8. STRATEGIC RESEARCH PLAN

Our Center develops tools to study nanoscale systems. We would like to control electrons and photons inside nanostructures for new nanoelectronic and nanophotonic devices, and to investigate how biological systems function at the nanoscale using techniques from the Physical Sciences. Three Research Clusters address these goals:

Cluster 1: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology and Medicine. Powerful new tools for manipulating and testing biological cells and tissues can be made using microfluidic systems, soft lithography, and semiconductor technology. Biology and Medicine offer an enormous range of engaging problems in functional biological systems, and the opportunity to think about "hybrid" systems that combine biological and non-biological components.

Cluster 2: Nanoscale Building Blocks makes new classes of nanostructures that exhibit size-dependent properties. We synthesize structures with unconventional shapes, as well as zero, one- and two-dimensional nanostructures including nanoparticles, nanowires, and heterostructures. New materials are introduced, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks are promising for nanoelectronics and nanophotonics as well as for biosensors.

Cluster 3: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons inside nanostructures using custom-made scanning probe microscopes, including cooled instruments. Imaging is an essential tool for the development of nanoelectronics, nanophotonics, and qubits for quantum information processing.

The desired outcomes for our Center's research are outlined in Figure 8.1. They are in two areas: Biology and medicine are addressed by the *Tools for Integrated Nanobiology* and *Nanoscale Building Blocks* research clusters. The outcomes are in the fields: *Microfluidic and Hybrid BioChips*, and *BioProbes*. Electronic and optical systems are

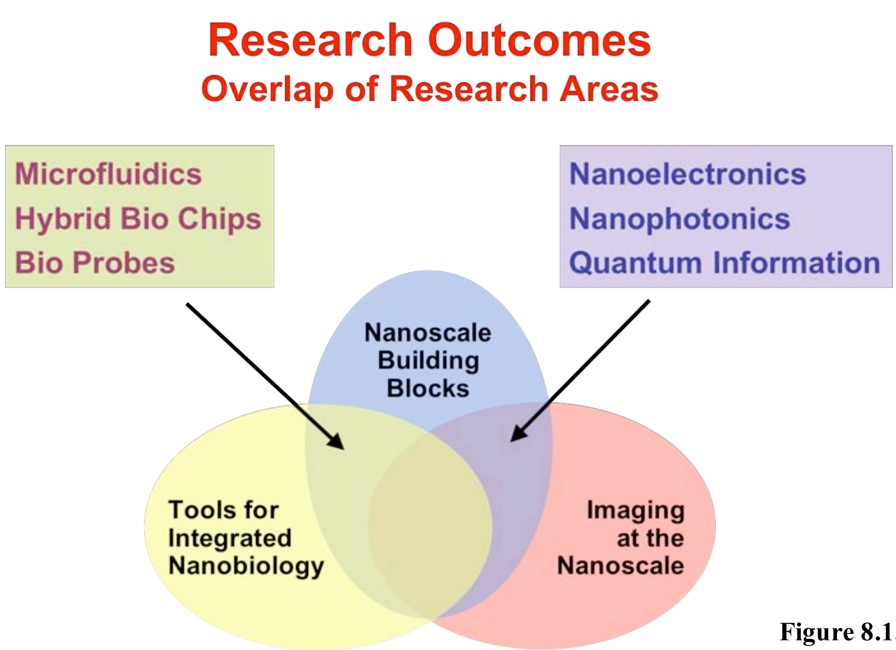

Figure 8.1.

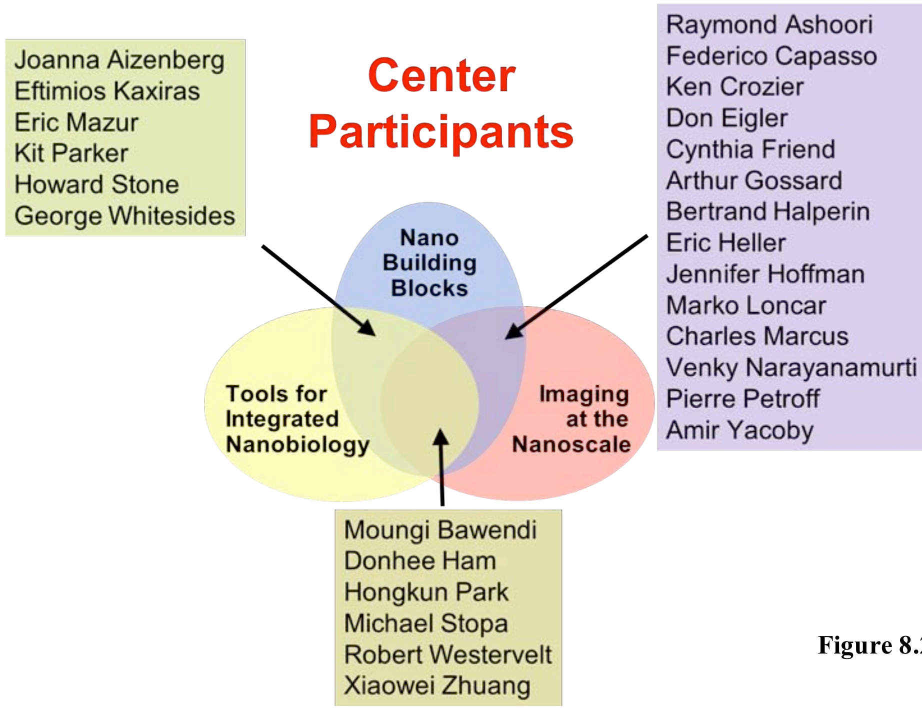

Figure 8.2.

addressed by the *Nanoscale Building Blocks* and *Imaging at the Nanoscale* Clusters. The outcomes are in the fields of *Nanoelectronics*, *Nanophotonics*, and *Quantum Information Processing*. These applications will benefit society, and they are an important product of the Center's research program.

All of the Center's researchers currently work in more than one cluster, as shown by the Venn diagram in Fig. 8.2. This overlap has increased substantially, since our Center was created in 2001, and it is good evidence of the benefits of collaborative research. The overlap between different research specialties creates exciting new topics, described in ***Section 9 – Research Program***.

In the paragraphs below we show how the Center's participants work together to address potential outcomes of their research:

Microfluidic and Hybrid BioChips

Joanna Aizenberg (SEAS	Efthimios Kaxiras (Physics & SEAS)	Robert Westervelt (SEAS & Physics)
Federico Capasso (SEAS)	Kit Parker (SEAS)	George Whitesides (Chemistry)
Donhee Ham (SEAS)	Howard Stone (SEAS)	Xiaowei Zhuang (Chemistry & Physics)

The investigators in this area create new microfluidic and hybrid electronic/ microfluidic chips for applications in Biology and Medicine. George Whitesides is a pioneer in microfluidics and soft lithography. Microfluidic systems create biocompatible environments for the study of cells individually, and be used to create lab-on-a-chip systems for medical analysis. Whitesides works closely with fluid dynamicist Howard

Stone, Joanna Aizenberg, Federico Capasso, Robert Westervelt and other members of this group. Joanna Aizenberg is an expert in biomaterials and microfluidics. Kit Parker studies the behavior of cells in a microfluidic system using optical and scanning probe microscopy. Xiaowei Zhuang develops ways to image viruses and proteins inside biological systems, and Efthimios Kaxiras simulates the motion of DNA molecules through small constrictions to understand their behavior. Hybrid CMOS/microfluidic chips that combine biocompatible microfluidics with integrated circuits and optoelectronics have been created by Donhee Ham and Robert Westervelt, and Federico Capasso makes hybrid optical/microfluidic systems for sensing.

BioProbes

Joanna Aizenberg (SEAS)	Hongkun Park (Chemistry & Physics)	George Whitesides (Chemistry)
Moungi Bawendi (Chemistry, MIT)	Kit Parker (SEAS)	Xiaowei Zhuang (Chemistry & Physics)
Efthimios Kaxiras (Physics & SEAS)	Michael Stopa (NNIN, Harvard)	

A group of Center investigators use probes based on nanoscale objects of different types to sense and image biological systems. Joanna Aizenberg, Moungi Bawendi, Hongkun Park and Xiaowei Zhuang develop nanoparticles and nanowires that can be biologically functionalized. Bawendi has developed composite silica microspheres that include both magnetic and fluorescent nanoparticles that can simultaneously magnetically tag a biological object and optically track its motion. Zhuang is developing fluorescent and Raman-active Ag nanoparticles as bio-labels for live cell imaging. George Whitesides is functionalizing interior surfaces of microfludic systems with biologically active materials. Kit Parker has developed an atomic force microscope tip that can selectively bind certain proteins and act as a scalpel for nanosurgury on biological cells. In related theoretical work, Efthimios Kaxiras and Michael Stopa simulate the motion of biomolecules.

Nanoelectronics

Raymond Ashoori (Physics, MIT)	Jennifer Hoffman (Physics)	Michael Stopa (NNIN)
Moungi Bawendi (Chemistry, MIT)	Marc Kastner (Physics, MIT)	Shriram Ramanathan (SEAS)
Cynthia Friend (Chemistry)	Charles Marcus (Physics)	Robert Westervelt (SEAS & Physics)
Arthur Gossard (Materials, UCSB)	Venkatesh Narayanamurti (SEAS & Physics)	Amir Yacoby (Physics)
Bertrand I. Halperin (Physics)	Hongkun Park (Chemistry & Physics)	
Eric Heller (Chemistry & Physics)	Pierre Petroff (Materials, UCSB)	

This group of investigators is developing new approaches in nanoelectronics. They combine the nanoscale building block synthesis and MBE growth with nanofabrication and theory to make, study, image and understand new types of nanoscale devices.

Moungi Bawendi, Hongkun Park and our international collaborator Lars Samuelson are experts in the synthesis of nanocrystals and nanowires from new materials and their assembly into electronic devices; Cynthia Friend grows and studies two-dimensional materials with only one atomic layer on a surface. Shriram Ramanathan joined Harvard from Intel - he is developing new oxide semiconductors for nanoscale logic switches. Arthur Gossard and Pierre Petroff use the MBE Lab at UC Santa Barbara to make new types of semiconductor heterostructures and self-assembled quantum dots. Using the nanofabrication facilities in Harvard's Center for Nanoscale Systems (CNS) and at MIT, Raymond Ashoori, Marc Kastner, Charles Marcus, Venkatesh Narayanamurti, Robert Westervelt and Amir Yacoby use e-beam and optical lithography to make a wide variety of nanoscale electronic devices. The nanoelectronic devices studied by this group range from transistors made from nanowires and self-assembled dots, to few-electron quantum dots, to open two-dimensional electron gas devices for studies in strong magnetic fields. Scanning-probe imaging techniques developed by Raymond Ashoori, Eric Heller, Jennifer Hoffman, Venkatesh Narayanamurti, Hongkun Park, Robert Westervelt and Amir Yacoby provide powerful tools to investigate how electrons move through these nanoscale devices. Collaborations with theorists Bertrand Halperin, Eric Heller and Michael Stopa allow the group to understand what the transport measurements and images mean.

Nanophotonics

Moungi Bawendi (Chemistry, MIT)	Marco Loncar (SEAS)	Xiaowei Zhuang (Chemistry & Physics)
Federico Capasso (SEAS)	Eric Mazur (SEAS & Physics)	
Kenneth Crozier (SEAS)	Pierre Petroff (Materials, UCSB)	

The Nanophotonics group of investigators develops new approaches to photonics using nanoparticles, nanowires, nanofibers and imaging techniques. Moungi Bawendi synthesizes CdSe/CdTe "nanobarbell" structures that act as photodetectors by separating electrons and holes. Using MBE growth, Pierre Petroff is making self-assembled InAs/GaInAs quantum posts that operate in a similar way. Federico Capasso and Marco Loncar are developing photonics systems with embedded nanoparticles and nanowires. Eric Mazur is developing subwavelength diameter optical fiber devices. Federico Capasso and Kenneth Crozier have made plasmonic metal resonators in the form of optical antennas that spatially confine the electromagnetic field. These are promising for use in Crozier's robust nearfield scanning optical microscope tips to image photonic systems. Xiaowei Zhuang uses functionalized Ag nanoparticles to image behavior inside living biological cells.

Quantum Information Processing

Bertrand I. Halperin (Physics)	Charles Marcus (Physics)	Robert Westervelt (SEAS & Physics)
Marc Kastner (Physics, MIT)	Michael Stopa (NNIN)	Amir Yacoby (Physics)

These investigators work closely with a group of international collaborators to implement and study systems for quantum information processing. Marc Kastner, Charles

Marcus and Robert Westervelt have developed one-electron quantum dots to implement qubits, and are developing ways to manipulate individual spins. Theoretical understanding and simulations are provided by Bertrand I. Halperin and Michael Stopa. This group has strong international collaborations with Leo Kouwenhoven, Daniel Loss and Seigo Tarucha (see ***International Collaborators*** below).

Custom Scanning Probe Microscopes

Raymond Ashoori (Physics, MIT)	Don Eigler (IBM)	Venkatesh Naryanamurti (SEAS & Physics)
Federico Capasso (SEAS)	Eric Heller (Chemistry & Physics)	Robert Westervelt (SEAS & Physics)
Kenneth Crozier (SEAS)	Jennifer Hoffman (Physics)	Amir Yacoby (Physics)

This group of investigators is well known for developing new imaging techniques to study of electrons and photons inside nanoscale systems, and for building their own scanning probe microscopes. These tools will be extremely useful for visualizing and understanding nanoscale devices and systems. Raymond Ashoori, Eric Heller, Robert Westervelt and Amir Yacoby use capacitive coupling between the tip of a cooled scanning probe microscope and the electrons to image their motion inside nanostructures. Jennifer Hoffman is constructing a cooled STM and a cooled high-spatial-resolution AFM to study high T_c superconductors and other materials. Venkatesh Narayanamurti has developed Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Luminescence (BEEL) Microscopy to study electron states inside nanostructures. Kenneth Crozier and Federico Capasso are developing a new type of Near-field Scanning Optical Microscope with a robust microlens tip that is equipped with a plasmonic metal resonator to more tightly focus the electromagnetic field. Don Eigler is on sabbatical at Harvard during the 2007–2008 academic year - we will benefit from his advice.

International Collaborators

Fabio Beltram (NEST, Italy)	Daniel Loss (Univ Basel)	Hiroyuki Sakaki (Univ Tokyo, Japan)
Leo Kouwenhoven (TU Delft)	Lars Samuelson (Lund Univ, Sweden)	Seigo Tarucha (Univ Tokyo, NTT, Japan)

Our Center has close collaborations with a strong group of investigators located overseas. Students and postdocs travel back and forth to carry out the research. Hiroyuki Sakaki is one of the founders of modern semiconductor physics through his development of superlattices and heterostructures. Leo Kouwenhoven, Daniel Loss and Seigo Tarucha are very well known for their activity in quantum information processing. Lars Samuelson is a leader in nanowire synthesis and growth, and Fabio Beltram heads an impressive group at NEST.

Frontiers in Nanoscale Science and Technology Workshops

Our Center holds international *Frontiers in Nanoscale Science and Technology (FNST) Workshops* focused on nanoelectronics, nanophotonics and quantum information processing. The workshops have attracted outstanding speakers, and they promote interesting and exciting discussions with the audience. Our Center provides scholarships to students and postdocs so that they can attend. The workshops they have proven to be a very effective way to connect students and postdocs with the newest ideas in nanoscience and technology.

Our fourth *Frontiers in Nanoscale Science and Technology Workshop* was held on March 29–31, 2007 in the Institute for Industrial Science at the University of Tokyo during Westervelt's sabbatical there, organized by Seigo Tarucha and Robert Westervelt. The workshop attracted an outstanding group of speakers, and promoted a very effective discussion of nanoelectronics and nanoelectronics, with the participation of George Bourianoff from Intel, Don Eigler from IBM and Jun'ichi Sone from NEC.

The fifth *Frontiers in Nanoscale Science and Technology Workshops* was held on January 6–8, 2008, organized by Daniel Loss and Robert Westervelt. A poster with a list of speakers is shown below. Bill Brinkman and Nobel prize winner Tony Leggett presented plenary talks.

We look forward to continuing this very effective series of workshops in the future.