Relevant Facilities for Nanoscience Research from Prof. Chen's Quantum Matter and Devices Laboratory:

Lab B76A (Nanophysics Measurement Lab) [Figs 5-6]

- A **variable-temperature probe station**: 4-400K, up to 2.5T magnetic field, 4 DC probes, 2 DC/AC probes with AC measurement capability up to 40 GHz, 1 back gate connection; this probe station can measure multiple devices without the need of wire-bonding; this probe station is also fitted with a 15-40keV X-ray source for in-situ radiation studies of nanoelectronic devices
- A **Variable-temperature Insert (VTI)**: can perform electrical and magnetotransport measurement in magnetic field up to 7 Tesla *and* at temperatures from 1.2K-300K; 25 DC wires, 2 rf coax cables up to 2GHz, a sample rotation stage allowing rotating the sample in-situ
- A **He-3 insert** with base temperature 280mK and magnetic field up to 5 T (or 7T when inserted into our VTI magnet dewar).
- A **cryogen-free dilution refrigerator** with base temperature of 10mK (ordered and expected to arrive in 04/2013)
- Various **electronic measurement instruments**: lock-in amplifiers, current/voltage source meters, current and voltage amplifers, multimeters, pico ampmeter, nanovoltmeters, oscilloscope (including a 1GHz scope with FFT), a semiconductor parameter analyzer, signal generators, a portable RF spectrum analyzers (up to 7GHz) and network analyzer (up to 6GHz) and variety of electronics to perform various DC/AC transport measurements
- A con-focal **Raman microscope** (with 532, 638, 780nm lasers) with **Raman mapping** scanning stage (100nm pixel/step size)
- Two **variable-temperature sample stages** with microscope optical access and electrical feedthroughs, allowing *combined Raman/optical/electrical transport measurement* from 4K to 900K;
- A **scanning probe microscope** (SPM) that can perform *ambient* AFM (atomic force microscopy, and various other modes of measurements including MFM, SCM, SGM, KFPM etc.) and STM (scanning tunneling microscopy)

Lab G57 (Materials/Device Fabrication & Processing Lab) [Figs 7-8]

- a fume hood
- a lamina flow station
- a manual wire-bonding station
- a semi-automatic wire bonder
- a vacuum oven
- a rapid thermal processor (RTP)
- a microwave plasma etching/cleaning system
- a high-magnification optical microscope with video camera
- a spinner and various hotplates
- a thermal evaporator
- a RF sputter (for both metal and dielectrics)
- a dedicated work station where "scotch tape" exfoliation of few layer graphene and other layered 2D materials (eg. MoS_2, BN, Bi_2Se_3) are routinely performed
- 2 tube furnaces with multiple gas sources that can perform CVD growth of graphene and other 2D materials as well as thermal annealing of samples

In addition, Prof. Chen has an optics lab (G61) with a wide variety of lasers and photonics facilities

Lab B76AC (Nanophysics Lab) [Figs 5-6]

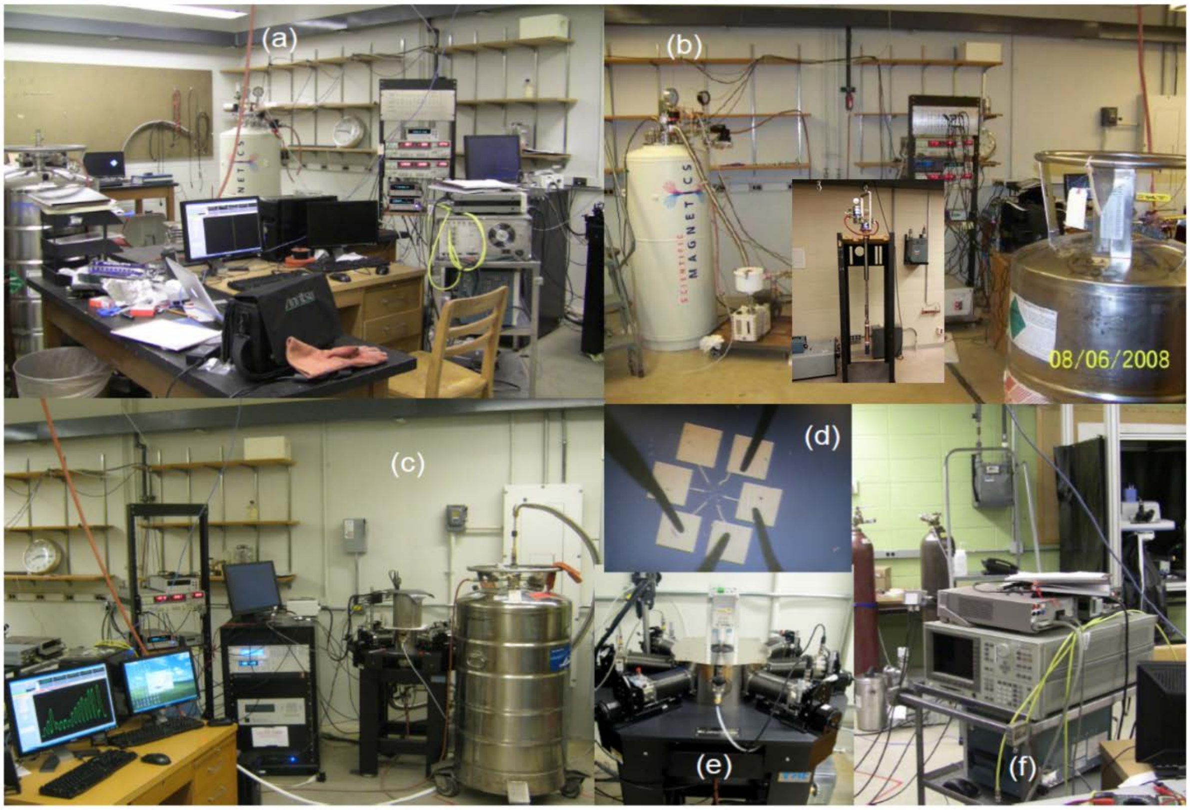

Figure 5. (a-b) Variable Temperature Insert (VTI) System (1.2-300K, 7T), inset of (b) shows the he-3 insert. (c-e) Variable Temperature Probe Station (4-400K, 2.5T) with X-ray source; (f) Semiconductor Parameter Analyzer and 1GHz Oscilloscope. Other major instruments including a 6GHz/7GHz vector network/spectral analyzer and many electronic test equipments.

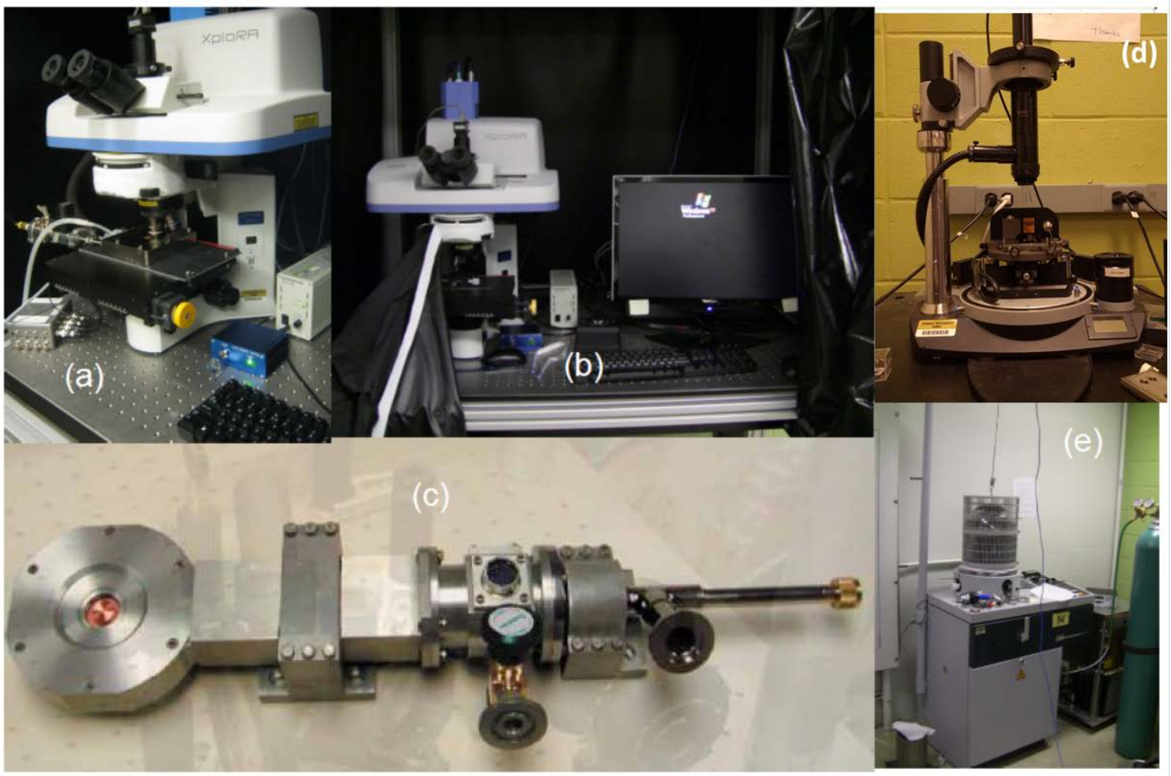

Figure 6. (a-b) Raman Spectroscopy Microscope with LN2 variable temperature sample stage (77-900K). (c) LHe Variable Temperature Electro-Optical Microscopy Cryostat (4-300K); (d) Atomic Force Microscope (including STM); (e) Thermal Evaporator

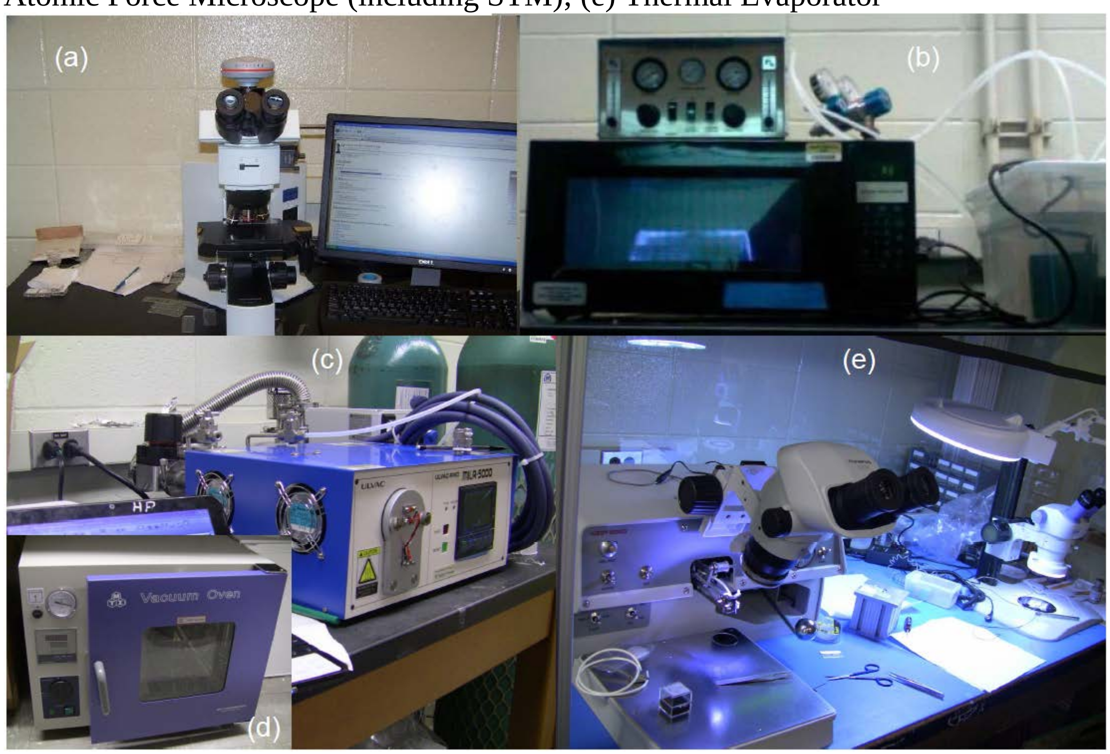

Figure 7. (a) High-magnification optical microscope with video camera; (b) Plasma etching and cleaning system; (c) High-vacuum Rapid Thermal Processing (RTP) System; (d) Vacuum Oven; (e) Wire bonder.

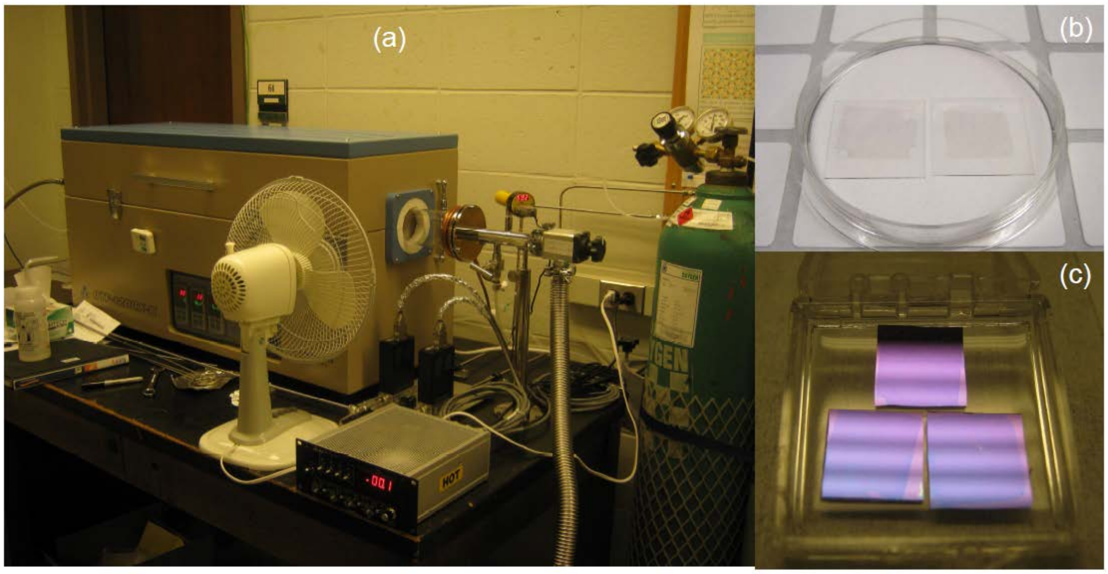

Figure 8. (a) Three-zone Tube Furnace Chemical Vapor Deposition (CVD) System. (b-c) Large-area monolayer graphene synthesized in this CVD furnace and transferred to glass (b) and Si (c) substrates.

<u>Other Departmental, University and Off-Campus Facilities accessed by Prof. Chen's group</u>

Physics Department Facilities

- A machine shop (with 2 full time staff machinist)
- An electronics shop (with 1 full time staff)
- Computing and network facilities (maintained by multiple full-time staff)
- A crystal growth facility (with 1 full time staff) and shared material preparation lab with several furnaces for semiconductor crystal growth, high temperature sample processing, and a sample polishing stage, various saws for crystal cutting
- A liquid helium liquefier and recovery system
- A small cleanroom and a Zeiss SEM and e-beam lithography system for nanodevice fabrication
- Various thin film deposition facilities including a RF sputter

Birck Nanotechnology Center (BNC) on Purdue Campus

Prof. Chen's group regularly access a wide variety of shared cleanroom nanofabrication facilities and materials/device characterization facilities in Purdue's state-of-the art Birck Nanotechnology Center (BNC), located on-campus (approximately 15 minute walking distance from Physics Department) in Purdue's Discovery Park (DP). Some examples of BNC facilities commonly used by PI's group include:

• Cleanroom (class-100, 10 & 1) Nanofabrication: optical and e-beam lithography, wet and dry (plasma, RIE, DRIE) etching, mask generation, FIB (focused ion beam), thermal and e-beam evaporators (including one e-beam evaporator supporting various magnetic metals for spintronics research), sputtering, and ALD (atomic layer deposition, including one recently added "metal-friendly" ALD system) etc.

• Materials characterization and microscopy facilities: SEM (scanning electron microscopes), AFM (atomic force microscopes), TEM (transmission electron microscopes, STM (scanning tunneling microscopes, both ambient and UHV), XPS (X-ray photoelectron spectroscopy), EELS (Electron energy loss spectroscopy), XRD (X-ray diffraction), Raman, FTIR (Fourier transform infrared spectroscopy) etc.

- Various electronic device probe station and characterization tools including I-V, C-V, A-V, A-F and microwave characterization tools up to 110 GHz.

A more detailed description of BNC facilities is provided at end of the document

National High Magnetic Field Laboratory (NHMFL, Tallahassee FL)
Prof. Chen's group regularly accesses the user facilities in NHMFL for transport measurements in high magnetic field and low temperatures, including:

- superconducting magnet systems (up to 18 T) equipped with a VTI (1.5 K – 300K), a He-3 system (base temperature 0.3 K) and dilution refrigerator (base temperature 50mK)
- resistive (up to 33 T) and hybrid (up to 45 T) magnet systems equipped with both He-4 (temperature down to 2K) probes and a portable dilution-fridge (temperature down to 50 mK)

All the above low T/high B systems are equipped with DC and microwave probes, with sample rotation stages. A more complete description is available at
http://www.magnet.fsu.edu/usershub/scientificdivisions/dcfield/facilities.html

Argonne and Oak Ridge National Laboratories (ANL & ORNL)
Prof. Chen's group also has been a user of the DOE nanoscience centers at ANL and ORNL, particularly their low temperature & variable temperature UHV STM facilities to perform STM/STM measurements.

The Birck Nanotechnology Center at Discovery Park of Purdue University

The Birck Nanotechnology Center is one of ten core centers in Purdue's $375M, 40-acre Discovery Park. Discovery Park provides an intellectual environment and facilities for multidisciplinary approaches to interdisciplinary challenges and opportunities spanning the domains of energy, the environment, healthcare, economic development, information access and homeland security. *Discovery* is intimately coupled with *delivery* in Discovery Park. Whether it be commercialization, community outreach, public policy, K-12 education or clinical translation, researchers in Discovery Park have their sights set on impact, and the resources and expertise needed to expedite the process to impact are integrated into the fabric of Discovery Park.

Overview. The Birck Nanotechnology Center (BNC) is an interdisciplinary research unit that provides infrastructure for 160 affiliated faculty members and their research groups from 36 academic units at Purdue. The new 187,000 sq ft. facility includes a 25,000 sq. ft. ISO Class 3-4-5 (Class 1-10-100) nanofabrication cleanroom – the Scifres Nanofabrication Laboratory – that includes a 2,500 sq. ft. ISO Class 6 (Class 1000) pharmaceutical-grade biomolecular cleanroom. In addition to the cleanroom, the facility provides 22,000 sq. ft. of specialized laboratories and offices for 45 resident faculty members, 30 post-docs, 30 staff, and approximately 200 graduate students. A flexible Nanotechnology Incubator lab may be leased by companies through the Purdue Research Foundation.

All of the equipment in the BNC is shared, and is accessible to qualified and trained users from Purdue and from academic, industrial, and government laboratories outside Purdue. Most of the major equipment is available through recharge centers that support maintenance, supplies and the time of dedicated staff scientists. Support for the facility, equipment, and processes is provided by a staff of 24 scientists, engineers, and support personnel with over 425 years of experience in academia and industry. Five of these staff members are Ph.D.-level scientists.

The Scifres Nanofabrication Laboratory

Cleanroom. The nanofabrication cleanroom consists of 25,000 sq. ft. of bay-chase cleanroom, with 45% of the bays operating at ISO 3 (Class 1), 40% operating at ISO 4 (Class 10), and the remaining 15% operating at ISO 5 (Class 100). The three-level structure consists of a full subfab, the cleanroom level, and an air-handling level above the cleanroom. A perforated raised floor ensures unidirectional airflow and bulkhead-mounted equipment separates operational functions from maintenance functions. A combination of careful control of the airflow path, multiple stages of filtration, careful choice of materials, and non-ionic-steam humidification ensure the control of both particulate and molecular contamination. A very tight waffle slab provides NIST "A" vibration rating, approximating quiet, slab-on-grade construction.

Lithography. Lithographic capability spans the nano and micro scale, with the capability of integrating nanoscale structures within micro-scale devices. A Vistec VectorBeam VB-6 UHR-UWF electron-beam lithography system provides the capability of 6 nanometer lines in resist across a 1.3 mm field and capable of 6 nm resolution in resist with high-speed patterning at a deflection speed of 25 MHz. A Raith e-beam nanolithography system with 20 nanometer resolution. An interference lithography system provides 100 nanometer resolution for less-critical operations.

Optical lithography is used in many operations in BNC, and is supported by a maskmaking operation and single- and double-sided mask alignment. 10x and 5x Criss-Cross Pattern Generator/Step-and-Repeat maskmaking systems, coupled with specialized image-reversal systems, provide a variety of photomasks to support research efforts.

Etching. Wet- and dry-etch capabilities allow the etching at high aspect ratios in a variety of materials. Two STS DRIE systems, a xenon difluoride etcher, an Oxford PlasmaTech system, and a soon-to-arrive Panasonic chlorine/fluorine system anchor the etching capabilities.

Deposition. Metal deposition is a strength in the BNC. Six evaporators and three sputterers allow the deposition of more than 20 different materials. Additionally, plasma-enhanced deposition systems and a soon-to-be operational LPCVD system provide further capabilities. Of special interest are three atomic-layer-deposition (ALD) systems designed especially for high-integrity high-k dielectric films. The third (recently added) ALD is a brand new remote plasma ALD reactor (Cambridge Fiji F200) dedicated to deposit high quality, ultra-thin gate dielectrics on novel nano-materials such as carbon nanotubes, nanowires, graphene etc. Besides high aspect ratio deposition and extremely precise thickness control that a normal ALD system can offer, this has a remote plasma attachment which makes material depositions more flexible in terms of deposition temperatures and precursor choices. The plasma enhancement also enables growth of exotic metals in the system which could be challenges for conventional e-beam or thermal evaporation.

Furnaces. A three-tube bank of process furnaces include clean (i.e., gate) oxidation, LTO, and LPCVD capabilities. This is supplemented by a separate two-tube pyrogenic oxidation system and several smaller high-temperature tubes and lower-temperature annealing tubes. Low temperature annealing and activation can be performed on two rapid-thermal-processing systems.

Ultra-Pure Water. The ultra-pure water (UPW) system at BNC supplies all laboratories and the cleanroom with incredibly pure water. Termed nano-grade water, this water is below the measurement limits of 15 parts per trillion of boron, the ion most loosely bound to the mixed beds and therefore the most likely ionic impurity in the water. This water also contains less than 225 parts per trillion of total oxidizable carbon (TOC) and less than 1 part per billion of dissolved oxygen.

Biocleanroom. Integrated into the Scifres Nanofabrication Laboratory is a pharmaceutical-grade cleanroom to allow sterile processing. This cleanroom is entered through a separate gowning room and has a completely separate air-handling system, but has a pass-through to the nanofabrication cleanroom to allow materials to be transferred into this facility without breaking cleanliness. Designed for sanitization, it trades a perforated floor for coved sheet-vinyl flooring and boasts a special pharmaceutical wall and ceiling system. Outside the entrance to the biocleanroom is an enclosed overhead walkway to Bindley Bioscience Center.

Specialized Laboratory Facilities

Overview. In addition to the cleanroom, the BNC includes a suite of specialized laboratories that provide outstanding capabilities to researchers. All BNC laboratories are designed for low acoustic noise, less than 1 milligauss EMI, and +/- 1 degree C temperature stability. Additionally, the first-floor laboratories achieve NIST A vibration rating. From this base, certain laboratories have been modified to provide even more stringent limits to accommodate specialized needs. For example, the TEM laboratory has tighter temperature controls, has specialized airflow patterns, and has special acoustic materials on the walls and floors.

Hall Nanometrology Laboratory and Scanning Tunneling Microscopy. For highly sensitive functions, the Kevin G. Hall Nanometrology Laboratory provides enhanced control of temperature, vibration, acoustic noise, and EMI. Temperature is controlled to +/- 0.01 degree C, EMI is controlled to less than 0.1 milligauss, acoustic noise is within NC-35 criteria, and vibration is controlled to NIST A-1 criteria. An Omicron UHV Scanning Tunneling Microscope located in the laboratory allows the study and manipulation of materials on the atomic scale.

Scanning Laser-Doppler Vibrometry. A specialized laboratory that meets NIST A-1 vibration criteria houses the Scanning Laser-Doppler Vibrometer. The Polytec MSA-400 Micro System Analyzer uses a variety of methods to characterize motion in micro- and nanostructures.

Scanning Probe Microscopy. Seven atomic force microscopes provide topographical data on surfaces as well as allowing the manipulation of materials at the nano scale.

Electron Microscopy. Four electron microscopes provide the ability to image nanoscale devices and materials, as well as to study reaction mechanisms at the atomic scale. An FEI Titan 80-300 keV Field Emission Environmental Transmission Electron Microscope – Scanning Transmission Electron Microscope provides resolutions to 0.7 by 1.0 Angstrom units. The system contains an in-situ reaction chamber, and is equipped with a high-performance camera and data server.

Supplementing the capabilities of the Titan are an FEI Field-Emission Scanning Electron Microscope, an FEI “Novalab” Focused Ion Beam – Scanning Electron Microscope system, and a dual-function JEOL Scanning Electron Microscope with electron-beam direct-write capability.

Surface Analysis. The surface analysis laboratory contains a Kratos Imaging x-Ray Photoemission Spectrometer (XPS) with an in-situ reaction cell and an Omicron surface analysis cluster tool. The XPS has a 15 micrometer spot size, and provides atomic-level analysis of materials. The cluster tool contains multiple devices to characterize the surfaces of materials, including a high-resolution electron-energy-loss spectrometer (EELS), a scanning electron microscope (SEM), a scanning auger spectrometer, a hemispherical electron spectrometer for XPS, AES, UPS, ISS, and a focused ion beam (FIB) system – all connected under ultra-high vacuum.

x-Ray Diffraction. The x-ray diffraction laboratory contains a high-resolution PANalytical “x”Pert Pro x-ray diffraction system.

Epitaxy. Several BNC laboratories contain equipment for specialized, highly precise epitaxial growth. A Varian Gen II Molecular Beam Epitaxy system for III-V epitaxy, an Epigress VP-508 hot-wall CVD reactor for SiC, an Aixtron AIX 200/4 metal-organic chemical vapor deposition (MOCVD) system for GaN, and a halide vapor-phase epitaxy reactor for GaN allow the growth of a variety of homoepitaxial and heteroepitaxial materials .

Deposition. An ASTeX plasma-enhanced chemical vapor deposition system allows film growth of specialized materials.

Biosafety Level 2 Laboratories. The BNC has two biosafety level 2 laboratories, one containing two tissue-culture rooms that operate at biosafety level 2+. These specialized laboratories allow for the safe handling of biological materials used in the development of devices and delivery methods.

Biosafety Level 1 and Nanochemistry Laboratories. The BNC also provides four laboratories for less hazardous nano-bio and nanochemistry research. These laboratories, classified at BSL-1 or below, are used for both mechanical and wet-chemical research activities.

Electrical Characterization Laboratories. A significant amount of BNC laboratory space is allocated to electrical characterization. From a Hall Effect measurement system to multiple shielded probe stations with hot and cold testing capabilities, these laboratories provide the equipment and facilities necessary to evaluate new materials, structures, and devices.

Laser Laboratories. Specialized laboratories for optical materials development, optically enhanced deposition, and optical characterization methods have been implemented in the BNC. Using lasers of various power levels – up to Class 4 – BNC researchers are able to develop materials, processes, and devices for energy conversion and other applications. These laboratories also support research strengths in nanoelectronics and nanophotonics.

Nanoincubator Laboratory. The BNC provides flexible laboratory space that can be leased by companies through the Purdue Research Foundation. This space is designed to provide a secure, specialized laboratory for companies wishing to use the infrastructure of the BNC while maintaining private laboratory space for specialized or proprietary work.