5. STRATEGIC RESEARCH PLAN

Our Nanoscale Science and Engineering Center develops tools to study nanoscale systems. We would like to control electrons and photons in nanostructures for nanoelectronic and nanophotonic devices. The Center plans to do this by synthesizing nanoscale building blocks and by developing new imaging techniques. We would also like to understand how biological systems function at the nanoscale by developing tools based on the Physical Sciences.

Three Research Clusters address these goals:

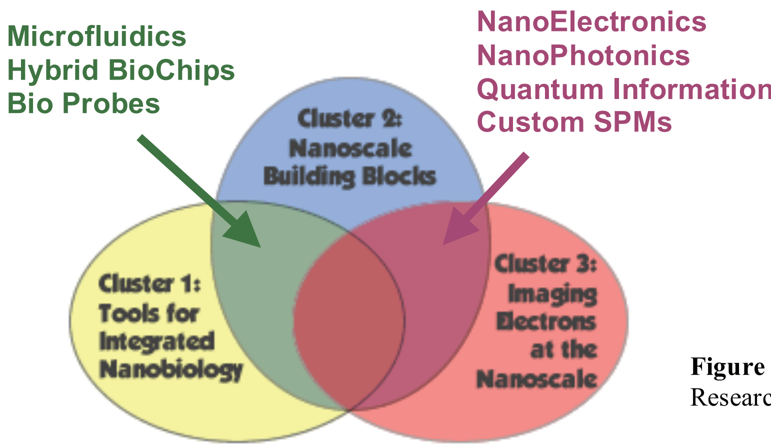

Figure 5.1. NSEC Research Clusters

Cluster I: Tools for Integrated Nanobiology builds bridges between the Physical Sciences, Biology, and Medicine. The Physical Sciences offer powerful new tools for manipulating and testing biological cells and tissues, based on microfluidics, semiconductor technology and biological probes. In turn, 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 II: Nanoscale Building Blocks addresses the synthesis of new classes of nanostructures that exhibit size-dependent properties. An emphasis is placed on structures with unconventional shapes, as well as on zero, and one-dimensional nanostructures including nanoparticles and nanowires. Techniques are being developed to synthesize nanostructures from new materials, including oxide semiconductors and metal chalcogenides. These nanoscale building blocks provide new approaches for nanoelectronics and nanophotonics as well as sensors for biological systems.

Cluster III: Imaging at the Nanoscale explores new ways to image the quantum behavior of electrons and photons in nanostructures using custom-made scanning probe microscopes (SPMs). New instruments include a liquid-He cooled Scanning Tunneling Microscope (STM) and a Near-field Scanning Optical Microscope with custom tips. These add to previously developed instruments for Ballistic Electron Emission Microscopy (BEEM), a dual tipped STM, and cooled SPMs for capacitive probing of electrons. These tools are used to develop devices for nanoelectronics and nanophotonics, and to control single electrons and photons for quantum information processing. Semiconductor heterostructures with novel properties are grown for this work using Molecular Beam Epitaxy (MBE) at UC Santa Barbara.

Figure 5.1 illustrates how the three research clusters overlap, and lists applications they address, described below. The clusters ***Tools for Integrated NanoBiology*** and ***Nanoscale Building Blocks*** address applications in Biology and Medicine: ***Microfluidic and Hybrid BioChips***, and ***BioProbes***. The clusters ***Nanoscale Building Blocks*** and ***Imaging at the Nanoscale*** create applications in Electronics and Photonics: ***Nanoelectronics***, ***Nanophotonics***, ***Quantum Information Processing***, and ***Custom SPM Development***. These applications will benefit society, and they are an important product of the Center's research program.

Most of the Center's researchers work in more than one cluster. The overlap between different research specialties creates exciting new topics, as illustrated by the descriptions in ***Section 6 — Research Program***. We describe these briefly here to show how the Center's participants work together.

Microfluidic and Hybrid BioChips

Federico Capasso (SEAS)	Joseph Mizgerd (School of Public Health, Harvard)	Robert Westervelt (SEAS & Physics)
Donhee Ham (SEAS)	Kit Parker (SEAS)	George Whitesides (Chemistry)
Efthimios Kaxiras (Physics & 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 that can be used to study cells individually, as well as create integrated microfluidic chips for medical analysis. He works closely with fluid dynamicist **Howard Stone**, immunologist **Joseph Mizgerd**, and the other members of this group. **Kit Parker** studies the behavior of interacting 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 in a fluid. Hybrid chips combine biocompatible microfluidics with integrated circuits and optoelectronics. **Donhee Ham** and **Robert Westervelt** create hybrid CMOS/microfluidic chips to manipulate individual cells, and **Federico Capasso** makes hybrid optical/microfluidic systems for sensing.

BioProbes

Moungi Bawendi (Chemistry, MIT)	Joseph Mizgerd (School of Public Health, Harvard)	George Whitesides (Chemistry)
Efthimios Kaxiras (Physics & SEAS)	Hongkun Park (Chemistry & Physics)	Xiaowei Zhuang (Chemistry & Physics)
Charles Lieber (Chemistry & SEAS)	Kit Parker (SEAS)	

A group of Center investigators use probes based on nanoscale objects of different types to sense and image biological systems. **Moungi Bawendi**, **Charles Lieber**, **Joseph Mizgerd**, **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 — they can simultaneously magnetically tag a biological object and optically track its motion. **Mizgerd** uses small 100-nm polymer particles to coat bacteria with an antigen, so that they will be destroyed by phagocytic immune cells. **Zhuang** is developing fluorescent and Raman-active Ag nanoparticles as bio-labels for live cell imaging. **George Whitesides** is functionalizing interior surfaces of microfluidic 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** simulates the motion of DNA molecules through small constrictions to understand their behavior.

Nanoelectronics

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

This group of investigators is developing new approaches in nanoelectronics. They combine nanoscale building block synthesis and Molecular Beam Epitaxy (MBE) growth with nanofabrication and theory to make, study, image and understand new types of nanoscale devices. **Moungi Bawendi**, **Charles Lieber**, **Hongkun Park** and 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 two-dimensional chalcogenide materials with only one atomic layer. **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** and **Robert Westervelt** and international collaborator Fabio Beltram use e-beam and optical lithography to make a wide variety of nanoscale electronic devices based on these materials. The nanoelectronic devices studied by this group range from nanowire and self-assembled dot FETs, to few-electron quantum dots and dot circuits, 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** and **Robert Westervelt** 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)	Charles Lieber (Chemistry & SEAS)	Pierre Petroff (Materials, UCSB)
Federico Capasso (SEAS)	Marco Loncar (SEAS)	Xiaowei Zhuang (Chemistry & Physics)
Kenneth Crozier (SEAS)	Eric Mazur (SEAS & Physics)	

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**, **Charles Lieber** and **Marco Loncar** are developing hybrid nanowire/photonic systems by imbedding optical nanowires in photonic systems. **Eric Mazur** is using a complimentary approach with subwavelength diameter optical fibers. **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 Near-field 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)	Marc Kastner (Physics, MIT)	Michael Stopa (NNIN)
Eric Heller (Chemistry & Physics)	Charles Marcus (Physics)	Robert Westervelt (SEAS & 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**, **Eric Heller** 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)	Eric Heller (Chemistry & Physics)	Robert Westervelt (SEAS & Physics)
Federico Capasso (SEAS)	Jennifer Hoffman (Physics)	
Kenneth Crozier (SEAS)	Venkatesh Narayanamurti (SEAS & Physics)	

This group of investigators is well known for their research to develop new imaging techniques for the study of electrons and photons in 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** and **Robert Westervelt** use capacitive coupling with the tip of a cooled scanning probe microscope to image the motion of electrons inside a two-dimensional electron gas, quantum dots, and nanowires. **Venkatesh Narayanamurti** has developed Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Luminescence (BEEL) Microscopy to study electron states inside small structures. **Jennifer Hoffman** is constructing high-spatial-resolution scanning tunneling and atomic force microscopes to image single flux quanta and single atoms. **Kenneth Crozier** and **Federico Capasso** are developing a new type of Near-field Scanning Optical Microscope with a robust microlens tip, equipped with a plasmonic metal resonator to more tightly focus the electromagnetic field.

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 Workshop. Our fourth international workshop was held on March 29–31, 2007 in the Institute for Industrial Science at the University of Tokyo; it was organized by Seigo Tarucha and **Robert Westervelt**. Three earlier workshops were held at the University of Tokyo, at Harvard, and in San Francisco. The workshop brought together international collaborators of the Center, and other outstanding researchers from Japan, Europe and the USA. Our NSEC provided travel support to send a dozen students and postdocs to the workshop from the USA, and Tarucha supported travel from Europe. The first day was devoted to imaging and nanowires including talks by Don Eigler (IBM), Hari Manoharan (Stanford), Ania Bleszynski (Yale) and Kathy Aidala (Mt Holyoke); Ania and Kathy did their PhD research with **Westervelt**. George Bourianoff (Intel) and Jun'ichi Sone (NEC) discussed the future of semiconductor electronics at the start of the second day, followed by talks on nanoelectronics and nanophotonics by Tsuneya Ando (Tokyo Tech), Yasuhiko Arakawa (Univ. Tokyo), **Federico Capasso**, Hideo Ohno (Tohuko Univ.), Hiroyuki Sakaki, and others. Quantum information was the topic of the third day, introduced by Daniel Loss and Lieven Vandersypen (Delft), with talks by postdocs from Seigo Tarucha's group. The *Frontiers in Nanoscale Science and Technology* workshops have proven to be an attractive and effective way to involve students and postdocs with the newest ideas in nanoscale research.