Collaboration with Industry and Other Sectors

- Summary of C-SPIN Partnerships
- Texas Instruments Collaboration
- International Collaborations
  - Santos and Murphy - NTT and Tohoku Univ. (Japan)
  - Salamo - Humboldt University (Germany)
  - Johnson - University of Alberta (Canada), National University (Singapore)
- Research Commercialization
  - C-SPIN originated spin-off companies
  - $\mu$EP Student and Staff (Innovation Incubator)
Selected Collaborations

Oklahoma
- NTT and Tohoku University, Japan
- Intel Corp.
- IBM Burlington
- IQE
- Dupont
- University of Alberta, Canada
- Singapore National University
- Sandia/ Los Alamos, CINT
- Amethyst Research Inc., OK
- Ekips/Phononics, OK

Arkansas
- Texas Instruments
- Army Research Laboratory
- Air Force Research Lab
- Quantum Dot Inc.
- NanoSonic
- Kodak
- Kovio
- Innovation Incubator

Relevant Regional Activities

Oklahoma
- OSU (materials)
- OU (polymers, genome)
- Nomadics Inc. (sensors)
- Frontier Engineering (sensors)
- Eagle-Picher (materials)
- Phillips and Conoco (polymers)
- Southwest NanoTechnolgies

Arkansas
- UA (materials)
- HiDEC (materials)
- Genesis Technology Incubator
- Integral Wave Technologies (passives)
- Space Photonics (systems)
- NN-Labs (materials)
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Nanoferroelectric RAM: C-SPIN/TI Collaboration

NSF/NRI Supplement to OU/UA MRSEC

- NSF/NRI Supplement: $50,000/yr
- Match: $50,000/yr

Personnel

- Greg Salamo, PI – MBE Growth, AFM Characterization
- Matthew Johnson, PI (Physics, OU) – TEM Characterization
- Laurent Bellaiche, (Physics, UA) - Theory and ferroelectric material design
- Post-Doc and Grad. Students.
- NRI Industrial Liaison Team
  - Rick Wise, TI – Team Lead; Simone Raoux, IBM; Uday Udayakumar, TI-Dallas

Research Collaboration Areas

- Critical field calculations – Matching theory with experiment
- MBE Growth of Ferro-electrics
- Strain measurement within a PZT film (TEM)
- Theory: multiferroics, ferro- electric & magnetic rings, dielectric susceptibility of nanostructures
Why FerroElectrics?

TIs Interest

• FRAMs (Ferroelectric RAMs) are a non-volatile memory alternative.
  – TI’s use a lead zirconate titanate (PZT) layer in the storage capacitor.
  – FRAMs are now on the market and will be incorporated into US “smart-passports” in the near future.
  – However, understanding of the PZT layer, especially within capacitor stack, is incomplete.
• Need to look at existing PZT layers on the nanoscale with the TEM - TI’s earlier efforts unsuccessful.
• Need to explore new growth techniques for FE materials, such as MBE.
• Need to model FE materials to better understand behavior with scaling.

Overall Interest

• Memory storage using ferroelectrics offer advantages over ferromagnetics, e.g. denser storage especially within toroidal geometries.
• Possible devices that directly use FE materials e.g. ferroelectric field effect.
• FE materials are a part of a bigger class of materials multi-ferroics have the potential to magneto-electric coupling.
• Need to theoretically explore the behavior of ferroelectric and multi-ferroic nanostructures.
Key Progress

Critical Field / Temperature vs. Thickness

• Calculated critical field & temperature ($E_c, T_c$) dependence on nanoferroelectric film thickness.

MBE Studies

• SrO (BaO) and TiO$_2$ grown as alternating layers on SrTiO$_3$ substrates to make high-quality SrTiO$_3$ (BaTiO$_3$) epitaxial layers.

TEM of FRAM Capacitors

• For the first time we have used cross-sectional TEM image the crystal grains of the PZT layer within the capacitor stack.
  – Typical grain size: height = 67 ± 5 nm; Width = 85 ± 27 nm
  – Orientation of grains obtained through Nano-Beam Diffraction (NBD)
  – Distinguish lattice parameter $c$ from $a$ using *in situ* calibration

Theoretical Studies: Multi-Ferroics & Dielectric Susceptibility of Nanostructures

• Finite temperature properties of multi-ferroic structures
• Hysteresis loops predicted in asymmetric, ferro- magnetic & electric rings
• First-principle calculations & phenomenological theory suggest a dependence of external & internal susceptibilities to nanostructure shape & surroundings
MBE of BaTiO$_3$ on SrTiO$_3$

*In situ* RHEED patterns

STO (100) substrate  
BaO layer on STO (100)  
TiO$_2$ layer on STO (100)

Grow monolayer of BaO then TiO$_2$ etc. to obtain a BaTiO$_3$ layer

**Shuttered RHEED Oscillation Curve**

8 loops: 160 seconds  
180 loops: 1 hour

**XRD indicates excellent film quality.**
**Embedded FRAM Data Storage**

**PbZr_xTi_{1-x}O_3 - Perovskite**

Ferro Cap Switching Characterization

Data stored by switching ions between stable positions in PZT crystal.

**FRAM Nonvolatile Memory**

- Reduced total cost & power consumption vs Flash
  - But flash Tunnel oxide (SiO_2 related) is simpler than PZT layers
- Reduced magnetic susceptibility vs. MRAM
- Will be in Passports

STEM showing PZT grains in a device capacitor.
NBD Orientation of PZT Grains: Cap 6

(X_T, Y_T)=(-3.8°, 2.4°) (-3.8°, 2.4°) (0.0°, 0.0°) (3.6°, 3.6°)

• c-axis is preferentially oriented perpendicular to capacitor
• Measured c/a ~ 1.02 -1.03 — indicating some strain in layer
Critical Field & Temperature vs. Thickness

Critical temperature ($T_c$) is the temperature below which the layer is ferroelectric (has remnant polarization).

Critical field ($E_c$) is the field required to switch the polarization of the layer.

For ultra-thin films, these values depend on boundary conditions at the surfaces. Free-charge available (short circuit) or not (open circuit).

Pb(Zr$_{0.4}$Ti$_{0.6}$)O$_3$ Films, Compressive Strain 2.65%, $T=10K$

For short or open circuit, at a thickness of 40 or 50 nm, $T_c$ and $E_c$ are the bulk values.

APL 91, 152909 (2007)
Behavior of Asymmetric FE & FM Vortices

Control of vortices by homogeneous fields in asymmetric ferroelectric (FE) and ferromagnetic (FM) rings: A unifying theoretical approach

Predicted hysteresis loops in asymmetric FM rings (a,b) and asymmetric FE rings (c,d).

**FM rings**: (a,b) show the evolution of the magnetization and magnetic toroidal moment, vs. the applied homogeneous ac $B$-field.

**FE rings**: (c,d) show the evolution of the polarization and electric toroidal moment, vs. the applied homogeneous ac $E$-field.

Insets show the rings' geometry and the dipole arrangement in the (x,y) plane for eight important states:

- Vortex states (1, 3, 5, & 7),
- Onion states (2 & 4), and
- Antiferrotoroidic pair states (6 & 8).

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InSb Ballistic Transport Devices

Collaborative Projects
- Laterally gated point contacts (NTT)
- Magnetic focusing devices (NTT)
- Extraordinary Magnetoresistance (Hitachi)
- All involve industrial internships for students

Conference Presentations
- APS March Meeting, 2002-2005
- Narrow Gap Semiconductors, 2003
- Modulated Semiconductor Structures, 2003
- Quantum Dots, 2004
- Electronic Properties of 2D Systems, 2005
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The mission of Nanolight, Inc. is to research and develop semiconductor nanofabrication techniques for implementation in cutting-edge infrared laser and detector systems and to assist others in their product development efforts by providing epitaxial-related services and acting as a distributor for nanofabrication equipment.

- Founded in 2004 by Zhisheng Shi
- $750K Phase 2 SBIR Grant to develop infrared technology for missile defense systems
- $90K from OCAST to develop photoconductive mid-IR detector using an assembly of nanowires.

Ekips Technologies develops innovative laser-based sensors. Using technologies similar to those found in DVD players, these sensors will improve health care by enabling more effective point-of-care diagnostics.

- Founded in 2000 by Patrick McCann
- $350K from OCAST to develop four-level mid-infrared lasers with low power consumption and room temperature operation

Phononic Devices

- Founded in 2008 by Patrick McCann
- Develop IV-VI Thermoelectric Devices
Minotaur Technologies is a biophotonics company whose mission is to develop new laser-based instrumentation for life sciences research. The company is developing instruments that are applicable to a broad range of cell biology problems in neuroscience and beyond, including chemotaxis, stem-cell differentiation and in vitro testing of cellular response to emerging treatments.

- Founded in 2003 by Min Xiao

NN-LABS, LLC

Nanomaterials and Nanofabrication Laboratories (NN-Labs) focuses on production, processing and applications of semiconductor nanocrystals and dendron ligands. Since 2002 the company has received a multitude of Phase I and Phase II SBIR contracts from various government agencies to aid in funding the development of a wide range of nanocrystals and nanocrystal applications.

- Founded in 2001 by Xiaogang Peng
Local Economic Impact

Invention (C-SPIN) → Patent Rights (OU or UA) → Patent licensing → Existing Firms, University Incubators → Startup companies

Nanomaterials & Nanofabrication Laboratories (NN-Labs)

http://www.nn-labs.com

- Highest quality
- Broadest wavelength range
- Large quantities

- Increase number of startup companies
- Dramatic increase in SBIR grants
UA Innovation Incubator – I²

NSF Partnership for Innovation Program

- Funded by a three-year, $840K NSF grant.
- Spans μ EP, Physics, College of Engineering, and the Arkansas Science and Technology Authority.
- Performs proof-of-concept research for those interested in expanding or starting a small business.