Low-Power Micromachined Microsystems

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ABSTRACT

Micromachined microsystems and Micro Electro Mechanical Systems (MEMS) have made possible the development of highly accurate and portable sensors and instrument for a variety of applications in the health care, industrial, consumer products, avionics, and defense. Design of low-power circuits for these applications, and use of micromachined sensors and actuators in combination with integrated circuits to implement even lower power microinstruments has now become possible and the focus of attention. This paper reviews the state of the art in the development of micromachined microsystems and MEMS, discusses low-power design approaches for microsystems, and reviews some recent development in power generation and energy harvesting from the environment.

Keywords

MEMS, Micromachining, Low-Power, Microsystems, Power Sources, Energy Harvesting

1. INTRODUCTION

The development of highly-integrated control and instrumentation systems that combine sensors, actuators, low-power signal-processing electronics, and wireless communication is very important to many applications, including industrial processing, health care, automotive systems, environmental monitoring, avionics, consumer appliances and products, and defense [1,2]. Most of these applications impose significant restrictions on the systems being developed forcing the technologies used for their implementation to have to satisfy a number of functional, fabrication, and systems requirements. During the past three decades much work has been done in silicon-based *micromachining* and microfabrication to build miniature instruments to address these needs and requirements.

The development of *micromachining* technologies dates back to the 1960's when various isotropic silicon etchants were developed for integrated circuit manufacturing. The 1970s saw considerable progress in the development of micromachining techniques for a number of silicon sensors. The automotive industry was a primary driver in these developments and was started volume production of silicon pressure sensors in the early 1980's. By the late 1980s, surface micromachining had also emerged, making possible a variety of new resonant sensors and microactuators, and circuits were being successfully merged with microsensors and actuators to ease signal-to-noise and packaging problems. In the 1990's, sensors, actuators, and electronics have been brought together to form micro electro mechanical systems, and it is clear that the next decade will continue to witness the development of many different types of integrated sensing/actuation microsystems.

MEMS systems are the only true "mixed-mode" systems, and their implementation requires that they incorporate a mixed set of "fabrication technologies" (bulk, surface, and electroplating), operate on mixed "signal modes" (analog, digital, and a variety of non-electrical signals), and that they provide a number of "functions" such as sensing/actuation, electronic computation, and wireless communication.

This paper first presents the generic architecture for micromachined integrated microsystems, and will discuss requirements for these systems in emerging applications. It will then present a short review of common micromachining technologies followed by a brief review of several examples of micromachined sensors and systems. Next, issues involved in the design of low-power microsystems involving low-power integrated circuits and transducers, and power sources and energy harvesting are presented.. The paper ends with a conclusion.

2. MICROMACHINED INTEGRATED SYSTEMS

Figure 1 shows the architecture of a measurement and control microinstrumentation system [1]. It consists of a number of front-end sensors or actuators that allow the user to interface with the external environment, measure different parameters, and deliver signals of interest based on sensed information. These signals are processed by electronics integrated with sensors or incorporated in the vicinity of the transducers, and the results are communicated with a remote unit using a wireless link implemented using RF or other wireless techniques. The entire system should ideally operate from a battery as the primary energy source. Many emerging applications for these microsystems require small size, low power, wireless operation, versatile and upgradeable architectures, and packages that allow them to be easily utilized in different environments.

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Low power has become one of the most important requirements for many electronic and instrumentation systems as these increasingly move towards becoming "portable" units that operate autonomously. This independence dictates the overall system to dissipate very low levels of power so that problems associated with power source, thermal management, and mobility can be avoided and overcome. Small size is another very important requirement that has to be achieved for a number of reasons. The drive towards lower cost together with the fact that many micromachining technologies obey the rules of economy of scale has steered the developers of such systems to continue to reduce size. The need for hand-held operation also dictates the system to be as small as possible. This is especially true in instruments that are more than just a single sensor or actuator and combine a number of these devices together with transceivers and package.

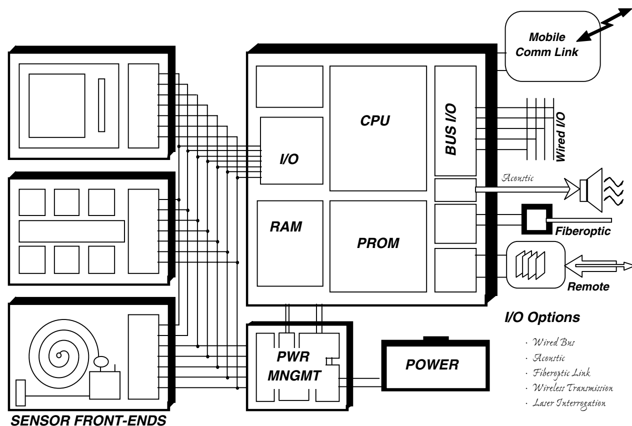

Figure 1: Architecture of a measurement and control microinstrumentation microsystem [1].

Reducing the size of transducers certainly is helpful in reducing the size of the overall unit. Versatility and improved functionality also require that more than just one sensor or actuator be incorporated into the system. Many instruments need to be multi-functional units that can not only measure a variety of parameters, but also do so with improved reliability and performance. The latter requires that these systems have built-in redundancy at various levels, and incorporate multiple transducers of the same kind with staggered dynamic ranges so that the entire measurement range of interest can be covered in a single unit. This can be achieved with micromachined devices because of their smaller size, the ability to scale their performance parameters by simply changing their dimensions, and the ability to operate and manipulate them with integrated on-chip electronics.

The ability to incorporate electronics into micromachined devices, either monolithically integrated or hybrid attached, is perhaps one of the most important advantages that they offer. Today's systems need to be "smarter" than their predecessors. They need to be able to do more than just "respond" to some external parameter. They need to communicate with a microcontroller, transmit processed and compensated sensed data to the microcontroller, alert the microcontroller of any malfunctions or faults, and respond to the microcontroller and implement many functions such as self-testing, self-calibration, and power management that we have come to expect of many microelectronics systems.

The issues discussed above pertain to most MEM systems and cover many applications. Many of the above requirements are only satisfied when appropriate micromachining technologies are used. These technologies, in turn, need to satisfy requirements of their own. As was mentioned before, micromachining technologies have been around for some decades now, and have been used to implement several commercial devices. The traditional requirements for these technologies have been the ability to form microstructures with precision, reproducibility, high-yield, and low-cost.

3. MICROMACHINING TECHNOLOGIES

The ability to form microstructures to operate on mechanical, fluidic, optical, chemical, and other signal domains using micromachining is instrumental to and lies at the heart of micromachined microsystems. Micromachining technologies generally fit into three categories. Bulk micromachined devices are made by carving their parts from a silicon wafer [2]. Surface micromachined devices are primarily made from deposited thin films and are released from the supporting substrate by etching sacrificial layers deposited under them [3], as illustrated in Figure 2. The microstructure material can be polysilicon, and the sacrificial layer is silicon dioxide. Both of these layers are COMS compatible and therefore CMOS circuitry can be integrated with micromachined components. Electroplated and high aspect-ratio devices with height of several hundred microns are formed using electroplating through molds made from a number of polymers [4].

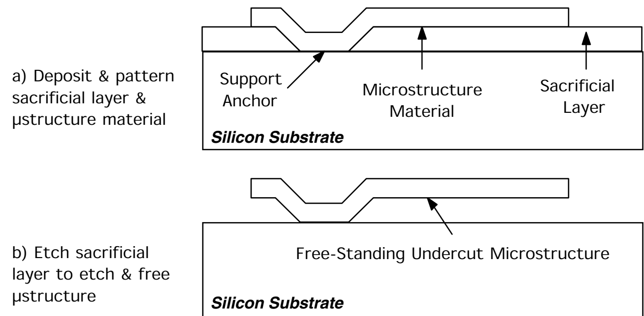

Figure 2: Fabrication process for surface micromachined devices [1].

As mentioned before, micromachining technologies have been around for some decades now, and have been used to implement several commercial devices. The traditional requirements for these technologies have been the ability to form microstructures with precision, reproducibility, high-yield, and low-cost. As we move towards more sophisticated and higher performance systems, still more is demanded of micromachining technologies, including the ability to form thick high-aspect ratio microstructures, the ability to integrate electronics with the devices in a manner that does not complicate the overall process or affect the yield of the circuits or the micromechanical devices, the capability to form a variety of microstructures so that different sensor signal types (physical, fluidic, radiative, magnetic, and optical) can be manipulated by the system, and the capability to fabricate the package for the individual device at the wafer level before individual dice are separated from the host wafer. Today we possess the ability to machine and mold a variety of materials,

including silicon, into practically any useful shape and structure that is needed for any given application. Many of these technologies are inherently compatible with integrated circuit fabrication, and when used together will change the way future microsystems are realized.

4. EXAMPLES

To illustrate the breadth of available technologies, and their use in different applications, the following presents a brief review of example microsystems and devices. These examples only highlight few of many developments achieved by researchers around the world. The applications of microsystems are indeed many and varied. They include microfluidic systems for manipulating and processing gases and liquids, miniaturized high-density data storage systems, inertial and position sensing microsystems, biomedical microsystems, wireless and optical communication microsystems, chemical microreactors and analysis microsystems, and micropropulsion microsystems.

4.1 Microinstrumentation Cluster:

Figure 3 shows a watch-sized microinstrumentation cluster developed for measuring environmental parameters such as humidity, temperature, barometric pressure, and vibration, and for processing and communicating this information via a wireless link to a remote controller [5]. The cluster is designed around an embedded Motorola 68HC11 microcontroller (MCU) having on-chip memory, an 8-bit ADC, a timer, and serial communications hardware. The architecture of the cluster is designed such that as new microcontrollers become available, they can be easily incorporated into it. The MCU communicates with the front-end sensors via a nine-line internal sensor bus and custom interface circuitry integrated on the transducer chips or on a separate hybrid. Sensor data collected by the MCU is calibrated in-module, stored, and sent out either through an on-board telemetry device or via a hardwired RS-232 I/O port. A custom power management chip performs several functions for minimizing power consumption in the battery-powered system. The cluster system employs an open architecture that permits it to be populated as desired by many different sensors using a mix of technologies. Sensors for measuring barometric pressure, temperature, humidity, and acceleration are included in the initial system.

Measurement of barometric pressure requires a sensor with very high-accuracy, wide dynamic range, and low-power for portable applications. These requirements dictate that the senosr be capacitive, and incorporate devices with staggered operating raange to cover the entire range of interest. Figure 4 shows a fully-integrated pressure sensing system, with five pressure sensors, a reference sensor, and integrated switched-capacitor readout circuit [6]. This BiCMOS interface circuit can resolve capacitance changes with a 1fF resolution, and provides over 15 bits of dynamic range. It is hermetically sealed in a cavity created when the individual sensors are fabricated. The figure shows the six devices and the circuit before the chip is bonded to a glass substarte to complete the chip-level and batch sealing of sensors and the interface circuit. The entire system is capable of resolving pressure changes in the range of 25.6mTorr, which is equivalent to a change in altitude of 1 foot of air. The sensor's dynamic range is 500-800 Torrs, and the entire chip measures 7.6x6.5mm^2. The sensor cannot operate and provide the necessary performance without the interface circuit. The circuit has to provide high resolution, and operate using low power and low voltage.

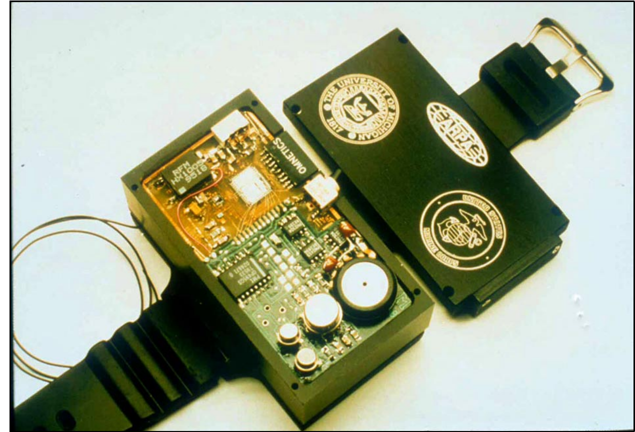

Figure 3: A multi-sensor microinstrumentation cluster for environmental monitoring [5].

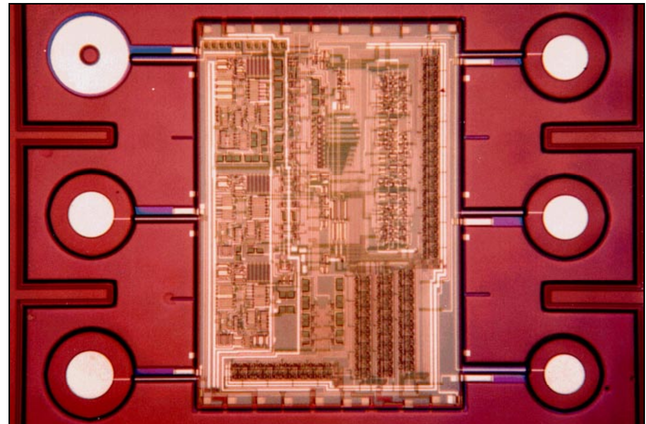

Figure 4: An integrated capacitive barometric pressure sensor consisting of six transducers and a BiCMOS switched-capacitor interface circuit [6].

4.2 Inertial Sensors:

Measurement of linear acceleration and rate of turn is needed in many applications, including automotive systems and inertial navigation [7]. One of the most widely used, and most advanced, commercial accelerometers has been developed by Analog Devices, Inc. for use in crash sensing and air bag deployment. Figure 5 shows a SEM view of the accelerometer surrounded by its interface and signal processing circuitry [8]. The sensor consists of a proof mass that is free to move above the substrate in response to changing acceleration. Two sets of comb fingers are used to sense and measure the movement of the mass. One set is attached to the mass and can move with it, while the other is fixed to the substrate and remains stationary. When the mass moves, the capacitance between the fingers changes. This change is measured by the on-chip circuitry and the resultant signal is used to reposition the mass using electrostatic forces generated by the on-chip circuitry through electrostatic attraction that keeps the mass in a null position. The entire sensor is fabricated using deposited polysilicon and is formed after the circuitry is fabricated. The circuitry is implemented using a customized BiCMOS process, and plays a central role in the operation of the

device. In addition to sensing and feedback control, the circuitry also performs a number of self-test functions at each start of the car. Such self-test capability has proven vital to the success of these micromachined sensors in the automotive application since it provides the manufacturer the ability to check the reliability of the device and warn the user in the event of a failure.

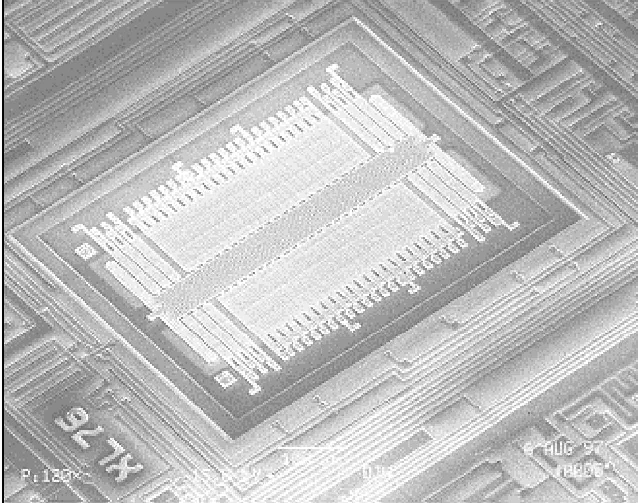

Figure 5: A micromachined silicon accelerometer and its associated interface circuitry developed by Analog Devices, Inc. [8].

In addition to accelerometers, gyroscopes are used in many inertial sensing systems to measure the rate of turn to provide heading information for inertial positioning applications in defense, automotive, avionics, and consumer electronic applications [7]. Almost all reported micromachined gyroscopes use vibrating mechanical elements to sense rotation. These vibrating gyroscopes have no rotating parts that require bearings and hence, they can be easily miniaturized and batch fabricated using micromachining techniques. All vibratory gyroscopes are based on the transfer of energy between two vibration modes of a structure caused by Coriolis acceleration. Coriolis acceleration is an apparent acceleration that arises in a rotating reference frame and is proportional to the rate of rotation. Figure 6 shows a Polysilicon Ring Gyroscope (PRG) fabricated using a high aspect-ratio polysilicon micromachining technology [9]. The polysilicon ring is 80µm tall, 2µm thick, and has a diameter of 1mm. By taking advantage of the thick high aspect-ratio polysilicon ring structure, sub-micron ring-to-electrode gap spacing and high quality factor of polysilicon, tactical grade vibrating ring gyroscopes such as that shown below with a resolution of 5°/hour in a 10 Hz bandwidth can be realized, providing orders of magnitude improvement in performance compared to previous MEMS structures [9]. This sensor requires interface circuitry to force the structure into mechanical resonance, provide feedback signals to calibrate and tune the two resonance modes, and sense the movement of the two resonant modes in response to rate of turn.

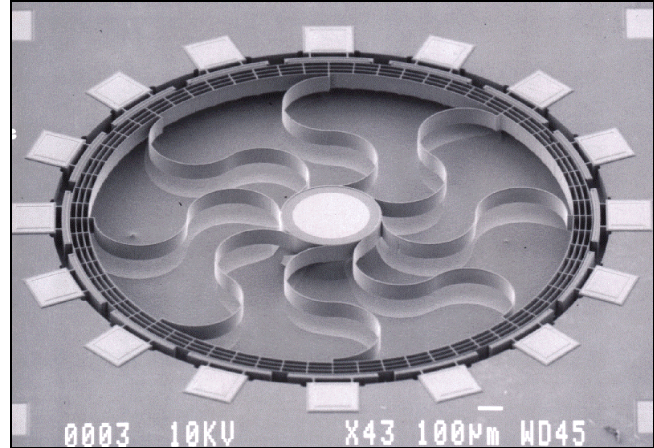

Figure 6: A micromachined vibratory ring gyroscope fabricated using a high aspect-ratio polysilicon micromachining technology. The polysilicon ring is 80µm tall, 2µm thick, and has a diameter of 1mm [9].

4.3 Biomedical Microsystems:

One application for biomedical devices is in implantable systems for use in closed-loop neural-based prostheses. In these systems, the sense and control channels which naturally exist within the intact human system need to be restored and communication between the central nervous system and the organs that have lost their connection to the brain need to be reestablished. Electrical signals generated by brain cells are recorded using miniature probes, the signals are processed to generate control signals, and these signals are in turn used to drive stimulators that directly interface with the disabled organ to restore some function to it. In order to develop such systems, implantable devices that can perform the functions of recording (sensing), signal processing, and stimulation (actuation) need to be developed. Furthermore, the overall system has to be biocompatible, stable, and should last in the body for an extended period of time.

Figure 7 shows the photograph of a multi-channel micromachined silicon microprobe for delivery of stimulating current pulses to individual nerve cells in the brain [11]. Probes such as this can be used in implantable auditory and visual prostheses and can interface directly with neurons in the brain and provide direct electrical stimulation. The silicon substrate is micromachined to be 15µm thick, and contains circuitry to deliver a bi-phasic programmable current pulse of ±100µA to any one of 4-of-64 individual stimulation sites. These sites are distributed on 16 shanks and have an area of 1000 μm^2. The probe is shown on the date of a US penny.

An important issue in the development of implantable biomedical systems is power transfer and communication. To avoid using wires to connect to these systems, RF telemetry is often used to inductively transfer power and data to the system. Figure 8 shows a fully integrated multichannel stimulation chip [12]. This Fully Integrated Neural Stimulation System (FINESS) includes an on-chip coil and capacitors integrated over a BiCMOS circuit for inductive power and data transfer. The chip includes a 5V voltage regulator, an AM demodulator, a clock recovery circuit, a CMOS microcontroller, and current drivers, consumes less than 5mW of power, and measures 2mm x 8.7mm. It is capable of delivering variable amplitude (up to 2mA) and duration (up to 1msec)

current pulses through any pair of 16 electrodes into tissue for electrical stimulation of peripheral nerves. The chip is powered by inductive coupling between an external flat antenna and the on-chip electroplated copper antenna and can receive as much as 20mW of power from a distance of up to 5cm. This wireless chip can be used with nerve cuff or micromachined silicon electrodes in auditory, visual, and functional neuromuscular prostheses.

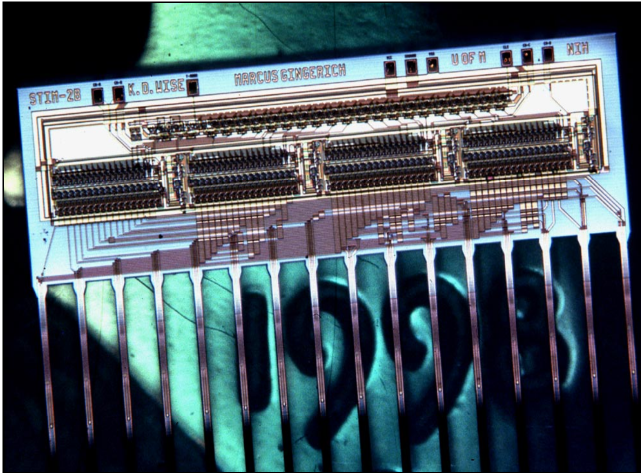

Figure 7: Photograph of a multi-channel micromachined silicon microprobe. It contains 16 shanks, with a 400µm pitch, and each shank contains 4 stimulation sites [11].

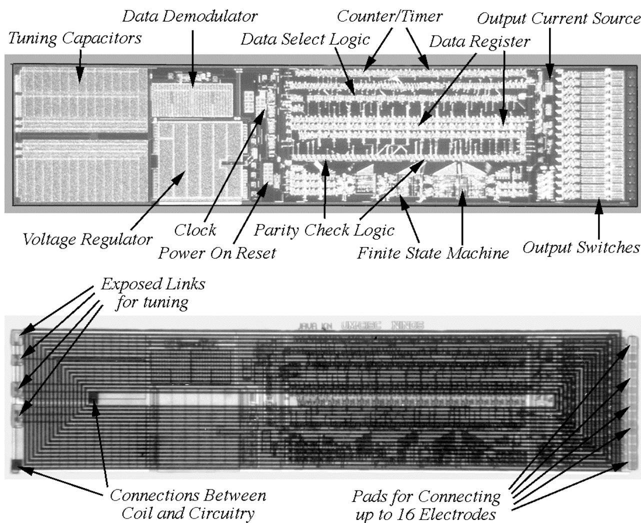

Figure 9: Photograph of the wireless FINESS chip. The top photo shows the BiCMOS chip , and the bottom photo shows the sqame chip after the on-chip coil needed for power and data transfer is fabricated [12].

4.4 MEMS For Wireless Communication:

In addition to sensing and actuation, micromachined devices and structures are increasingly used to perform functions traditionally implemented using electronic devices. One of these applications is in components for wireless communication systems. Figure 10 shows the architecture of a typical superheterodyne receiver. Such receivers use several circuit blocks for amplification, mixing, and signal processing. However, to achieve required performance, they also have to use mechanical devices such as SAW resonators and crystal oscillators for functions such as channel selection and filtering. These mechanical devices are usually large and cannot be integrated with the circuit chip. They can be potentially replaced by micromachined resonators and oscillators formed using silicon-based processes. Figure 11 shows a micromachined polysilicon resonator with a resonant frequency of ≈92MHz, and Q of over 7000. Hundreds of these resonators can be fabricated on the same chip used for fabricating the electronic functions.

In addition to their low-power and high performance, these micromachined resonators can be used to provide channel selection in cellualr phones thus avoiding the need for circuitry to achieve such function. It is this possible to replace much of the electronics and reduce the power disspation, while improving performance [13].

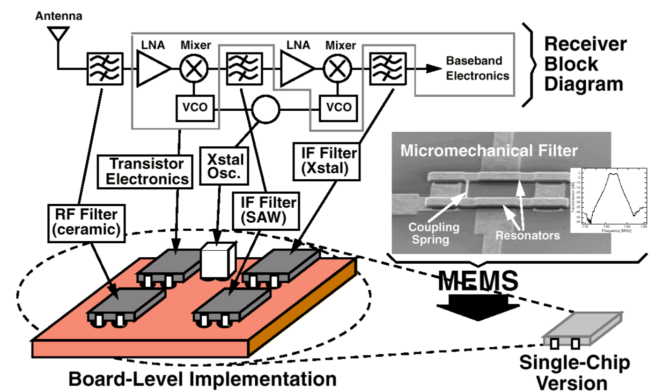

Figure 10: Architecture of a typical superheterodyne receiver. Many of the hybrid components, such as filters, currently used in such systems can be replaced with micromachined resonators to produce a single ship transceiver [13].

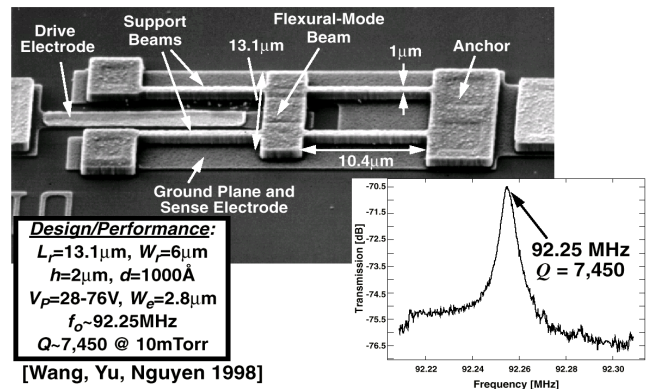

Figure 11: A 92MHz micromachined polysilicon resonator with a Q of >7000 for use in wireless communication [13].

5. POWER ISSUES

As discussed above, portability has become an increasingly desirable and in many cases required feature for computers, communication devices, and microinstruments. Therefore, issues involving power sources, low-power design, and low-power sensors and actuators have to be considered carefully. In the following issues related to low-power design of microsystems and

MEMS will be first discussed, followed by a discussion of power sources and potential energy harvesting approaches that are being considered for use in MEMS.

5.1 Low-Power Design Approaches:

To design microsystems for low-power operation, several different approaches can be taken. First, sensor technologies and transduction mechanisms that lend themselves to low-power operation should be adopted. Second, the interface and signal processing circuitry required to operate the sensor should be designed for low power operation. Third, micromachined devices and elements can be utilized in electronic systems, and in some instances replace electronics, in order to reduce power dissipation while maintaining device and system performance. Finally, many emerging systems are based on passive sensors that operate with zero standby power and are activated by the energy generated by a specific event or by a remote energy source. Each of these approaches are discussed below:

5.1.1: Low Power Transducers:

Sensors and actuators utilize a number of transduction techniques to convert non-electrical signals into electrical signals. These include piezoresistive, capacitive, piezoelectric, pyroelectric, magnetic, optical, thermal, and others. Each of these approaches requires a specific amount of energy to provide a given level of performance. One of the most efficient approaches that provides high sensitivity and resolution and requires low power is the capacitive approach. The cross section of an air gap capacitive pressure sensor is shown in Figure 12. One plate of the sensor is formed using a metal conductor patterned on a glass support wafer, and the other plate is formed using a thin silicon diaphragm that deflects in response to changing pressure [6]. When the diaphragm deflects the capacitance between the two plates changes thus providing a measure of the capacitance. Other types of sensors, including accelerometers can also be made using this capacitive transduction method [7]. These capacitive sensors do not consume static power and require little power in operation. Many low-power applications use the capacitive approach to minimize power dissipation.

5.1.2 Low-Power IC and System Design:

In addition to using a low-power transduction method, many emerging low-power instruments employ low-power and low-voltage interface and signal processing circuitry to minimize power dissipation [14]. The techniques utilized to achieve low power are similar to what is currently used to design low-power analog and digital circuits. These are not discussed in detail here.

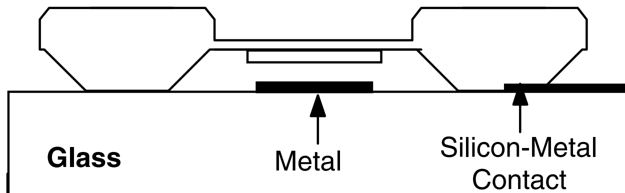

Figure 12: Cross section of a variable air gap capacitive pressure sensor.

5.1.3 MEMS-Based Low-Power IC Design:

MEMS devices are increasingly used to replace electronics in many emerging application to achieve better performance and reduce power dissipation at the same time. One excellent example of this is in telecommunication. Micromachined silicon resonators are being utilized to implement very high Q mechanical filters, high-performance switches, and oscillators [13]. Examples of these devices were shown in Figures 10 and 11. These micromechanical elements can be integrated with integrated circuitry and will eventually produce fully-integrated transceiver chips that provide at least comparable performance but at reduced power dissipation. A detailed discussion of this is provided in [13].

5.1.4 Passive Sensors

One of the most effective ways to reduce power dissipation in microinstruments is to use sensing techniques that require very little or no power for their operation. These passive sensors respond to the parameter being measured without the need for active circuitry. An excellent example of this is in the measurement of acceleration using an array of acceleration-sensitive switches [15]. The SEM of an array of these switches is shown in Figure 13. The switches consist of a proof mass that is suspended over the substrate using tin and flexible oxide beam that anchor it to the substrate. Under acceleration, the proof mass moves until it touches the substrate. At the tip of the proof mass is a metal strip that shorts out two metal lines formed on the substrate when the mass touches the substrate. Note that the sensor does not require power to detect acceleration.

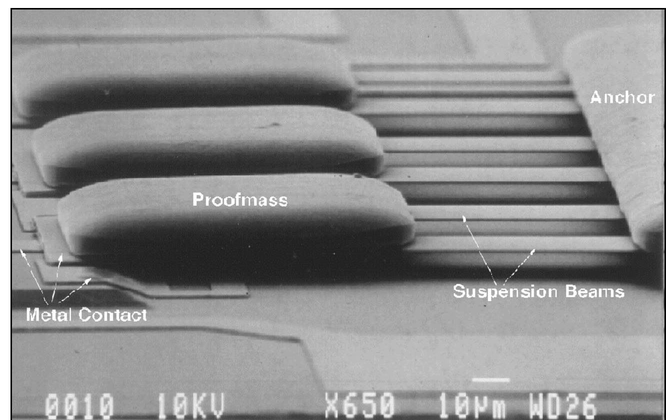

Figure 13: SEM picture of an array of three acceleration sensitive switches [15].

The sense channels can be read out individually or as an output that is a logical combination of individual channels (Fig. 4). This output gets activated when any of a pre-programmed subset of channels sense their inputs switching. Hence, the system output can be used as an "interrupt" or "wake-up call" in smart low-power microsystems to trigger system re-activation from a sleep mode, or a specific service request, in case of 'an acceleration event detection'. The ability of selecting a subset of the channels in this mode of operation enables the system to be user definable to specific thresholds at any instant, as required by the application. Additionally, the interface chip incorporates a bus interface unit that enables it to communicate over a standard sensor bus with a microcontroller [1].

To sense the closing of the switch, a simple circuit as shown in Figure 14 can be used. In the normal mode of operation, the channel is selected and enabled, i.e., transistor M3 is on and M4 is off. M1 and M2 act as a pull up chain for the channel input. To limit the current flow through the input switch, the pull-up is designed to be weak. In fact, M1 is normally shorted, and can be added to the pull up chain by laser trimming if a weaker pull-up is needed. This is particularly important since, instantaneous large current flow through the sensor may cause its contacts to fuse together. Moreover, limited current supply at the input reduces the overall chip power dissipation. The input high-to-low transition is amplified by a CMOS inverter (M5-M6) and latched at the channel output. The signal remains latched until a readout acknowledge signal – such as an interrupt acknowledge signal from an external microcontroller is received. The ultra low-power operation of the interface is obtained by designing for virtually no static current flow in the circuitry, and using an asynchronous design approach. Most of the circuit blocks are digital CMOS, which do not draw static current. Furthermore, application of feedback avoids steady current flow at the channel front-end.

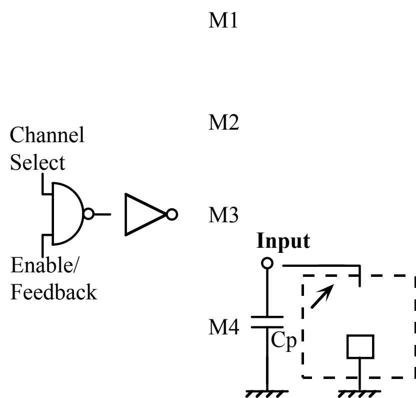

Figure 14: Schematic of a sense channel [15].

In adddition to using passive sensors, many sensing and actuation systems are being developed that can be energized and operated using a remote power source. This is usually done using inductive coupling of energy from an outside transmitter to a receiver coil. These remotely-powered and operated systems can be designed to be very low power, and obviously operate only when energized by the external unit. An example of a multichannel stimulator was shown in Figure 9. Another example of a remote and wireless humidity sensor is given in [16]. Most of these sensors utilize a capacitive transduction method and are very energy efficient and provide high sensitivity for most applications.

5.1.5 Power Sources and Energy Harvesting

Several groups in the US have started programs to develop micromachined power generation microsystems. Many of these use combustion and chemical reaction to convert chemical energy to electrical energy as is typically done in a generator. Many of these efforts are still in their very early stages and have not be published. One of these is the program at MIT on microchemical reactors [17] and also on a turbine jet engine [18]. There are other programs at Georgia Institute of Technology, University of Southern California, and elsewhere. If successful, these micromachined generators provide an energy per weight that is at least 10-100x higher than any current battery technology. This is an exciting technology and in the next few years we will see the results of these efforts. Several efforts are also underway to build micromachined fuel cells. In addition to active power generation, it is also possible to use MEMS to harvest energy from the environment. One example of these that utilizes a micromachined mechanical resonator is discussed in [19]. This micromachined resonator can run a programmable DSP at 1.5V and 560nW of power dissipation. Although this is a very small amount of energy, it is possible to harvest this energy and store it on super capacitors for future use. All of these examples show that a range of research programs are underway to generate power in extremely small microsystems for many future and current portable applications.

6. CONCLUSIONS

The examples given above constitute only a small fraction of the types of systems and devices that can be developed using micromachining and microfabrication technologies. However, they indeed demonstrate the capabilities these technologies can offer by combining sensors, actuators, circuits, communication, and packaging into a miniature unit that can interface with the external world and record a number of parameters of interest. Micromachining is a critical technology in developing these systems as it permits the implementation of small sensors and actuators, and is extensively used to package these systems so that they can operate without loss of performance.

This paper has reviewed some of the most recent advances made in integrated systems. Small size, low-power, wireless operation, and functional versatility are some of the most important requirements at the system level. Fabrication technologies used in many emerging applications for microsystems have to support circuit integration, have to permit the formation of the package at the chip level using batch-processing techniques, and have to be accessible and low-cost. Low-power sensors, interface circuits, and signal processing electronics are being developed to address the needs of emerging consumer applications that require portability and affordability. One of the main challenges to the community working on the continued development of these systems is to transfer the knowledge and technology into real world application. At the heart of this challenge is the ability to develop manufacturing techniques that are capable of producing these instruments at low cost. Commercial products are beginning to appear on the market. This trend will hopefully continue as new applications are developed for this technology and as researchers and the user communities become familiar with the possibilities that micromachined microsystems offer.

7. ACKNOWLEDGMENTS

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