IEEE Annual Mini-symposium on Electron Devices and Photonics

October 22, 2015
12:00 – 5:00 pm

Notre Dame room of LaFortune Student Center

Program Chairs: Anthony Hoffman, Kajun Feng, Owen Dominguez

Short Schedule

11:45 – 12:30	Lunch (will be provided)
12:30 – 1:40	Session A: Photonic Devices & Integration
1:40 – 1:50	Break
1:50 – 2:40	Session B: Nanomagnetics & Low-dimensional Systems and 2D Crystals
2:40 – 3:00	Coffee & Snacks
3:00 – 4:10	Session C: Applied Photonics and Biophotonics & Other Topics
4:10 – 4:20	Break
4:20 – 5:00	Session D: Electronic Devices

Session A: Photonic Devices & Integration

Chair: TBD

1. (12:35 p.m.) *Invited talk:* Deep UV LEDs with GaN/AlN quantum structures using polarization-induced doping
   SM Islam, Vladimir Protasenko, Sergei Rouvimov, Samira Chandra, Jai Verma, Huili (Grace) Xing, and Debdeep Jena

2. (12:50 p.m.) Surface Plasmon Propagation in Cut Waveguides
   Paul Johns, Gregory Hartland

3. (1:00 p.m.) Engineering the Reststrahlen Band with Hybrid Plasmonic/Phononic Mode
   W. Streyer, K. Feng, Y. Zhong, A.J. Hoffman, and D. Wasserman

4. (1:10 p.m.) Compound semiconductor native oxides for direct wafer bonding in optical integration
   Yuan Tian and Douglas C. Hall

5. (1:20 p.m.) Application of critical dimension metrology techniques for the fabrication of low loss optical waveguides
   Zachary C. Santonil and Douglas C. Hall

6. (1:30 p.m.) Oxide-confined high index contrast ridge waveguide lasers
   Jinyang Li and Douglas C. Hall

10 minutes Break

Session B: Nanomagnetics & Low-dimensional Systems and 2D Crystals

Chair: TBD

1. (1:50 p.m.) Tunnel transistors using atomically thin semiconductors
   Sara Fathipour and Alan Seabaugh

2. (2:00 p.m.) Fine-Tuning of Thermal Transport across Graphene-Metal Interfaces through Controlled Functionalization
   Xin Mu, Suresh Vishwanath, Vasily Kanzyuba, Tao Jiang, Xueqiang Zhang, Denis Sokolov, Sylwia Ptasinska, David Go, Huili Xing, Tengfei Luo

3. (2:10 p.m.) Novel coupling scheme for nanomagnet logic (NML) applications
   Himadri Dey, Gyorgy Csaba, Gary H Bernstein, Wolfgang Porod

4. (2:20 p.m.) Nonconcentric PbSe/CdSe Colloidal Quantum Dots
   Gary Zaiats, Arthur Shapiro, Diana Yanover, Yaron Kauffman, Aldona Sashchiuk and Efrat Lifshitz

5. (2:30 p.m.) Spin-wave-based Computing
   Ádám Papp, György Csaba and Wolfgang Porod

20 minutes Coffee Break

Session C: Applied Photonics and Biophotonics & Other Topics

Chair: TBD

1. (3:00 p.m.) Saturation Multiphoton Microscopy toward super resolution and super penetration
   Genevieve Vigil, Scott Howard

2. (3:10 p.m.) Sparse Tensor Approximation for Uncertainty Quantification on 2D Periodic Gratings
   Gerardo Silva Oelker, Carlos Jerez-Hanckes, Patrick Fay

3. (3:20 p.m.) Super-resolution imaging with mid-IR photothermal microscopy on the single particle level
   Zhongming Li, Massaru Kuno, Gregory Hartland

4. (3:30 p.m.) Designing Mid-infrared Mie-based Optical Metamaterials
   Owen Dominguez and Anthony Hoffman

5. (3:40 p.m.) Holography Undergraduate Research and Outreach Activities at Notre Dame
   Charles L. Filipiak and Douglas C. Hall

6. (3:50 p.m.) 3-Dimensional, High-Resolution Oxygen Microscopy in Vivo Through Multiphoton Phosphorescence Lifetime Imaging
   Aamir A Khan, Genevieve D Vigil, Susan K Fullerton-Shirey, and Scott S Howard

7. (4:00 p.m.) On increasing the imaging rate of frequency-domain multiphoton fluorescence lifetime imaging microscopy
   Yide Zhang, and Scott S. Howard

10 minutes Break

Session D: Electronic Devices

Chair: TBD

1. (4:20 p.m.) Experimental Demonstration of Single Electron Transistors Featuring SiO2 PEALD in Ni-SiO2-Ni Tunnel Junctions
   Golnaz Karbasian, Alexei O. Orlov, and Gregory L. Snider

2. (4:30 p.m.) Ion-locking electrolytes: a room temperature doping solution for 2D electronics and optoelectronics
   Erich Kinder, Ashley Fuller, and Susan Fullerton

3. (4:40 p.m.) Fabrication of high density nanoelectrode arrays via directed self-assembly of block copolymers
   Kaiyu Fu, Paul W. Bohn

4. (4:50 p.m.) Platinum Oxidation and Reduction during Single Electron Transistor Fabrication
   Michael S. McConnell, Alexei O. Orlov, Gregory L. Snider

Abstracts

A1. (Invited) Deep UV LEDs with GaN/AlN quantum structures using polarization-induced doping

SM Islam, Vladimir Protasenko, Sergei Rouvimov, Samira Chandra, Jai Verma, Huili (Grace) Xing, and Debdeep Jena

The 230-270 nm emission is very attractive for water purification, sterilization application, diagnostics and hazardous chemicals detection. Unfortunately, LED devices emitting at short wavelengths and utilizing AlGaN for active area suffer significant energy losses due to non-radiative recombination near structural defects. Replacing AlGaN with ultra-thin GaN quantum wells (QWs) and quantum dots (QDs) and AlN for barriers can solve this problem due to better carrier localization in quantum dots, absence of compositional variation in GaN/AlN structure, and better light extraction with TE polarized emission. Also traditional impurity doping schemes are difficult for such high Al content AlGaN alloys due to the large activation energies of dopants. In order to solve the issue of doping, polarization-induced (or Pi-) doping scheme is used in the devices. In this work, we experimentally demonstrate electrically injected tunable deep UV emission from GaN/AlN quantum structures. The emission wavelength is tuned over 231 nm→270 nm range by changing thickness of GaN layer placed between similar thicknesses of AlN barrier.

We grew the LED structures on commercially available AlN templates on Sapphire with a threading dislocation density of ~1e10 cm-2 using plasma assisted molecular beam epitaxy (PAMBE). Polarization doping (Pi- doping) is established by changing the chemical composition linearly for both p and n doped regions of the LED structures. The Pi-doping ensures flat bands for both electrons and holes in the n and p doped regions respectively which facilitates smooth injection of carriers into the active region that emits the light. Thin AlN barriers in the active region enables tunneling of carriers which further enhances carrier injection. We grew 1-4 monolayers (MLs) thick GaN QDs by Stranski-Krastanov mode between 2 nm thick AlN barriers. By varying the GaN thickness, the emission wavelength can be tuned over 231-270 nm range.

A2. Surface Plasmon Propagation in Cut Waveguides

Paul Johns and Gregory Hartland

Nanoscale optical waveguides can be used to create nano-circuits, perform logic functions, split signals, or aid in the development of plasmonic lasers. In these applications, long propagation lengths and control of the modes is desireable. Developing plasmonic devices requires an under-standing of how defects in the waveguides affect propagation, and how plasmons couple between devices. An example of a plasmonic waveguide is a gold nanobar (a nanowire with a rectangular cross-section), which supports bound and leaky propagating surface plasmon polaritons. Defects were introduced into single-crystalline gold nanobars by cutting them in several places using FIB milling. Plasmons were launched using end-fire coupling, and a pump-probe spectroscopy technique was used to directly image the plasmon propagation in the nanobars. The intensity of the plasmon mode was shown to decrease at the cuts. Finite element method calculations as implemented by COMSOL Multiphysics were used to study how the mode shapes were changed by the discontinuities and to study damping of the modes during propagation. The results of the calculations are in good agreement with the experiments, and show that a resonance effect occurs at gap sizes of ~30 nm. It was determined that of the two primary modes that propagate through the structures, the leaky mode (which occurs at the interface of air and gold) is heavily damped by the cut while the bound mode (which occurs at the interface of glass and gold) is not as severely affected.

A3. Engineering the Reststrahlen Band with Hybrid Plasmonic/Phononic Modes

W. Streyer, K. Feng, Y. Zhong, A.J. Hoffman, and D. Wasserman

The so called phononic materials has drawn more and more interest because of their superiorities over the traditional plasmonic materials in the mid-infrared (mid-IR) spectral range. Comparing to the surface plasmon polaritons (SPP), the surface phonon polaritons (SPhP) supported by phononic materials suffer from much smaller material loss, which can result in longer propagation length and higher Q factors in propagation and localized modes, respectively. However, the SPhP modes are confined within the spectral range between a material's transvers and longitudinal phonon frequencies, also known as the Reststrahlen band. In order to break the limitation of the fixed spectral range for SPhP modes, here we demonstrate that for materials with appropriate free carrier concentration, the hybrid surface plasmon/phonon polariton (SPPhP) modes can be supported across a range of frequencies including those generally forbidden by purely phononic materials. In this work, we first characterize the intrinsic and doped GaAs samples by measuring their reflection spectra around the Reststrahlen band of GaAs. The samples are then patterned with gratings so that the incident light can couple to the surface of the samples as SPhP or SPPhP modes. The reflection spectra of TE polarized light with different azimuth angels are obtained from both RCWA simulation and measurements. Dispersion curves of the hybrid modes are calculated and mapped out based on the RCWA simulations. The TM reflection spectra are also acquired in the same way. It is observed that localized resonance modes have been excited around the LO phonon frequency of GaAs, which can be the potential bridge between LO phonons and free space photons at the same energy.

A4. Application of critical dimension metrology techniques for the fabrication of low loss optical waveguides

Yuan Tian and Douglas C. Hall

For Silicon photonics applications aimed towards integrating light-emitting compound semiconductors with Si electronics integrated circuits, wafer bonding is often preferred to III-V heteroepitaxial growth on Si for its smaller resulting density of interface misfit dislocations and other advantages. Oxide to oxide wafer bonding, where strong bonding can be formed at annealing temperatures <350°C, is essential when bonding GaAs or InP wafers to Si in order to avoid thermal dissociation of the compound semiconductor and issues related to mismatched coefficients of thermal expansion. We propose and demonstrate that optimized III-V compound semiconductor wet thermal native oxides with low surface roughness, typically < 1 nm, offer additional flexibility for photonic/silicon wafer bonding, as the surface roughness can readily meet the sub-nm requirement even for thick oxide layers. The method can be applied through oxidation of a variety of III-V compound semiconductor alloys used in both GaAs and InP systems. Compared to other complicated pre-bonding treatment processes including fabrication of outgassing channels and plasma activation, our wet thermal native oxide mediated bonding technique may enable a more reliable, lower cost process readily applicable to large scale wafer bonding. Possible applications include the development of broadband, low-cost on-chip Erbium-doped waveguide amplifiers employing InAlP thermal native oxides (a promising rare earth host), and the improved fabrication of silicon hybrid lasers to combine the communication advantages of photonic devices with well-established Si CMOS fabrication techniques. Preliminary calculations suggest that both oxidation and annealing steps can be achieved under 350°C to avoid known thermal degradation

mechanisms in InP-based quantum well laser heterostructures. Experiments demonstrating successful low temperature wafer bonding of compound semiconductors with thin wet thermal native surface oxides to oxidized Si wafers will be discussed.

A5. Application of critical dimension metrology techniques for the fabrication of low loss optical waveguides

Zachary C. Santonil and Douglas C. Hall

This talk presents the use of critical dimension (CD) metrology as a means to optimize the fabrication of low-loss deep-etched high-index contrast (HIC) III-V compound semiconductor waveguide structures. HIC waveguides have been a topic of interest in the area of photonic integration in that they can be used to attain micrometer bend radii as opposed to the millimeter band radii exhibited by conventional waveguide structures. However, as the lateral refractive index contrast increases, these structures are much more susceptible to scattering loss due to sidewall roughness. Previous work conducted by our research group has focused on improving sidewall roughness through an isotropic oxidation smoothing process.

In order to realize the lowest possible loss HIC waveguides, it is essential to further optimize each fabrication stage in order to fully minimize the final sidewall roughness accumulated after several processing steps. Thus, CD metrology was recently implemented with the intention of extracting quantifiable and relative metrics to observe the various contributions to sidewall roughness introduced throughout the fabrication of the waveguide structure. Using modern line digitization techniques with the SuMMIT CD Suite on images obtained through scanning electron microscopy, fabrication steps can be analyzed and optimized by comparing various CD metrics – in particular – line edge roughness (LER) and correlation length (Lc). For waveguide optimization, reduced LER is always desirable, whereas the more complex relationship between waveguide loss and correlation length is non-monotonic and depends on the waveguide geometry.

This talk will discuss the implementation of line digitization techniques to obtain the LER and Lc of waveguide processing steps such as lithography, pattern transfer to a hard silicon nitride etch mask, and inductively coupled plasma reactive ion etching of the waveguide ridge structure. Various other process improvements useful for achieving reduced sidewall roughness for low HIC waveguides will be discussed.

A6. Oxide-confined high index contrast ridge waveguide lasers

Jinyang Li and Douglas C. Hall

A self-aligned fabrication process has been developed for a variety of novel high efficiency, high power GaAs- and InP-based in-plane laser devices. Deep dry etching followed by oxygen-enhanced wet thermal oxidation yields a high index contrast ridge waveguide structure confined by the high quality native thermal oxide grown directly on the waveguide ridge sidewalls for both excellent electrical insulation and strong optical confinement with a lateral index contrast of ~1.7. The native oxide also smoothes the etched waveguide sidewalls and passivates the etch-exposed active region for lower scattering loss. Additionally, the waveguide core width can be easily narrowed from a wider ridge width defined using low cost optical lithography to realize narrow single-mode waveguides by simply controlling the lateral oxide thicknesses on the ridge sidewalls while maintaining a large, low resistance ridge top contact area. A double trench structure provides both better heat dissipation and stronger mechanical support for laser chip heat sinking and packaging. With the complete structural elimination of lateral current spreading, the excellent overlap of the optical field with the gain region provides high slope efficiency performance (ranging from 1.05 W/A at w=6.75 μm to 1.3 W/A for w=150 μm broad area stripes) for 300 K cw operation of bonded, p-side down 808 nm InAlGaAs graded-index separate confinement heterostructure (GRINSCH) active region lasers. The devices exhibit threshold currents as low as 16 mA and threshold current densities of 801 A/cm2 (w=6.75 μm), compared to the 250 A/ cm2 of broad area devices (w>100 μm) that have negligible scattering loss. When driven to 14X threshold current, output powers over 100 mW are achieved. Other recent progress on the application of oxygen-enhanced wet oxidation to GaAs-based single mode straight lasers, teardrop ring lasers and InP-based quantum cascade lasers will be reported.

B1. Tunnel transistors using atomically thin semiconductors

Sara Fathipour and Alan Seabaugh

The tunnel field-effect transistor is being explored as a replacement to the modern transistor. The tunnel transistor uses electric field control of interband tunneling in a heavily-doped p-n junction as the current control mechanism. This mechanism allows the on-off ratio of the transistor to be maintained while lowering the supply voltage. Lower supply voltage means lower power. This talk will explain the physics of this transistor and show the progress made in fabrication using two-dimensional crystals.

Transition metal dichalcogenides (TMDs) are a good candidate to be used as a transistor channel material. Atomically thin bodies, band gaps ranging from ~1-2 eV, and surfaces free of dangling bonds are all desirable attributes of TMDs for tunnel transistors. Realization of the tunnel field-effect transistor (TFET) requires a uniform and pinhole free gate dielectric, with a subnanometer equivalent oxide thickness (EOT). However, due to the absence of surface dangling bonds in TMDs, the direct deposition of dielectric on TMDs is challenging. Another requirement for the fabrication of TFET is the formation of an abrupt p+n+ junction. However, controlled doping of TMDs has not yet been well studied in the community.

Addressing the above two issues is a necessary step towards the realization of TMD TFETs. Using a flat molecule, titanyl (TiO) phthalocyanine (C32H18N8), TiOPc, as a seeding layer on tungsten diselenide, WSe2, we have achieved a record low EOT of 2.2 nm and a low leakage current density of 0.046 pA/μm2 at a 1 V gate bias . Also, we demonstrate controllable p-doping and n-doping of WSe2, by using polyethylene-oxide cesium-perchlorate solid polymer electrolyte (PEO:CsClO4). In this approach, the channel is electrostatically doped by positioning positive or negative ions onto the channel, to induce electron or holes, respectively, in the channel.

B2. Fine-Tuning of Thermal Transport across Graphene-Metal Interfaces through Controlled Functionalization

Xin Mu, Suresh Vishwanath, Vasily Kanzyuba, Tao Jiang, Xueqiang Zhang, Denis Sokolov, Sylwia Ptasinska, David Go, Huili Xing, Tengfei Luo

To fully utilize the high in-plane thermal conductivity of graphene for heat spreading, efficient thermal transport from the substrate to graphene is needed. In this work, we perform fundamental studies using molecular dynamics (MD) simulations and experimental measurements to investigate the impact of chemical functional groups on the thermal transport at graphene-metal interfaces. Our primary focus is to understand how the covalent bonding between oxygen (O) and copper (Cu) enhances heat transfer across a graphene-Cu interface. MD simulation is used to systemically study the thermal conductance across a Cu/graphene oxide/Cu system as a function of the oxygen coverage. At low O coverage, the interfacial thermal conductance decreases with the O coverage, but at higher O coverage, the thermal conductance increases. When the O coverage is 25%, the interfacial thermal conductance is 356.1 MW/m2K, which is almost threefold larger than the interfacial thermal conductance of Cu/Graphene/Cu system. This phenomenon can be well explained by characterizing the relative contributions of covalent bonding and van der Waals (vdW) interactions to the thermal conductance increase. Our experimental results show good consistency with the MD results. Our samples consists of CVD graphene grown on Cu foil oxidized by ultraviolet ozone (UVO) treatment and then depositing a thin (~3 nm) layer of Cu on the oxidized graphene surface. X-ray photoelectron spectroscopy (XPS) is used to characterize the O/C atomic ratio and confirm oxidative state, while time-domain thermoreflectance (TDTR) is used to measure the thermal conductance at the Cu/graphene oxide interface. We find that the thermal conductance increases with the O/C atomic ratio, which is attributed to the strong covalent bonds formed by the functional O groups between the Cu layer and graphene. This work can guide the application of chemically-functionalized graphene as a high performance heat spreader to address hot spot issues in microelectronics.

B3. Novel coupling scheme for nanomagnet logic (NML) applications

Himadri Dey, Gyorgy Csaba, Gary H Bernstein and Wolfgang Porod

Engineering the magnetic coupling between nano-scale magnets is of great interest both from a fundamental physics point of view, and for potential applications as magnetic memory and logic. Complex logic structures were experimentally demonstrated based on dipole-coupled nanomagnets and exchange-coupled multilayers, indicating the potential of magnetic coupling-based devices for future information processing.

In this work, we experimentally demonstrate a novel coupling mechanism between two laterally adjacent nanomagnets, which is based on the exchange coupling mediated by a ferromagnetic film beneath the nanomagnets. The exchange-coupled system consists of a very thin Ru layer (8 A) sandwiched between two sufficiently thin ferromagnetic (CoFe) layers. Here, two elongated CoFe nanomagnets (side by side) are anti-ferromagnetically coupled to an underlying CoFe layer via a thin Ru layer. Ground state of the system occurs, when both magnets are anti-parallel to the underlying layer and the all magnets are in a single-domain state. Effectively, the exchange coupling ferro-magnetically couples the two laterally adjacent dots. This coupling mechanism works against magnetic dipole coupling, which would prefer an anti-parallel alignment of the nanomagnets.

From micro-magnetic simulations, we studied energetics of the system, and the exchange coupling energy was found to be almost six times larger than the dipolar coupling energy. The underlayer-mediated exchange coupling overwhelms dipolar coupling, and both dots turn upwards when a strong field applied along the hard axis of the dots is relaxed to zero, coupling the dots ferromagnetically. Simulation results were experimentally verified by magnetic force microscope (MFM). Using exchange interaction in addition to/ besides dipolar coupling, would therefore drastically increase coupling energies between nanomagnets, and could potentially open up new avenues in the research of magneto-logic devices.

B4. Nonconcentric PbSe/CdSe Colloidal Quantum Dots

Gary Zaiats, Arthur Shapiro, Diana Yanover, Yaron Kauffman, Aldona Sashchiuk and Efrat Lifshitz

Lead chalcogenide colloidal quantum dots are attractive candidates for applications operating in the near infrared spectral range. However, their function is forestalled by the limited stability under ambient conditions. Prolonged temperature-activated cation-exchange of Cd2+ for Pb2+ forms PbSe/CdSe core/shell heterostructures, unveiling a promising surface passivation route and a method to modify the dots' electronic properties. Here, we follow early stages of an-exchange process, using spectroscopic and structural characterization tools, as well as numerical calculations. We illustrate that preliminary-exchange stages involve the formation of nonconcentric heterostructures, presumably due to a facet selective reaction, showing a pronounced change in the optical properties upon the increase of the degree of nonconcentricity or/and plausible creation of core/shell interfacial alloying. However,

progressive-exchange stages lead to rearrangement of the shell segment into uniform coverage, providing tolerance to oxygen exposure with a spectral steadiness already on the formation of a monolayer shell.

B5. Spin-wave-based Computing

Ádám Papp, György Csaba and Wolfgang Porod

We study the use of spin waves for computing and signal processing purposes. Spin waves are propagating excitations of the spins in magnetic materials that can represent and carry information. The idea of utilizing spin waves for computing is not new, however, it got special interest in the last decade in nanoscale devices. Spin-wave devices promise high speed, low power devices with relatively simple fabrication.

While most devices presented so far aim to create novel switches to replace transistors in logic applications, we focus on wave-based approaches where the spin waves are used to perform linear transformations on analog signals. We borrow ideas from the well-established optical computing theory, but instead of light we use spin waves in magnetic films which can be integrated on-chip straightforwardly. We propose spin-wave elements analogous to optical elements like lenses, mirrors and gratings [1]. Using micromagnetic simulations we demonstrate that although there are many differences between light and spin waves, it is possible to redesign the optical computing concepts to be realized on magnetic medium. One of the most important concept in optical computing is the Fourier transform property of a lens which is the basis of many optical algorithms, like signal filtering and pattern matching. We show that a spin-wave lens can also realize these functions. Our calculations suggest that in both speed and power consumption multiple orders of magnitude improvement is achievable (not including the supporting circuitry). Although there are many proposed devices for spin-wave generation and readout, these are still the bottleneck of the energy consumption of the envisioned system, but even considering these losses our proposed device has a significant gain compared to state-of-the-art CMOS realizations.

[1] G. Csaba, A. Papp and W. Porod, “Spin-wave based realization of optical computing primitives,” J. Appl. Phys. 115, 17C741 (2014).

C1. Saturation Multiphoton Microscopy toward super resolution and super penetration.

Genevieve Vigil, Scott Howard

Multiphoton microscopy (MPM) has advanced biomedical imaging in recent years by allowing high contrast, high resolution, 3D, functional in vivo imaging. MPM represents a drastic improvement over single photon fluorescence microscopy but is still restricted by traditional limits of diffraction and scattering to resolutions of ~λ/2 and penetration depths on the order of millimeters. Furthermore, after the onset of saturation, signal strength does not continue to improve according to Fl_em∝I_ex^2 and the emission point spread function (PSF) is degraded, further limiting contrast, resolution and penetration depth. Proposed here a method to modulate the excitation pulse train (pulse width ~100 fs, repetition rate ~80 MHz) with a periodic signal and acquire higher frequency components which result from saturation. All fluorescent signals suffer from excitation saturation and as such, the PSF of an excited signal will degrade with high intensity excitation. When the excitation signal is amplitude modulated in time (modulation frequency slower than fluorescent lifetime: $f_m \ll 1/\tau$), harmonics occur where saturation occurs and proportionally to the amount of saturation. Instead of restricting studies the sub-saturation regime, saturation effects can be leveraged to perform super-resolved imaging. By Fourier transform of the resultant modulated and saturated emission signal, the higher harmonic components can be found in with smaller spatial extents than the degraded PSF of the MPM emission alone and therefore can be used to reconstruct a super-resolved MPM image. Presented here are simulation results of periodic modulation signals and the resulting improved PSF as well as a proposed experimental set-up. The model accounts for absorption, stimulated and spontaneous emission in a two level system excited by femtosecond width Gaussian pulses. Initial investigation shows potential improvement for SNR, depth of penetration and even a mechanism for lifetime quantification, however this work will focus on the improvements and limitations on resolution.

C2. Sparse Tensor Approximation for Uncertainty Quantification on 2D Periodic Gratings

Gerardo Silva Oelker, Carlos Jerez-Hanckes, Patrick Fay

Grating structures have been considered in many applications, such as spectroscopy and energy conversion devices. Exhaustive theoretical and numerical analyses have been performed in order to design gratings optimally. However, real-life manufacturing processes can create random variations on the surface that greatly influence the properties of the gratings. In this work, we implement a numerical algorithm based on the Boundary Element Method (BEM) for randomly perturbed ideal surfaces, considering one dimensional gratings with rough surfaces and satisfying Dirichlet boundary conditions. We calculate first and second statistical moments of the scattered field with a sparse tensorization and a discretization based on wavelets. Calculations are provided for different geometries and angles of incidence.

C3. Super-resolution imaging with mid-IR photothermal microscopy on the single particle level

Zhongming Li, Massaru Kuno, Gregory Hartland

Mid-infrared (MIR) imaging, also known as chemical imaging, provides a wealth of chemical information and has been widely used as a powerful tool for biological and semiconductor samples. But MIR imaging encounters difficulties of diffraction-limited spatial resolution and scarcity of ideal detectors. Photothermal microscopy, on the other hand, has achieved single molecule sensitivity. However, the analytes are usually restricted to be natural absorbers in the visible light region. Here we present Mid-IR photothermal heterodyne imaging (MIR-PHI) microscopy as a high sensitivity, super-resolution mid-IR imaging technique. In MIR-PHI, a tunable Mid-IR pulsed laser at 150 kHz is used to excite a micron sized particle. Energy relaxation creates a temperature gradient around the particle, changing the refractive index of the surrounding solvent and creating a thermal lens. A collinear, counter propagating probe beam (a 532 nm CW laser) is modified by the thermal lens and generates a super-resolution photothermal image. The counter-propagating geometry enables us to utilize a high NA oil immersion objective to form a tighter focus for the probe beam. We studied 1.1 μm polystyrene beads at the single particle level using this technique. Various solvents with different heat capacities and refractive indices are tested for the best image contrast. The wide applicability and potentially high sensitivity of this technique make it promising for advancing MIR imaging to the single cell level for biological samples, and single particle level for semiconductor objects.

C4. Designing Mid-infrared Mie-based Optical Metamaterials

Owen Dominguez and Anthony Hoffman

A great amount of research has been focused on metamaterials, especially for their interesting physics and novel applications such as negative refraction, perfect lenses and cloaking devices. In general, optical metamaterials are engineered composite structures whose properties are determined by arrangement of metamolecules held together. A metamolecule is the basic building block and must be sub-wavelength sized in order to ensure continuum; if designed properly this metamolecule will resonate on the desired spectral region, accounting for the total scattering of the metamaterial; effectively acting as a dipole. This scattering can be engineered by designing the effective permittivity and permeability, which differs from the constituents elements. The simplest case studied is a single cubic structure with a single nanoparticle as the metamolecule; for this case the effective permittivity and permeability can be calculated using effective medium theory. This calculation is done by idealizing the nanoparticle as a sphere, which is valid for sub-wavelength size geometries, and applying Mie scattering theory. The results from this analysis can be extended to periodic metamaterial structures. The calculations for more complex structures require FDTD tools, such as COMSOL, to determine the scattering parameters. Dielectric nanoparticles have been shown to be optimal candidates for mid-infrared region metamaterials, because of the large permittivity and low optical loss. These nanoparticles could be used to assemble highly complex 3D structures as a means of resonance control. For this purpose, techniques such as Holographic Optical Trapping will be used to trap small particles and place them in the desired spatial position. The engineering of these materials allows for unusual properties such as negative permittivity and permeability, large positive refractive index, perfect absorption and non-linear optical properties which are desirable for chemical and medical applications in the mid-infrared region.

C5. Holography Undergraduate Research and Outreach Activities at Notre Dame

Charles L. Filipiak and Douglas C. Hall

The work of holography blurs the lines between science and art. It utilizes the latest technology in lasers, lenses, and film to create incredible visual images that anyone can appreciate. This makes holography not only an exciting area for undergraduate research, but also a rich subject that lends itself well to creative and interactive projects suitable for sharing with the local community. Reflection holography takes a three-dimensional image of a small object and allows it to be displayed under any single point light source. Creating a hologram of this kind involves reflecting coherent laser light off of the target object and creating a wave interference pattern with a clean reference beam wavefront. The film then records this interference pattern, which can then be replicated with white light. One of the ultimate goals for the holography undergraduate research program at Notre Dame has been to develop a method to make holograms quickly, easily, and reliably for local area workshops. By experimenting with various film types, lasers and low-vibration optical components, we significantly improved the quality and yield of our holograms with a portable setup and fast process well-suited for outreach activities. Working with the physics teacher at St. Joseph High School in South Bend, we developed a curriculum for a holography workshop to follow and complement their learning unit on waves and light. By combining an information session, worksheet, and interactive applet on laser science with actual practice, in April 2015 we introduced over 75 students in four different physics classes to the art and science of holography. Every student was able to make a hologram of their own and demonstrate that they had an understanding of the concepts that were used in its creation. Finally, other aspects of the holography undergraduate research program at Notre Dame will be briefly discussed.

C6. 3-Dimensional, High-resolution Oxygen Microscopy in Vivo through Multiphoton Phosphorescence Lifetime Imaging

Aamir A Khan, Genevieve D Vigil, Susan K Fullerton-Shirey, and Scott S Howard

Oxygen is one of the most important molecules for life. It is involved in all stages of life and biological activity. Hence the measurement of oxygen plays a crucial role in medical research. For example, quantitative information about oxygen levels in tumors can lead to optimized treatment methods in oncology, whereas oxygen imaging of brain vasculature can lead to a better understanding of brain activity in neurological research. At the intracellular level, oxygen imaging can provide insights into cellular signaling pathways and metabolic activity.

Optical oxygen sensors offer a minimally invasive and non-consuming approach to measure oxygen via phosphorescence lifetime imaging microscopy (PLIM). To achieve a sub-micrometer spatial resolution in oxygen measurement, PLIM is used in conjunction with multiphoton microscopy (MPM) – a laser scanning microscopy technique that yields high-resolution, 3D images in thick samples. However, MPM-FLIM for biological oxygen imaging requires water-soluble phosphorescent dyes that have high oxygen-sensitivity and a large two-photon cross-section. Unfortunately, no molecule exists that possess all of these properties. Therefore oxygen-sensitive phosphorescent dyes are usually modified by attaching hydrophilic functional groups to them in order to enhance water-solubility and two-photon cross-section, as in the case of PtP-C343 for example. These probes though perform well, however, require complex chemical synthesis procedures, making them inaccessible to the most of the bioimaging community.

Our work presents a simple and inexpensive alternative to the well-established, high-performance probes. We describe an easy encapsulation method to use a commercially available hydrophobic ruthenium-complex dye, [Ru(dpp)3]2+. The dye is encapsulated in nanometer sized micelles formed by a poloxamer (a biocompatible surfactant), allowing for uniform dispersion in aqueous media. Detailed characterization experiments have been performed and show that the probes possess a near-optimal sensitivity to dissolved oxygen as well as a two-photon cross-section that surpasses that of the well-established and widely used oxygen-sensitive probes. Two-photon imaging is also performed on live mice using these probes. The resulting 3D images show excellent detail and contrast, thereby demonstrating the viability of [Ru(dpp)3]2+ nanomicelle probes as easily prepared probes for 3D, high-resolution, quantitative oxygen imaging in vivo.

C7. On increasing the imaging rate of frequency-domain multiphoton fluorescence lifetime imaging microscopy

Yide Zhang, and Scott S. Howard

Multiphoton microscopy combined with fluorescence lifetime imaging microscopy (MPM-FLIM) is a technique that allows for imaging the lifetime of fluorescence created by two-photon excitation. It not only possesses the advantages of MPM such as large imaging depth, but also the strengths of FLIM including the ability to discriminate different fluorophores with similar emission spectra. In FLIM, the frequency-domain (FD) method, which relies on periodic intensity-modulated excitation light and its response to obtain lifetimes, is most commonly used for living animal imaging. The imaging rate of a FD-MPM-FLIM imaging system, however, is limited by the signal-to-noise ratio (SNR) of the lifetime measurement. In this study, we show that the DC and higher harmonic components generated by nonlinear optical mixing of the excitation light can be exploited to improve the SNR of FD-FLIM, reducing the required number of photons, thus increasing the imaging rate, by 50%. Another approach called frequency-multiplexed MPM-PLIM can drastically increase the imaging rate by modulating the excitation light at a number of different fundamental frequencies, instead of a single one. The imaging rate, therefore, can be increased by up to a factor of 100. The modulation frequencies, however, should be within a single octave to avoid crosstalk between the fundamental and second-harmonic terms, which puts a limit to further increasing the imaging rate. In this study, we propose that by changing the excitation light's waveform from sinusoid to square-root of sinusoid, the crosstalk between the fundamental and second-harmonic signals can be neutralized. Thus the limit on the frequency-multiplexing can be alleviated to further increase the imaging rate. Overall, the imaging rate of FD-MPM-FLIM can be 4 times as fast as that of conventional one-photon FD-FLIM by exploiting DC and harmonics components, and the rate can be increased by more than a 100 times using the improved frequency-multiplexing technique.

D1. Experimental Demonstration of Single Electron Transistors Featuring SiO2 PEALD in Ni-SiO2-Ni Tunnel Junctions

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Plasma enhanced atomic layer deposition (PEALD) enables atomic growth of a number of materials at a lower temperature, and with higher quality compared to thermal ALD. We report the use of PEALD in single electron transistor (SET) fabrication to form ultra-thin (≈ 1 nm) tunnel-transparent SiO2 in Ni-SiO2-Ni tunnel junctions. In addition to being capable of detecting a fraction of elementary electron charge, as small as 10-6 e/√Hz, SETs can be used to study and characterize the ultra-thin dielectric barriers in the tunnel junctions. The reported SiO2 barrier is formed at 300˚C using Bis(diethylamino)silane (BDEAS) and O2 plasma. Based on our observations, as a result of the O2 plasma steps in PEALD, the surface of the underlying Ni electrode is oxidized, forming NiO that exhibits features typical of thermally activated transport. Additionally, the bottom surface of the top Ni electrode is also oxidized where it is in contact with the deposited SiO2, most likely as a result of oxygen-containing species on the surface of the SiO2. Due to the presence of these surface parasitic layers of NiO, the resistance of Ni-SiO2-Ni tunnel junctions is drastically increased. Moreover, the transport mechanism is changed from quantum tunneling through the dielectric barrier to one

consistent with thermally activated resistors in series with tunnel junctions. The reduction of NiO to Ni is therefore necessary to restore the metal-insulator-metal (MIM) structure of the junctions. We have shown that forming gas anneal and H2 plasma treatment are both effective in reducing the parasitically formed NiO layers. The fabricated SETs are used to study the effect of each reducing process on the properties of the tunnel junction. Based on our experiments, reduction of the tunnel barrier and intermixing of the metal electrode with the barrier can result from both treatments.

D2. Ion-locking electrolytes: a room temperature doping solution for 2D electronics and optoelectronics

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Ion gating with an electrolyte offers an effective way to dope two-dimensional (2D) field-effect transistors (FETs) via an electrostatic double layer (EDL). The EDL, consisting of the ions within 1 nm of the channel and their image charges in the channel, can induce sheet carrier densities greater than 1013 cm-2. To prevent the EDL from dissipating, a constant bias must be applied. For polymer electrolytes, the EDL can be "locked" into place at temperatures below the glass transition temperature (Tg) of the electrolyte, and the applied bias can be removed. For traditional polymer electrolytes such as those based on polyethylene oxide (PEO), with Tg = -40°C, the device must be cooled below room temperature to lock in the EDL. Moreover these electrolytes are air-sensitive and cannot withstand the chemicals commonly used in photolithography. In this work, we utilize an electrolyte based on polyvinyl alcohol (PVA), a polymer with Tg = 85°C. Following a "programming" step at T > Tg to establish the EDL, the Tg of PVA:LiClO4 permits the ions to be locked in place at room temperature. Sheet carrier densities in excess of 1013 cm-2 are measured using a graphene Hall bar, with time-resolved measurements on a graphene FET indicating that 80% of the EDL is retained after 8 hours at room temperature. This represents improvement of 108x over PEO-based electrolytes at the same temperature. In addition to these favorable doping characteristics, due to PVA's chemical stability, the electrolyte is compatible with i-line photolithography, allowing for a patterned metal top gate to be deposited directly onto the electrolyte. Novel devices utilizing PVA:LiClO4 will also be discussed.

D3. Fabrication of high density nanoelectrode arrays via directed self-assembly of block copolymers

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The unique electrochemical properties of nanoelectrode arrays, such as fast mass transfer, steady state current, amplified current signal, etc. have inspired the researchers to fabricate nanoelectrodes with a variety of geometries and applications. Although the size of single nanoelectrode can be decreased to a few nanometers, most reported nanoelectrode arrays are composed of small nanoelectrodes with low density (around 1 to 100 elements per μm2). Since the electrochemical signals are largely determined by the effective area of all electrodes, therefore it is necessary to balance the Faradic current and charging current to achieve an optimum areal density of nanoelectrodes in a given area. In this work, we proposed an approach to nanoscale recessed ring disk electrode (RRDE) arrays with high areal density by using layer-by-layer deposition, block copolymer nanolithography and a multistep reactive ion etching process. Here the RRDE arrays are basically composed of two closely packed working electrode layers which separated by a thin dielectric layer. By choosing the proper chemical composition and molecular weight of block copolymers, we succeeded in fabricating polymeric nanodot arrays on the 3 inch silicon wafter with an areal density above 1000 elements per μm2 under well-controlled process of self-assembly. The polymeric nanodot arrays, which served as the nanolithographic mask, are then transferred into the metallic and dielectric layers and finally formed RRDE arrays. Our future work will include using these nanopore electrodes as the analytical platform to investigate heterogenous electron transfer reactions and electrocatalytic process of the enzymes and analytes.

D4. Platinum Oxidation and Reduction during Single Electron Transistor Fabrication

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Due to its precise control of film thickness, atomic layer deposition (ALD) is well suited to the creation of dielectric tunneling barriers in metal-insulator-metal single electron transistors (SETs). While oxides formed on metal nanowires at the beginning of the ALD process may aid nucleation by providing reaction sites, they also increase the thickness of the tunnel barrier, limiting the SET conductance. Our research shows that for Al2O3 on Pt nanowires a thin native oxide is formed and that this oxide can be reduced back to metallic platinum by annealing in either forming gas (5% H2 in Ar) or pure argon. Platinum's oxides are known to be much less thermodynamically stable than other metal oxides, to the point that they will dissociate around 500C [1]. Thus annealing in pure argon can cause the platinum oxide to decompose back to metallic platinum, causing a large increase in SET conductance. Platinum oxides' instability also makes them susceptible to reduction by hydrogen. Our research has shown that since reduction by hydrogen is dependent upon diffusion of hydrogen into the junction, unlike decomposition, the increase of SET conductance is much more dependent upon the uniformity of the ALD layer on the nanometer scale. Our results show that at thicknesses of approximately 1 nm, there are significant variations in ALD uniformity. For devices annealed in forming gas, we also observe a steady, time-dependent drop in conductance immediately after annealing, which we attribute to the re-oxidation of the tunnel junction.

[1] M. P. H. Fernandez, B. L. Chamberland. J. Less Common Metals, 99, pp. 99-105 (1984).