FORTY YEARS OF MEMS INNOVATION AT HILTON HEAD WORKSHOP: FROM EMERGING TECHNOLOGIES TO COMMERCIAL PRODUCTS

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ABSTRACT
Today, the global MEMS industry generates more than US $20B in revenue annually and continues to grow [1]. This revenue can be linked directly to research that had been presented and discussed at the Hilton Head Workshop over the past forty years. Nurtured by government funding and investor capital, this body of research has evolved into families of essential products we interact with on a daily basis in our smartphones, homes, vehicles, factories and hospitals. The Hilton Head Workshop community should be celebrated as an unusually prolific source of hundreds of commercial MEMS products, process methods, tools and companies.

KEYWORDS
Commercialization, product development, startup companies, investment, government funding, MEMS, sensors, actuators, microfluidics.

INTRODUCTION
In 1984, about an hundred people arrived at Hilton Head Island, South Carolina for the inaugural IEEE Solid-State Sensor Conference to discuss and explore the unusual devices they had been developing in laboratories scattered around the world. Using semiconductor process techniques, they had been etching and depositing features to form electromechanical sensors instead of transistors on silicon wafers. They had organized their own small event because their research didn't quite fit into the established conferences of the day.

Prof. Kensall D. Wise of University of Michigan, the conference general chairman, declared in his welcome letter in the 1984 proceedings, "Sensors now hold the keys to the successful application of microelectronics in a variety of new areas - including health care, transportation, and automated manufacturing - and as such they exercise tremendous leverage on the broader electronic field." His words remain true today, especially for additional unforeseen areas such as consumer electronics and in particular the smartphone.

Within the four decades of Hilton Head workshop proceedings is the ancestry of the commercial MEMS industry. This written record illustrates how early research evolved and thrived to create a bushy MEMS family tree with many branches. The variety (hundreds), significance (life-saving and awe-inspiring) and value (billions of USD) of the commercial products which spawned from this body of work are truly impressive. It would not be an exaggeration to claim that every MEMS product today is in some way derived from the prototypes, methods or tools which were presented, discussed and debated at this workshop.

This paper provides a brief tour through the Hilton Head proceedings of the 1984-2022 workshops and shines a spotlight on the research which eventually generated commercial products.

1984-1992 WORKSHOPS
By the time of the 1984 workshop, the first solid-state sensor products were already being sold for use in medical equipment, automobiles and scientific equipment. These included gas chromatographs, piezoresistive pressure sensors, metal oxide gas sensors, magnetometers, ink jet printheads, and bulk accelerometers. The first ten years of workshop proceedings document research on new surface acoustic wave (SAW) devices, capacitive pressure sensors, microphones and uncooled infrared detectors. The main companies working to commercialize MEMS during this era were Transensory Devices, IC Sensors, Novasensor, SenSym, Honeywell, Motorola, Kulite, Ford, General Motors, Foxboro ICT, Endevco, Kodak, Hewlett-Packard, Analog Devices, AT&T Bell Labs, IBM and Texas Instruments.

Although they would not be commercialized for many more years, micromachined neural probes were presented by several groups at the 1984 workshop [2-4]. Decades later, probes for deep brain stimulation to treat Parkinson's disease (Medtronic, Abbott) as well as for neural prosthetics (Neuralink) would descend from this work.

During this ten year period, there was also significant work on new process methods in particular the development of silicon fusion bonding which laid the foundation for future MEMS formed in multiple wafers and having hermetic cavities. Investigations into micro-scale phenomena such as squeeze film damping and stiction began during this period. This foundational work would later become critical to design, manufacturing and reliability of many commercial MEMS products.

1994-2002 WORKSHOPS
The second decade of workshops document a Cambrian explosion of new MEMS device types stimulated by generous government funding (DARPA, NSF, NIH, DOE) and an influx of venture and corporate capital for product commercialization.

Notable in the proceedings are devices that soon became commercial products, such as the grating light valve (Silicon Light Machines), navigation grade accelerometers (Litton) and gas valves (Redwood Microsystems). Piezoelectric microphones and speakers appear at this time but would be commercialized more than 10 years later.

In 1994, Honeywell presented a paper on a commercial product integrating multiple sensor die in a format that would later become known as the "combination sensor" or "combo sensor." Honeywell's compass product consisted of three thin-film permalloy magnetometers packaged with three piezoresistive MEMS accelerometers [5]. This package-level integration design would feature prominently in commercial sensors starting in the mid 2000's.

Also during this series of workshops, research on MEMS gyroscopes appeared, with the vibrating ring gyroscope debuting in 1994 and a Z-axis gyroscope in 1996. Commercial gyros sold in the 2000's feature design elements from this research.

Research presented by IBM on cantilevers having sharp, nano-meter radius orthogonal tips would lead to numerous atomic force microscopy (AFM) tools [6]. AFM cantilevers would find commercial success as metrology tools for surface analysis and force measurement (Veeco). Companies formed to commercialize AFM cantilevers to read/write data for a new type of non-volatile memory (Nanochip) and nanoscale lithography (Nanoink) but ultimately did not succeed.

Within this period, research on MEMS for biotechnology applications blossomed. Blood analysis on a chip, immunoassays, DNA and protein analysis, and flow cytometry were developed using silicon, glass and plastic as substrates. Companies such as Caliper Life Sciences, Soane BioSciences and Perkin Elmer developed early products. An HIV mutation assay (Affymetrix) [7], PCR cartridge (Cepheid) [8] and a point of care blood analysis cartridge (iStat) [9] found significant commercial success. Microfluidics grew so quickly as an area of research that in 1994 it branched off into a new conference called Micro Total Analysis Systems (µTAS). Early research on medical devices such as microneedles and drug delivery chips also occurred during this period although commercialization would still be years away.

Piezoelectric thin films such as zinc oxide (ZnO) and aluminum nitride (AlN) were fashioned into chemical sensors, radio frequency resonators, filters (Avago, TriQuint Semiconductor), and variable capacitors, as well as high displacement actuators for gas and liquid valving.

The telecom bubble of 1996-2000 rapidly accelerated development of MEMS optical components. Several billions of investment dollars poured into commercialization of MEMS components for fiber optic networks. Optical switches, cross-connects, micro-mirror arrays and more appear in the proceedings starting in 1996. Companies such as Tellium, Xros, Nortel, Dicon, Astarte Fiber Networks, Transparent Networks and dozens more participated in this technology development frenzy that ultimately was decades too early for marketplace demand. Much of the foundational work on MEMS mirrors would be re-purposed years later for autonomous vehicle LiDAR systems (Innoviz, AEye) and AR/VR optical systems (Microvision, Texas Instruments, Maradin).

Meanwhile in the automotive sector, companies like Bosch, Delco and Ford continued to engineer MEMS sensors for vehicle safety systems. The proceedings record assembly of tire pressure monitoring systems (TPMS) and airbag deployment systems consisting of MEMS plus ASIC chip [10].

Other types of MEMS devices emerging during this period included capacitive micromachined ultrasound transducers (CMUT), flow sensors, magnetic sensors and microcalorimeter gas sensors.

Our colleagues were also busy improving methods and materials to facilitate invention. MEMS-specific modeling tools emerged during this time; the company Microcosm (later named Coventor) was founded leveraging research on electrostatic device modeling; Tanner L-edit mask layout software deftly managed the non-Manhattan geometry favored by MEMS designers and Intellisense developed process simulation tools.

With improvements in fusion bonding and wafer thinning, silicon-on-insulator (SOI) wafers (Okmetic, IceMOS) improved in quality and became the preferred substrate for MEMS devices needing thin single crystal silicon membranes or structures. High-aspect ratio deep silicon etch (DRIE) tools became widely available during this period (STS, Alcatel), enabling manufacture of the popular electrostatic comb finger drive-sense configuration. Self-assembled monolayer (SAM) coatings were developed to combat stiction in electrostatic MEMS [11] and the company Applied MST later emerged to sell SAM deposition tools.

Early efforts on through silicon vias (TSV), a process technology that would later become vital to the MEMS and semiconductor industry, began during this period [12]. The development of eutectic wafer bonding techniques led to advanced wafer bonding tools (EVGroup, Suss Microtec) and mass production of inertial sensors having hermetic cavities. MEMS-specific foundries such as MEMSCAP, Standard MEMS, Micralyne and Silex Microsystems were founded to provide manufacturing services to proliferating fabless MEMS product companies.

2004-2012 WORKSHOPS

Innovation in methods, materials, devices and tools continued throughout the workshop's third decade. The ecosystem of MEMS product, equipment, software, foundry and service companies was steadily expanding, as evidenced by the increased number of corporate sponsors for the workshops.

Insight into the physics of thermoelastic dissipation was leveraged to optimize resonators and gyroscopes for ever higher Q factors. The introduction of the Nintendo Wii in 2006 and then the Apple iPhone in 2007 created intense market demand for MEMS inertial sensors and incentivized research into ever smaller, lower cost, lower power consumer-grade gyroscopes and accelerometers. Corporate research groups at Analog Devices, InvenSense, Bosch and STMicroelectronics led the way in innovating high volume MEMS devices, with academic researchers focusing on higher performance, navigation grade gyros. The startup company MEMSIC, spun out from ADI, presented their creative thermal convection gas bubble accelerometer at the 2008 workshop [13].

Studies on XeF_2 and HF as selective vapor-phase etchants for releasing sacrificial layers of silicon and oxide, respectively, inspired new equipment companies such as Xactix and Primaxx. These commercial tools were quickly put to use in research laboratories to create many more types of MEMS devices. Development of low temperature, plasma-activated wafer bonding processes (Ziptronix) during this period enhanced scalable manufacture of MEMS formed from multiple wafer bonds. The process discovery that annealing etch-damaged silicon surfaces in a high temperature hydrogen environment could make them atomically smooth [14] was leveraged by SiTime's silicon oscillator products to achieve superior frequency stability and outperform the traditional quartz-crystal oscillator [15].

With the proliferation of battery-powered consumer electronics such as laptop computers and cell phones and motivation to connect distributed sensors to form an Internet of Things, research interest during this period turned towards micro-scale power generation. The startup Lilliputian attempted to commercialize butane-fired micro fuel cells for power-hungry products like a laptop. MicroGen and EnOcean focused on aluminum nitride-based energy harvesters.

Further explorations in aluminum nitride-based MEMS devices resulted in the piezoelectric microphone (Vesper), RF filters for cell phones (Avago) and in 2012, the piezoelectric micromachined ultrasound transducer (PMUT) [16]. The startup Chirp was formed in 2013 to commercialize the PMUT for gesture recognition applications; the technology is deployed today in TDK's fingerprint sensors as well as in ultrasound medical imaging systems (eXo).

Microfluidics research continued on diagnostic chips to detect circulating tumor cells, chips for cell sorting and whole blood separation, chips for immunoassays and PCR for DNA analysis. Soft polymers like PDMS and photo-patternable polymers such as SU-8 and polyimide were explored by many research groups to create flexible sensors and low cost biotechnology chips.

Exciting developments for medical MEMS devices included a retinal protheses by Second Sight [17] and a glass capacitive pressure sensor with RFID readout for aortic stent management (CardioMEMS). Development of nanoporous membranes aims at the ambitious goal of creating a life-saving artificial kidney [18] and continues still today with hope for commercialization in the near future.

Other innovative MEMS reported during this period which have since been commercialized were chip scale atomic clocks (Symmetricom), spatial light modulators for maskless lithography (Texas Instruments, Heidelberg Instruments), deformable optical arrays (IrisAO), plasmonic devices and metamaterials.

2014-2022 WORKSHOPS

More recently, MEMS research has expanded well beyond silicon and traditional CMOS process materials. Physical sensors and actuators emerged using thin-film diamond, graphene, gallium nitride, atomic layer deposition (ALD) materials and scandium-doped aluminum nitride. Medical and agricultural prototype sensors and devices were made from an assortment of biodegradable polymers. Precision material deposition methods expanded to include 3D printing, ink-jet style printing, and thermoplastic micro-molding (Edge Embossing). Widespread availability of nano-scale patterning facilitated research into tunable metamaterials, currently being commercialized by companies such as Kymeta and Metalenz.

More sophisticated device and process modeling tools (ANSYS, Comsol, Coventor, SoftMEMS) and improved understanding of microscale physics such as energy dissipation in anchor loss facilitated continued optimization of high frequency resonators and navigation-grade gyroscopes. The workshop proceedings document the steady evolution of legacy MEMS inventions such as uncooled infrared bolometers, switches (Menlo Micro) [19], neural probes [20], point of care chips and biological assays [21] into more sophisticated and capable products. Zero power sensors, MEMS which draw little or no electrical current until a triggering event occurs [22], are currently in early commercialization at the startup company Zepsor.

Pressing environmental crises such as urban pollution and wildfires have been providing motivation for more recent research into air quality sensors such as volatile organic compound (VOC) gas sensors and PM 2.5 particle sensors (N5 Sensors, Aclima). The COVID-19 pandemic crisis, which forced cancellation of the 2020 workshop, continues to motivate our MEMS community to improve high throughput virus diagnostic chips [23, 24].

Most recent workshops featured next generation technologies such as biodegradable and ingestible sensors [25], flying and jumping microrobots [26-28], fiber and textile-based sensors, 3D printed microstructures [29] and even paper-based batteries powered by bacteria [30]. While some may debate whether these non-silicon devices are truly MEMS, the proceedings validate their heritage as direct descendants of our MEMS research community. The future will reveal how and when they might yet become commercial products.

CONCLUSION

Fostering an environment for collaboration was a founding principle of the Hilton Head Workshop. In 1984, Prof. Wise's welcome letter encouraged the attendees to socialize: "The primary emphasis at this meeting, however, is on informal interaction among those of us in the sensor field - sharing ideas, debating approaches, and simply getting better acquainted." The community's revered senior members continue to promote informality and approachability by dressing in tropical-themed casual clothing. Successful MEMS invention and development requires a team of multi-disciplinary engineering and scientific experts; it was a stroke of genius to bond that team together with a convivial workshop held at a seaside resort.

The bi-annual migration back to Hilton Head compels MEMS professionals from all corners of the world and still includes some attendees of the 1984 workshop. The unusually nurturing conditions of this beloved event could arguably be the secret ingredient to 40 years of prodigious scientific and commercial contributions by this very talented community.

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The Hilton Head Workshop proceedings are available online at: https://transducer-research-foundation.org/technical_digests/past_digests.html

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