Oxford system is another inductive couple and plasma reactor.

Plasma-Therm Corial ICP RIE
Inductively coupled plasma reactive ion etch system with laser endpoint detector and in situ optical emission spectrometer.

Drytek Plasma Asher
Utilizes an exclusive passivation method, which produces a greater number of active species.

PVA Plasma Asher
The PS210 utilizes microwaves as its energy source for ion/radical formation to remove photoresistant and organic residues.

Tegal Barrel Asher
The Tegal PlasmaLine asher is a general purpose O_2 plasma used to remove photoresist and organics.

UVO Cleaner
Model 144AX produces near-atomically clean surfaces in less than one minute by utilizing the UV/ozone cleaning method.

Memstar XeF_2 Etcher
Vapor-phase silicon etch system using xenon difluoride (XeF_2).

Plasma-Therm RIE
Plasma-Therm's 790 Series provides a platform for parallel plate (capacitively coupled) reactive ion etch (RIE) processes.

Alcatel DRIE System
Deep reactive ion etch tool used for plasma etching of silicon and related materials utilizing the Bosch Process.









CHARACTERIZATION

Clean room characterization tools used to validate process performance

Confocal Microscope
The Olympus LEXT is a confocal laser (405nm) microscope capable of taking high-resolution 3D images.

Optical Microscopes
Various optical microscopes are available for use in the lab with magnifications that range from 2.5x up to 100x.

Hitachi SEM
This field emission scanning electron microscope is capable of producing high-resolution images between 20k and 500k.

Bruker Dektak Profilometer
Features a benchtop design that enables critical nanometer-level surface measurements with an unmatched repeatability of 4 Å.

P6 Profilometer
Offers complete high-resolution 2D and 3D analysis of surface topography in a versatile platform.

Gaertner Ellipsometer
The L117 Ellipsometer can be set with angle of incidence between 45 and 90 degrees. Used to obtain refractive index and/or layer thickness.

VASE Ellipsometer
Automated, thin film characterization system that uses high-precision angle and a wide spectral range (240 to 1700 nm) to dielectric thicknesses and refractive indices.

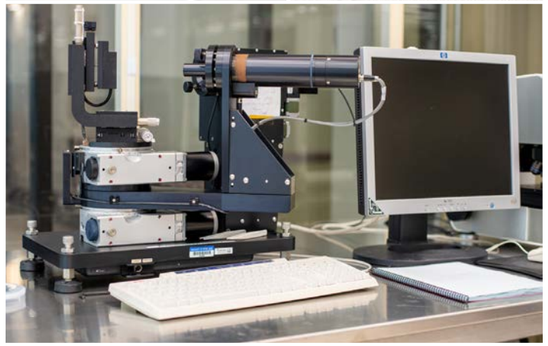
Filmetrics Thin Film System
Uses special reflectance to measure the thickness of transparent and semi-transparent thin films.

Four-Point Probe
This inline probe is used in conjunction with a Keithley model 530 measure sheet resistance.









Semiconductor Parameter Analyzer
A high-performance probing station that allows for precision electrical measurements, from DC to 10 MHz.

Veeco Four-Point Probe
The FPP 5000 is a four-point probe used to measure semiconductor sheet resistance.



Microelectronics and Semiconductors Education and Workforce Development at the University of Notre Dame

WORKFORCE DEVELOPMENT

The University supports national and regional efforts to promote U.S. leadership in semiconductors and microelectronics. The graduation of engineers and scientists with the capability to innovate in manufacturing and technology is critical to the success of this nationwide effort.

Hands-on Learning

Digital Integrated Circuits course: Students design and fabricate a 180nm circuit through the eFabless openFlow as well as TinyTapeout.

Computer Science and Engineering (CSE) Undergraduate Research: CSE undergraduate students completed research projects to develop pedagogical materials, including flows in the nanoHub with Cadence and Synopsys, Northrop Grumman, NASA Jet Propulsion Laboratory, and TinyTapeout.

Computer Architecture course: Students leverage an open-source toolchain to design and simulate a RISC-V processor in commercial 130nm technology.

Senior Design: Two-semester hands-on project course where students apply their knowledge of electrical/electronics engineering, wireless communication, and control to deliver a working application prototype.

Integrated Circuit Fabrication: Students fabricate and test a 5000-transistor CMOS integrated circuit sound chip.

RF and Microwave Circuits for Wireless Communication: Microwave circuit design and analysis techniques with laboratory to teach measurement techniques for device and circuit characterization.

Active Microwave Circuits for Wireless Applications: Advanced treatment of modern microwave amplifier design with a lab for fabrication and testing, including linear and nonlinear characterization.

Optics and Photonics: In both the classroom and hands-on lab, students learn the fundamentals of light-matter interactions employed in lasers, optical fibers, integrated optics, optical signal processing, holography, and optoelectronic devices/modulators.

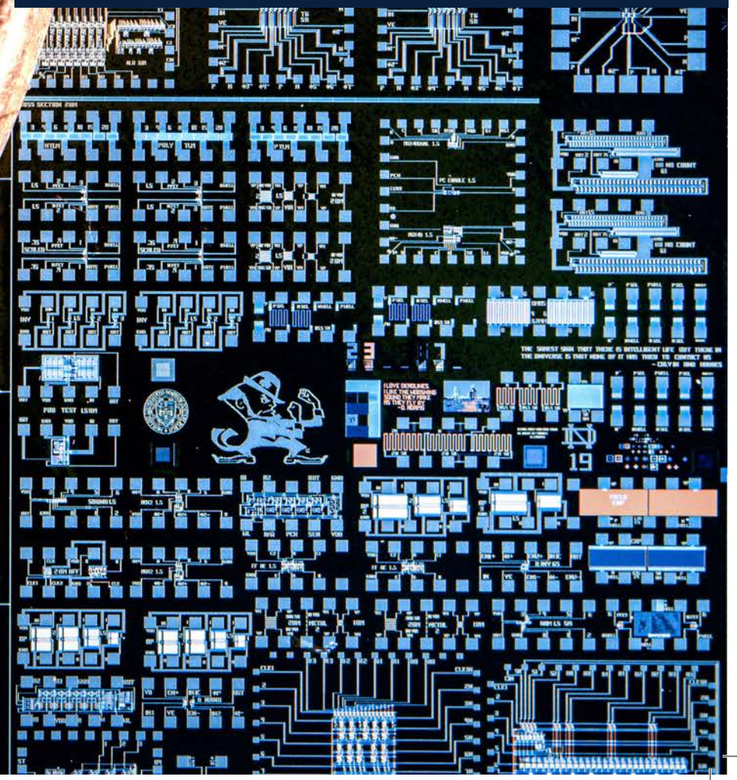


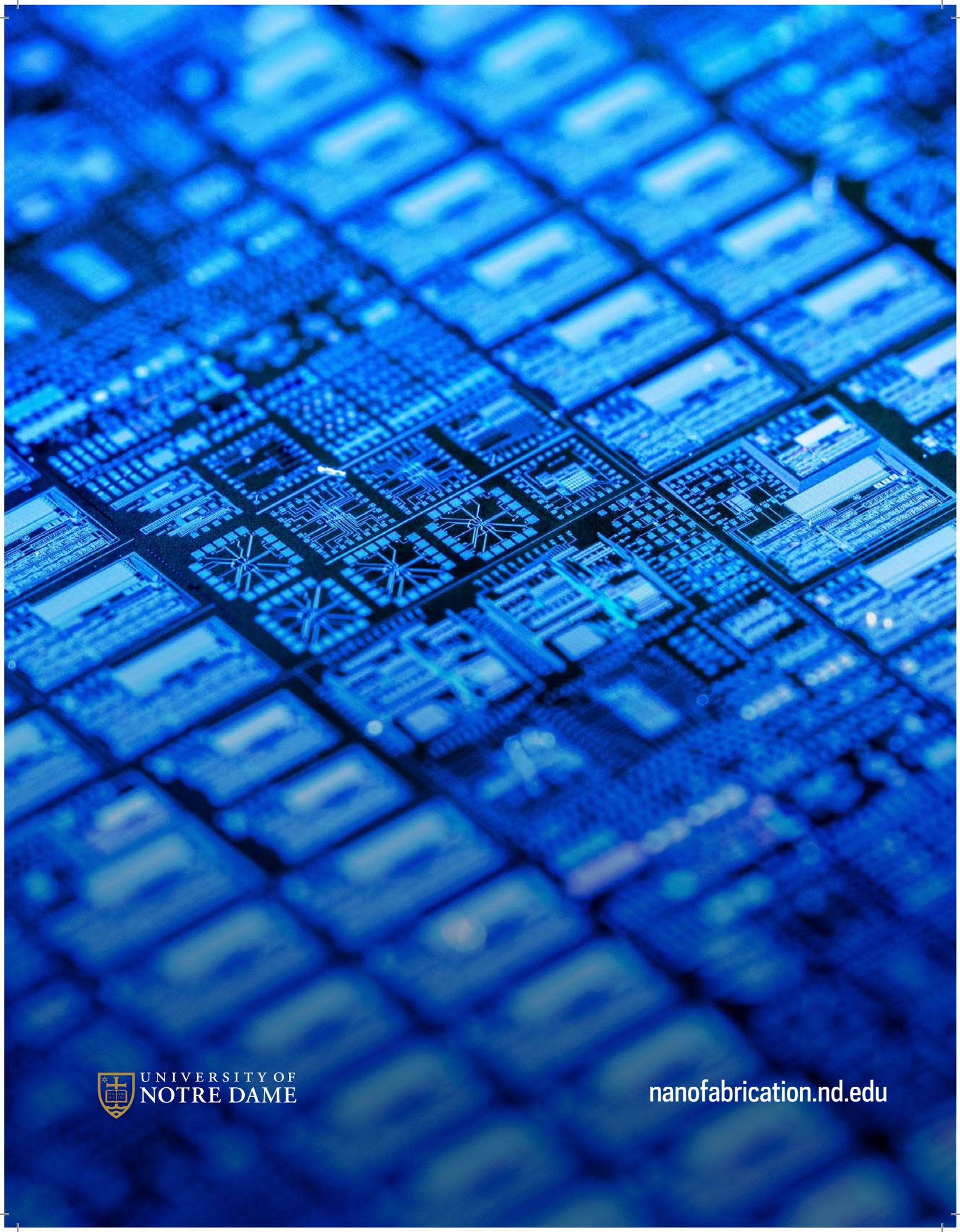


Students in Notre Dame's Integrated Circuit Fabrication Course fabricate a 5000-transistor integrated circuit in a single semester. The circuit, which plays the Notre Dame fight song, was designed in an undergraduate design course. Notre Dame endeavors to offer an unsurpassed education that nurtures the formation of mind, body, and spirit.

To learn more about the fabrication course, please read 'The Chip Makers' by scanning the QR code below.

Photo: A completed wafer produced for Notre Dame's Integrated Circuit Fabrication course here shown in relation to a penny. The icons related to Notre Dame (like the leprechaun near the bottom) help students orient their location relative to the circuit patterns.




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