FACILITIES AND EQUIPMENT: Yong Chen/Purdue University

Prof. Chen has access to extensive state-of-art facilities related to the research in this proposal.

Laboratory: Relevant Facilities in Prof. Chen's Quantum Matter and Devices (QMD) Laboratory:

Lab G61 (Atomic-Molecular-and-Optical Physics Lab)

- Optical tables: Two Newport RS4000 optical tables.
- Lasers:
  - A tunable wavelength **CW Ti:Sa laser** [M-Square] that provides laser excitation source with wide tunable wavelength (350-500nm, 532nm, 700-1000nm)
  - A 765nm-795nm Toptica wavelength-tunable TA Laser system (800mW);
  - A 780nm tunable DFB laser (50mW);
  - A 671nm Toptica tunable TA100 Laser system (400mW);
  - Several homemade external cavity diode lasers and tapered amplifiers (TA) based lasers covering various wavelengths including particularly 780-795nm;
  - A 5W Verdi laser (532nm);
  - A 1W, CW fiber laser amplifier covering wavelength from 1540-1590nm;
  - A 1550nm single frequency IPG photonics erbium fiber laser system (45W) for optical trapping/lattice;
  - A 632nm He-Ne laser;
- Various electronic and rf instruments, such as oscilloscopes (including an 1GHz phosphorous scope with FFT), multimeters, general electronic test equipment, r.f. oscillators, rf/microwave signal generators and synthesizers, rf power meters, NI digital/analogue control cards, etc.
- Various optics and photonics components and analysis instruments, including many optical components (mirrors, lenses, waveplates, beam splitters, etc.), AOMs (acoustic optical modulators) and drivers, a Bristol and a Coherent wavemeters, spectrum analyzer, home-made scanning FP cavities, a New Port spectrometer, etc.;
- Several CCD cameras (including in particular a high performance Andor iXon 885 CCD camera);
- Various vacuum equipments and components, UHV pumps, leak detector (shared) etc.
- ***Atom trap and BEC apparatus***: An optical-trap-based ^{87}Rb cold atom trap and Bose-Einstein condensation (BEC) apparatus equipped with Raman-coupling-based synthetic spin-orbit-coupling and gauge fields, involving many components above. Currently this apparatus routinely produces BECs of ~ several 10^4 atoms (^{87}Rb) in a cross-beam dipole trap (wavelength 1550nm) subject to synthetic spin-orbit coupling or gauge fields generated by counter-propagating Raman beams (at wavelength ~790nm); in addition, QMD lab has access to another dual-species (Li & Rb) atom trap (co-developed with collaborator Prof. Dan Elliott and located in his lab in MSEE building) that can trap cold Li and Rb atoms in MOT (magneto-optical trap), produce cold LiRb molecules by photoassociation and detect them by trap loss or REMPI (resonant multi photon ionization).
- *Faraday/Kerr rotation setup*: a home-made setup to measure Faraday and Kerr rotation based on polarization bridge (balanced photodetectors).

Lab G57 (Materials/Device Fabrication & Processing Lab)

- a dedicated work station where "scotch tape" exfoliation of graphene and other layered 2D materials (eg. Bi_2Se_3, MoS_2, h-BN, $NbSe_2$, FeTeSe, $CrGeTe_3$, etc.) including topological insulators are routinely performed; this station also contains a micromanipulator based setup to transfer 2D crystal layers to build stacked (van der Waals) heterostructures

- 2 tube furnaces with multiple gas sources that can perform CVD growth of graphene and other 2D materials (eg. Bi_2Te_3, MoS_2) as well as thermal annealing of samples
- 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)

Lab B76A & B76C (Condensed matter/Nanophysics Measurement Lab)

- A con-focal **Raman microscope** (with 532, 638, 780nm lasers) with **Raman mapping** scanning stage (100nm pixel/step size) [Horiba JY Xplora]; can also perform photoluminescence (PL) measurements.
- Two **variable-temperature sample stages** with *microscope optical access and electrical feedthroughs*, allowing *combined optical (eg. Raman/photoluminescence) & electrical transport measurement* from 4K to 900K;
- A **magneto-optical cryostat** with a 5T magnet allowing magneto-optical (Raman and PL) measurements down to 4K.
- A **scanning probe microscope** (SPM) [NT-MDT] 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)
- A **Variable-temperature Insert (VTI)** [Scientific Magnetics]: 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 **variable-temperature probe station** [LakeShore]: 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 various illumination/laser sources and a 15-40keV X-ray source for in-situ photoconductivity or radiation studies of nanoelectronic devices;
- A **He-3 insert** [Cryogenic Industries America] with base temperature 280 mK and magnetic field up to 5 T (or 7T when inserted into our VTI magnet dewar).
- A **cryogen-free dilution refrigerator** [BlueFors] with base temperature of 10mK and magnetic field up to 12T, allowing low temperature magnetotransport measurements.
- Various **electronic measurement instruments**: lock-in amplifiers, current/voltage source meters, current and voltage amplifiers, 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) that can be used as **rf/microwave source** and variety of electronics to perform various DC/AC transport measurements

Other Resources

Physics Department Facilities

- A **crystal growth facility** (operated by one staff scientist, this facility is managed by Prof. Chen) and shared material preparation lab with several Bridgman and multi-zone furnaces for growth of bulk crystals, high temperature sample processing, and a sample polishing stage, various saws for crystal cutting; in the past few years this crystal growth facility has produced a wide range of Te and Se based semiconductors, semimetals, topological insulators, and Fe-based superconductors (such as Bi_2Se_3/Bi_2Te_3/Sb_2Te_3, GaSe, HgTe, FeTeSe etc.)
- Various portable radioactive sources to give gamma-rays, alphas, and neutrons for testing materials/devices responses under such radiations. These sources are compatible with our variable temperature probe station for example.
- A machine shop (with 2 full time staff machinist)
- An electronics shop (with 1 full time staff)
- A small clean room with an SEM/E-beam lithography system used by faculties in experimental condensed matter physics group
- A liquid helium liquefier and recovery system
- Various thin film deposition facilities including dc and rf sputters; we have used these facilities to deposit high quality superconducting thin films of Nb and NbN
- Computing and network facilities (maintained by multiple full-time staff)

Birck Nanotechnology Center (BNC) on Purdue Campus

Dr. Chen's group regularly accesses a wide variety of shared cleanroom nanofabrication facilities and materials/device characterization facilities in Purdue's state-of-the-art Birck Nanotechnology Center (BNC, a more detailed description of BNC facilities is provided at end of this document), located on-campus (approximately 15 minute walking distance from the Department of Physics) in Purdue's Discovery Park (DP). Some examples of BNC facilities commonly used by Dr. Chen'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 dedicated to magnetic metals), sputtering (including one sputter for Nb), and ALD (atomic layer deposition, including one recently added "metal-friendly" ALD system) etc.
- Materials and surface 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. In the surface science lab, there are also 2 vacuum glove boxes for sample handling in vacuum or controlled environment.
- Various electronic device probe stations (including 2 low temperature probe stations with magnetic fields) and characterization tools including I-V, C-V, A-V, A-F and microwave characterization tools up to 110 GHz.
- Quantum Design PPMS (Physical Property Measurement System) and MPMS (Magnetic Property Measurement System) for transport and magnetic (SQUID magnetometry) characterizations under variable temperature (4-400K) and magnetic field (7T)

National High Magnetic Field Laboratory (NHMFL, Tallahassee FL)

Prof. Chen's group regularly accesses the user facilities at the 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 ~40mK)

- 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 ~40 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 remains an active user of the DOE nanoscience centers at ANL (http://www.anl.gov/cnm) and ORNL (http://www.cnms.ornl.gov/capabilities/cap.shtml), particularly their low temperature & variable temperature UHV STM facilities to perform STM/STM measurements. Other facilities accessed by Chen's group at ANL's Center for Nanoscale Materials (CNM) include various material characterization facilities including PPMS/MPMS, AFM, Raman etc.

More details on 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 includes several unique resources and services, including:

- ***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.

Additional Specialized Laboratory Facilities in 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. The surface analysis lab also has 2 vacuum glove boxes for sample handling in vacuum or controlled environment.
- ***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.
- ***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. The lab also has a pair of quantum design **PPMS** and **MPMS** (added recently) that enable electrical transport measurements and magnetometry in variable temperature and magnetic field. Ferromagnetic resonance (FMR) measurement capability has also been recently added.
- ***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.