**HIEA: Heterogeneous Integration of Everything onto Anything**

Core faculty: Eric Pop and H.-S. Philip Wong (EE, co-leads), Jonathan Fan (EE), Kenneth Goodson (ME), Subhasish Mitra (EE), Yoshio Nishi (EE), James Plummer (EE), Krishna Saraswat (EE), Debbie Senesky (AA), Xiaolin Zheng (ME)

It is apparent that if one goes by the technology node number, the semiconductor industry will reach the size of the atom in a short number of years. However, device technology progress is not simply measured by how small a transistor is. New generations of technology will offer benefits, such as energy efficiency, for exciting emerging applications via a variety of means. The underlying device technology will become increasingly heterogeneous, with Si CMOS serving as a platform for the integration of a variety of application-specific, architecture-specific device technologies. Industrial partners often do not have the breadth to tackle the full range from nanomaterials to systems.

The HIEA theme of SystemX comprises three (deliberately) overlapping areas of inquiry, which go beyond what individual companies can address: 1) 3D monolithic integration of logic and memory, including thermal challenges of such dense systems, 2) heterogeneous integration of novel materials on Si and on flexible platforms, and 3) autonomous sensors and energy harvesting that enable processing of data in an energy-efficient fashion at the source.
1) Monolithic 3D Integration

Memory will play a central role in the 21st century data-centric computing environments. Developing new ways to achieve high-bandwidth, low latency, low energy memory access will take center stage. New techniques to store and retrieve data that are commensurate with the system architecture will need to be explored. Wong, Pop, and Mitra will create new generations of nanosystems that demonstrate 3D monolithic integration of computation units and memory in a fine-grained manner. They will develop device, fabrication, and design technologies that allow monolithic 3D integration of 1D carbon nanotube (CNT) and 2D transition metal dichalcogenide (TMD) transistors with memories such as STT-MRAM, RRAM, PCM, and CBRAM. Mitra, Pop, and Wong will create models and perform system-level analysis of new architectures (as well as create new architectures and corresponding design techniques) that capitalize on this tight integration of memory and logic with high bandwidth communication made possible by highly dense inter-level vias. Wong will further explore innovative use of emerging memories for use in alternative computing architectures targeted for specific tasks such as machine learning and classification.

In addition to the electronic research, Goodson will pursue a monolithic thermal platform (MTP) to address thermal challenges in dense 3D monolithic systems. The MTP will combine heat conduction solutions at nanoscale dimensions (e.g. using nanomaterials like graphene and BN, provided by Pop and Wong) with phase-change material (PCM) solutions at microscale dimensions including the use of Cu nanomesh or nanowire heat exchangers with paraffin wax PCMs to suppress extreme temperature transients. Adding to the utility of the monolithic 3D systems, Saraswat will explore the use of on-chip optical interconnects and on-chip detectors, lasers and modulators, based on his pioneering work to induce a direct band gap in Ge via strain.

2) Heterogeneous Integration of X-on-Si and X-on-Flex

The Plummer group has pioneered the use of microcrucibles to create high-quality crystalline nanomaterials on Si for device applications. Example demonstrations to date include Ge, GaSb, InAs and GaAs, and future possible demonstrations include InSb, AlSb and InP, as long as the melting temperatures of the nanomaterial is lower than that of the Si substrate (~1400 C). Pop and Wong will explore the challenges of material and device integration of TMDs like MoS2 with Si and flexible substrates. For instance, atomically thin 2D materials like MoS2 (<1 nm thickness) could enable transistor length scaling below the so-called 3 nm technology node. Key challenges for enabling such technology include the making of low-resistance contacts to atomically thin layers, the science of which could be applicable to other materials as well. Another challenge is the integration of high-quality high-K dielectrics with the 2D devices.

At the low end of the temperature spectrum, J. Fan plans to explore the integration of hard materials (e.g. metals, semiconductors or dielectrics) with soft substrates (e.g. elastomers) to construct multi-functional skin-like devices. Similar techniques can also lead to stretchable RF electromagnetic systems, which can be used as components for antennas and can be integrated
into skin-like power harvesters. **Nishi** plans to examine device and nanomaterial integration on simple paper (cellulose) substrates. Cellulose is the most abundant polymer in the world, with good mechanical properties in addition to being renewable and biodegradable. Devices comprised of P3HT or CNTs as well as their top gate dielectrics can be inkjet printed at room temperature and promising early results already exist. **Zheng** will focus on transfer printing from rigid, expensive substrates onto flexible and cheap substrates. Important milestones already include cheap and light solar cells, as well as other “peel and stick” electronics achieved by transfer printing techniques. Future work will focus on ultrathin biosensors, flexible memory devices, and collaborations within SystemX to enable transferring atomically thin nanomaterials such as CNTs and TMDs onto flexible substrates.

### 3) Autonomous Sensors and Energy Harvesting

Heterogeneous system integration is complemented by the availability of sensors that can be monolithically integrated with electronics. **Senesky** works on the nanofabrication of GaN heterostructures for M/NEMS sensors, and her work leverages a brand new MOCVD tool that was installed in Allen-X. Sensors are suitable for harsh environment operation (e.g. high temperature, chemically corrosive, even radiation-rich environments) and can be integrated for temperature sensing with power electronics modules. Powering such sensors and ubiquitous electronics in general, will require thermoelectric (TE) energy scavenging from a variety of heat sources such as HVAC, water pipes, windows, allowing “truly wireless” sensors networks, e.g. in Smart Buildings. **Goodson** will focus on low-power (µW to mW) and low-temperature (ΔT = 5-10 K) TE conversion, which demand revolutionary new materials and designs, unlike traditional TE power modules that are tailored for high-power and higher-temperature harvesting. In addition, **Pop** will pursue the integration of nanomaterials (like CNTs and TMDs) with flexible materials (like polymers) for the realization of flexible TE energy harvesters. Such new devices will optimize and exploit nanomaterial TE properties for energy harvesting from low-grade heat sources as common as the human body (e.g., calculations show up to 0.5 W could be captured from the body heat of a single person, sufficient to power a large array of sensors and wearable, low-power electronics).

In summary, the HIEA SystemX theme recognizes that heterogeneous integration could enable extreme advances in electronics, much beyond the end of “traditional” Moore’s law. The HIEA theme will pursue monolithically 3D integrated low-power logic and memory, thermal engineering, sensors and energy harvesters, and the heterogeneous integration of nanomaterials onto Si and unconventional, flexible platforms.