Berkeley Sensor and Actuator Center (BSAC)

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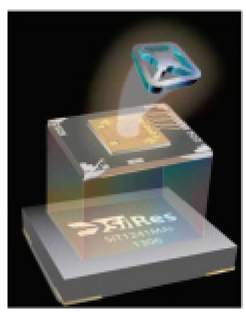
MEMS-Based Timing Components

Today (and for most of the past century), electronic systems depend upon or have depended upon quartz crystals for generation of basic timing signals. That is about to change. Microelectromechanical systems (MEMS) include an important class of devices that "resonate" at high frequencies and that can be used to create precise electronic timing and frequency-selective systems. These promise to change the way electronic systems derive their timing.

Several BSAC-inspired startup companies including SiTime (co-founder BSAC and co-Director Bernhard Boser), Harmonic Devices (acquired by Qualcomm), and Silicon Clocks founded by former BSAC co-Director Roger Howe and BSAC post-doctoral researcher Emmanuel Quevy (acquired by Silicon Labs), and current and former BSAC industrial member companies including Japanese NDK, and University of Michigan startup Discera Corporation (founder BSAC and co-Director Clark Nguyen) have been introducing quartz replacement technology based on these MEMS resonators.



MEMS resonator-based timing components (left) will likely be embedded in most computing and mobile devices (above).

Image courtesy of SiTime Corporation.

Economic Impact: The current US timing devices market of nearly $2B/year represents only the initial target market for MEMS timing components (source: BCC Research Inc). In 2006, this market was 99% served by quartz crystal devices. Private estimates by both crystal and MEMS technology companies suggest a MEMS resonator penetration of approximately 5% in 2012 and 10% to 50% of a $5B/year worldwide market by 2020.

Before end of this decade, it is nearly certain that high frequency filtering required for all mobile devices including cellular telephones and mobile computers as well as communications systems for wireless sensor networks, will depend upon integrated components with thousands of interconnected MEMS resonators. These will perform most of the radio frequency filtering functions currently done with external discrete surface acoustic wave (SAW) and discrete Film Bulk Acoustic Resonators (FBAR) devices. At that time, more than 2 billion portable computers and mobile (cellular) telephones will make use of this technology pioneered in large part at BSAC.

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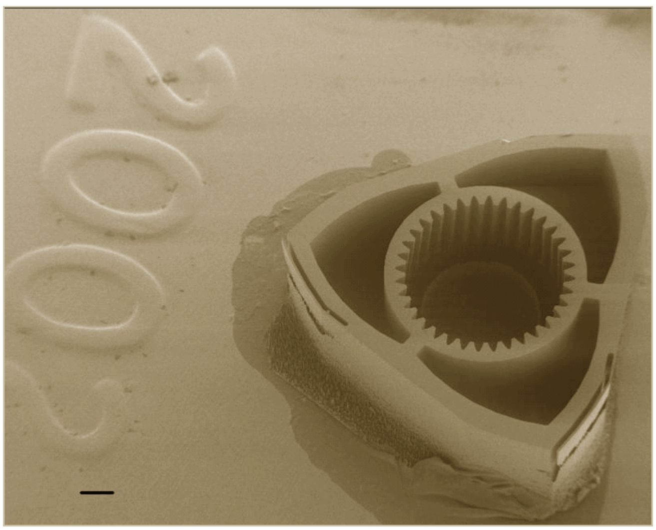
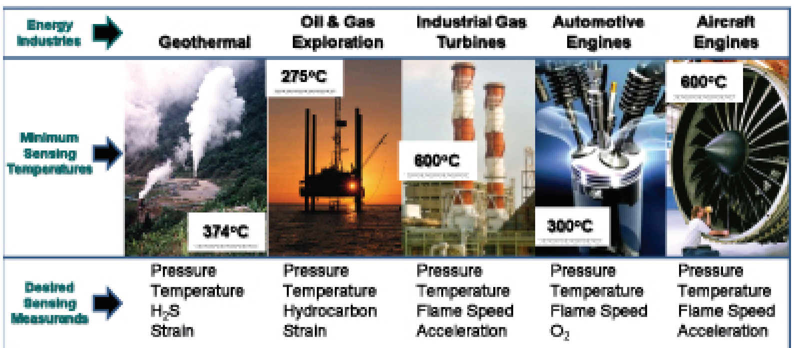
Silicon Carbide Materials and Processes for Rotary Internal Combustion Engine on a Chip



Microelectromechanical system (MEMS) rotary engines convert the stored chemical energy of liquid hydrocarbon fuels into usable electric power in the 10-100 mW range.

Researchers at the NSF Berkeley Sensor and Actuator Center (BSAC) at the University of California-Berkeley designed and micro-fabricated engine components with features on the scale of tens of microns and an overall scale of millimeters with etch depths as large as 900 µm. Evolving from machined stainless steel millimeter scale engine research of Professor Carlos Fernandez-Pello and BSAC researchers, the DARPA funded, Al Pisano-led BSAC MEMS REPS (MEMS Rotary Engine Power System) Program required research and development of new materials and processes. These MEMS engines - much like conventional-sized gasoline-powered generators - have been shown to convert the stored chemical energy of liquid hydrocarbon fuels into usable electric power in the 10-100 mW range. The system was able to deliver specific power (W/kg) superior to conventional systems and to leverage the inherent advantages of liquid hydrocarbons: storage, safety and specific energy (W-hr/kg). Several BSAC NSF-Center member companies, such as Chevron Corporation, Textron Systems and Harris Corporation, have participated in the DARPA-funded research and testing of this device. While federal research on such internal combustion, hydrocarbon fueled systems has diminished, the by-products of the engine research have been substantial. Research efforts to develop the required auxiliary systems, similar to those found on a modern automotive hybrid engine (ignition, fuel delivery, integrated generator), have led to entirely new applications for the materials and processes originally developed for the micro-fabricated engine. In particular, silicon carbide-based sensors and actuators) have led to a very important class of MEMS devices for harsh environment sensing. This enables more efficient the generation of clean power, geothermal wells, and gas and steam turbines.

Economic Impact: The microwankle engine itself may not have the economic impact that was once envisioned, though it spawned the development of materials and processes with larger and environmentally more important impact than envisioned under the original program. Downstream indirect impacts will be felt in increased energy efficiency in large power generation systems. Embedded sensors operating at up to 600 degrees C will create performance improvements and condition-based maintenance for myriad of steam and gas turbines used in geothermal, nuclear and gas-fired plants, and even internal combustion and aircraft turbine engines. For example, a 2% improvement in efficiency of a large single gas or steam electric power generation turbine with output of 200MW can represent additional 35 giga-watt hours/year of energy, or $3.5M/year at retail pricing of $.10/KWH.



The Energy Information Administration (EIA) estimates that between 2009-2015, 21 GW of new gas fired power plant electricity will be become available. Each 1% improvement in efficiency of the turbines generating only this power, represents $160M/year savings at retail pricing of $0.10/KW-H. These numbers can be multiplied by similar efficiencies in geothermal generation. A conservative estimate of the impact of the emerging harsh environment sensors enabled by these new processes and devices, spawned in part by the microwankle research and used to make efficient these energy sources, is expected to exceed $300M/year.

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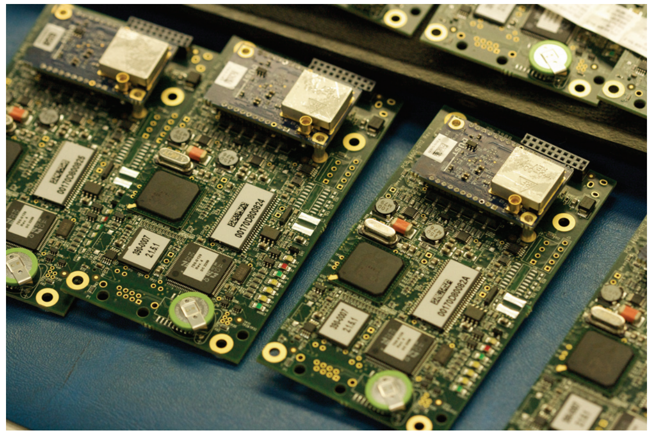
Radio-Equipped Wireless Sensors called "Smart Dust"



Kris Pister of the Berkeley Sensor and Actuator Center popularized the term "Smart Dust" to help visualize his goal of an autonomous network of highly miniaturized "motes" containing microradios and microsensors that can be deployed at random, that wake up; identify who and where their neighbor motes are; and form a dynamic ad hoc self-organized mesh data network over which sensor data such as location, motion, light, pressure, temperature, etc, is communicated wirelessly, reliably and without human intervention.

This Smart Dust story is really a story of collaborative "stone soup" in which Pister contributed the stone from a $25,000 industrial award from I/UCRC member company Hughes and a $10,000 California (state) MICRO industrial matching grant that eventually led to a $1.7M DARPA "Smart Dust" program. This work resulted in a groundswell of industrial and new venture capital investments in wireless sensor networks (WSN). UC Berkeley computer science collaborators developed an open source small footprint (4KROM, 256 bytes RAM) network operating system called "Tiny OS" for the little "micro motes" that were built from off-the-shelf components, and later miniaturized. The micromotes were dropped from UC Berkeley unmanned aerial vehicles; installed at 1/100th the installation cost of wired sensors in a structure of a sister I/UCRC: "Center for the Built Environment (CBE)" on page 41. This inspired academic and industrial collaborations that haven't subsided today. This technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2006.

Economic Impact: Economic Impact: Market forecasts of more than $8B/year made some 8 years ago by market analyst InStat*, of overall wireless sensors and network components enabled in large part by the "Smart Dust revolution", were about 8 years too early; but these technology-enabled promises to revolutionize homeland security, environmental control, power management, and infrastructure monitoring, are now materializing into the multi-billion dollar market envisioned. *Source: InStat/MDR 11/2003 (Wireless); Wireless Data Research Group 2003; InStat/MDR 7/2004 (Handsets).

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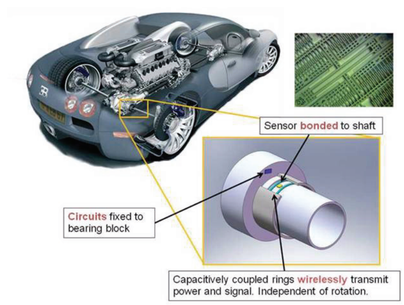
Surface Micromachining of Micro-Electro Mechanical Systems (MEMS)

MEMS “surface micromachining of polysilicon” was perfected in the 1980’s at the Berkeley Sensor and Actuator Center. Like prior “Bulk” micromachining, “Surface” micromachining (SM) creates moving electro-mechanical structures (like clock pendulums or guitar strings on a microscale). But unlike Bulk micromachining, SM uses polysilicon as the mechanical structure and is therefore compatible with standard CMOS microelectronic processing, This breakthrough put MEMS on a similar cost and complexity path to mainstream CMOS memory and microprocessors that benefit from “Moore’s Law” in which component complexity and value double every 24 months.



Economic Impact: Benefits from resulting MEMS components are remarkable. Accelerometers which are used in automobile crash mitigation (airbag deployments) have been estimated to save more than 7,000 lives per year in the U.S. alone. Implantable inertial sensors are now used for early detection of heart pre-failure conditions, in time for interventions. Inertial MEMS will be in 300 million cellular phones sold in 2011. Fast-forward two and a half decades from the BSAC pioneering work in surface micromachining of polysilicon and you find that these “microelectronic inertial sensor” applications have grown into an international multibillion dollar product category that creates even higher value in the products and systems in which they are employed.

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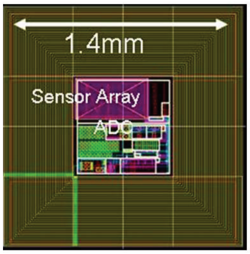
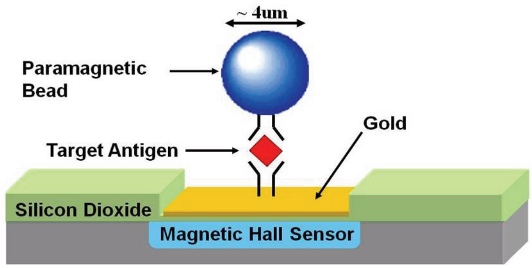
Magnetic Immunosensor





A portable device suitable for handheld field deployment by moderately trained personnel has been developed and demonstrated by researchers at the Berkeley Sensor and Actuator Center. This technology allows verified diagnostic assays for infectious diseases, including Dengue, Malaria, and HIV. The device has allowed dramatic simplification of testing protocol compared to ELISA (the current optical immunoassay standard), with the advantage of allowing sophisticated assays in a point of care or at home setting, where the facilities and advantages of a research laboratory are not available.

A high level of system integration is necessary for replicating the functionality of a diagnostic immunoassay protocol in an inexpensive, palm-held device. Segregation of labels which match the suspected disease from non-specific bound labels (those which do not match) and label detection present major obstacles to implementing an integrated immunoassay device. Magnetic bead labels are particularly attractive in this context since they can be electromagnetically detected and manipulated in opaque solutions such as blood, where the optical ELISA method may fail. Finally, the integration of differential magnetic sensors with local magnetic field generation for internally implemented magnetic washing, represents system miniaturization and potential cost reduction (because of mass producible CMOS) that is unprecedented for complex field-or-home deployable assay.

> **Economic Impact:** The immuno-assay market represents $15B a year in sales in the US, and over two thirds of that market consists of laboratory tests. Recently, emphasis on healthcare cost reduction in combination with the increasingly burdensome liabilities of running a clinical laboratory have incentivized POC (Point of Care) testing. Unfortunately, adoption of POC testing has been very slow due to the poor performance of current products on the market and to CLIA regulations that impose stringent quality control requirements on providers. A BSAC-originated startup company, Silicon BioDevices, Inc., has begun commercializing this immunosensor assay technology through their unique product line that is easy to use, accurate and fully integrated. This approach has begun to catalyze the transition of immuno-assays from the laboratory to the POC.

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