Research Interests of Prof. Xingguo Xiong

Prof. Xingguo Xiong’s research interests include, but are not limited to: MEMS (Microelectromechanical Systems), Nanotechnology, Low Power VLSI Design and VLSI Testing.

1) MEMS inertial sensors for navigation applications

MEMS (Microelectromechanical Systems) technology is an exciting cutting edge new technology aiming at miniaturizing devices and systems into the size range of microns. MEMS integrate both electrical and mechanical components into a tiny chip. Due to their extremely small size, MEMS have the advantages of low weight, low cost, low energy consumption and high resolution. MEMS have found broad applications in many fields, including automobile industry, aerospace, light projection display, optical and RF communications, medical health care. My research in MEMS includes design, simulation, fabrication and testing of various MEMS sensors and actuators, such as inertial MEMS, MOEMS (Micro Opto Electro Mechanical Systems), RF-MEMS, Bio-MEMS, etc. In the field of inertial MEMS, my research focuses on inertial MEMS sensors for navigation applications, such as novel MEMS accelerometers and MEMS microgyroscopes. MEMS gyroscopes are inertial sensors used to sense angular velocity or angular acceleration. MEMS gyroscopes have been equipped in many microelectronic products. For example, the iPhone 4th generation (Apple Inc.) is the first smart phone equipped with a built-in three-axis MEMS gyroscope. The MEMS gyroscope allows it to sense even the smallest user movements. The equipped gyroscope enables iPhone to have more motion gestures and greater precision for a superior gaming experience. In my research, I conceived a novel bulk-micromachined MEMS gyroscope with glass-silicon-glass sandwich structure, as shown in Figure 1. The device utilizes electrostatic comb activation and differential capacitance sensing. Due to glass substrate, the parasitic capacitance of the device is greatly reduced. By using deep reactive ion etching, the device thickness can be significantly increased so that the device capacitance is much larger, which greatly ease the signal sensing of the gyroscope. The proposed microgyroscope can be used for inertial navigation of spaceship/satellite, automobiles, sailing, military missiles, and consumer electronic products. It may also be utilized in the inertial navigation systems in the UAV (Unmanned Aerial Vehicle) projectile project which is currently funded by US army ARDEC (funding amount: $2.4 million).
2) MEMS piston/torsional/dual-mode micromirrors

MEMS micromirrors can modulate the phase and/or magnitude of incident light, or reflect it to different directions. They are widely used in light projection display, monitor and fiber optical communications. According to the working modes, MEMS micromirrors can be divided into two categories: piston and torsional micromirrors. As an example commercial product of MEMS torsional micromirrors, DMD (Digital Micromirror Device) by Texas Instruments Inc. has now been widely used in projection TVs and projectors. In my research, I conceived a novel surface-micromachined dual-mode aluminum micromirror device, as shown in Figure 2. The micromirror device uses electrostatic driving for the mirror actuation. It can work in either torsional or piston modes, depending on the voltage scheme applied to the bottom driving electrodes. The mirror has a nominal maximum displacement of 4μm in its piston mode, and a nominal maximum rotation angle of ±7.8º in its torsional mode. The proposed micromirror can be used to modulate the phase as well as the direction of the incident light due to its dual-mode modes.
3) **MEMS testing, built-in self-repair (BISR) and reliability analysis.**

MEMS technology has been widely used for various applications. In order for successful commercial applications, MEMS fabrication yield and device reliability are important factors. Especially for those safety-critical applications, such as aerospace and biomedical applications, the reliability is a vital consideration. However, MEMS devices are vulnerable to various defect sources during the fabrication and in-field application. Various defects and failure mechanisms may degrade the yield and the reliability of MEMS, such as particle contamination, etch variations, stiction, etc. Before MEMS devices are released to the market, a thorough, quick and efficient testing is required. However, unlike its VLSI counterpart, due to the diversity of MEMS devices and their working principles, a well-developed universal testing strategy for MEMS is not available yet. I am conducting active research in MEMS testing and fault analysis. I have conceived a novel dual-mode built-in self-test for capacitive MEMS devices. I also developed a self-repairable MEMS comb accelerometer design. As shown in Figure 3, the proposed self-repairable MEMS accelerometer consists of 6 identical module. Among them, four modules work jointly to sense the input acceleration, and the rest 2 modules act as redundancy. If any of the working modules is found to be faulty during built-in self-test, it can be replaced with a good redundant module and the whole device is still guaranteed to work properly. I also developed MEMS yield model and reliability models to quantitatively assess the yield and reliability enhancement due to the built-in self-repair.
4) Nanotechnology and NEMS (Nanoelectromechanical Systems)

Nanotechnology is the science and engineering involved in the design, synthesis, characterization and application of materials and devices with the size in nanometer (10^{-9} m) scale. Nanotechnology is a general-purpose technology which will have significant impact on almost all industries and all areas of society. It can offer better built, longer lasting, cleaner, safer and smarter products for home, communications, medicine, transportation, agriculture and many other fields. My research in nanotechnology includes carbon nanotube (CNT) based NEMS devices, quantum dots, single-electron-transistor (SET), crossbar nanoelectronic circuits design and testing, nanoelectronic circuits based on quantum-dot cellular automata, etc. With the rapid development of nanotechnology, it is bringing a revolution to the current silicon-based VLSI technology. There are many possible implementation strategy of future nanoelectronic circuits. Among them, Quantum-dot Cellular Automata (QCA) is an attractive solution leading to more powerful computing with faster microelectronics. As shown in Figure 4, a QCA circuit consists of QCA cells constructed from four quantum dots arranged in a square pattern. QCA cell is loaded with two extra electrons which tend to occupy the diagonals of the cell. A QCA cell utilizes its two possible polarizations to represent "0" and "1" states. Since QCA cells operates using Coulomb interaction, no current flows between cells hence no power is dissipated. It utilizes the propagation of cell polarity instead of current to transfer signals. QCA circuits work with extremely fast speed (1~10 THz) and low power consumption. Due to extremely small size of quantum dots, QCA circuits are also 100 times denser than current CMOS VLSI circuits. The schematic of a QCA full adder circuit is shown in Figure 4.
Bio-MEMS and bio-nanotechnology are the applications of MEMS and nanotechnology in the field of biomedical and health sciences. Due to its tiny size, bio-MEMS and nanotechnology devices lead to quicker, lower cost, more convenient and efficient solutions for disease diagnosis and treatment. Bio-MEMS and bio-nanotechnology can be used in the fields of micro/nano fluidics (biochips, DNA chips, biomedical lab-on-a-chip), smart drug delivery, microsurgical tools, etc. In bio-MEMS, we frequently need to manipulate micro-fluidic samples (e.g. blood, saliva, sweat) along micro-channels. Such manipulations include driving, separation, mixing, etc. Since the microfluid is basically laminar flow instead of turbulent flow, the mixing of microfluidic samples prove to be very challenging. The microdroplet streams joined from two channels will simply flow side by side, with intermixing only by diffusion, which is very slow. A MEMs digital microfluidic system based on the manipulation (driving, splitting, mixing) of microfluidic droplets has been developed by Prof. Krishnendu Chakrabarty in Duke University. An effective MEMS micro-mixer is in pressing need in such a digital microfluidic system. I am developing an piezoelectric-driven MEMS mixer by utilizing piezoelectric actuators to vibrate the mixer to overcome the surface force for a thorough and quick mixing of the microdroplet. I am doing the research in collaboration with Prof. Prabir Patra and Prof. Hassan Bajwa in UB. Based on the initial research results, we plan to prepare a NSF proposal on a novel piezoelectric MEMS micro-mixer device collaborating with Prof. Chackrabarty from Duke University. Furthermore, I am also doing research on BioMEMS micropump for Lab-on-a-chip and drug delivery applications. For example, diabetic patients need to inject insulin every day, which is a painful process. Using MEMS technology, a tiny micropump can be embedded under the skin of a diabetic patient, and gradually release a tiny amount of insulin into human body as needed. This can greatly reduce the pain of diabetic patients. In my research, I have conceived a novel piezoelectric micropump design. It utilizes piezoelectric actuation to drive microfluid from its inlet to outlet.
In my research in bio-nanotechnology field, I have conceived a novel non-invasive breath test with extremely high sensitivity for diabetes diagnosis using carbon nanotube based acetone sensor. Current blood glucose test for diabetes diagnosis requires pricking a fingertip to get blood sample from patient, which is painful and inconvenient. It also involves the risk of the cross-infection of blood transmitted diseases (e.g. AIDS, hepatitis). As a result, non-invasive diagnosis of diabetes is of great interest. I am working on developing a non-invasive breath diagnosis for diabetes utilizing carbon- nanotube based acetone mass sensor. Current research proves that diabetic patients have trace amount of acetone in their breath, which can be utilized for the diagnosis of diabetes. However, the acetone concentration in the breath of diabetic patients is generally extremely low. The resolution of traditional acetone chemical sensors is not high enough to detect it. To overcome this challenge, I have conceived a carbon nanotube based acetone sensor. As shown in Figure 5, it consists of a double-walled carbon nanotube anchored to an electrode. The nanotube cantilever is electrostatically activated to vibrate at a characteristic resonance frequency. If an acetone molecule from breath sample is attached to the end of the carbon nanotube, the vibration resonant frequency of the nanotube will be shifted, due to the mass increase in the load of the cantilever. Measuring this frequency shift can identify the existence of the acetone, hence help the diagnosis of diabetes. The proposed sensor can detect the existence of individual acetone atoms with extremely high resolution. Such non-invasive breath diagnosis of diabetes have the advantages of being safe, easy, convenient, low cost and painless. It can be used to monitor the blood sugar level 24 hours a day.

Figure 5. Carbon nanotube based acetone sensor for breath test in diabetes diagnosis

6) Low Power VLSI design and VLSI testing

Low power VLSI circuit design is a very hot research area as more and more portable electronic products are being used, and energy conservation has become an urgent need due to global warming concern. More and more computers, TVs, home consumer electronic products are becoming energy-star compliant. In low power VLSI field, my research mainly focuses on various low power VLSI design techniques, such as logic shut-down technique, gated-clock technique, adiabatic computing, sub-threshold low power memory design, low power content-addressable memory (CAM) design, etc. I am also conducting research in VLSI testing, including scan testing of sequential circuit,
boundary-scan chain, built-in self-test, memory testing, etc. In addition, I am also
advising students doing research in analog and mixed signal VLSI design. For example, I
have advised students doing their master project research in developing a high-resolution
differential capacitance sensing circuitry design. Such a sensing circuitry can sense a tiny
differential capacitance change in the range of 1fF or below. This is very important for
the MEMS capacitive accelerometers and microgyroscopes because the typical
capacitance change of such devices is in the range of 1fF or below.