Wireless Integrated Microsystems (WIMS):
Coming Revolution in the Gathering of Information

Kensall D. Wise

Engineering Research Center for Wireless Integrated Microsystems
The University of Michigan
Ann Arbor, MI, USA, wise@umich.edu

ABSTRACT

This paper discusses recent developments in microsystems, including progress in low-power sensing, circuit integration, wireless interfaces, and wafer-level packaging. Increasingly, such systems are realized on two or three chips in stacked configurations or embedded in silicon platforms, customized by the sensors selected and by embedded software. Microsystems for remote data collection, cortical and cochlear prostheses, and environmental monitoring are described, all based on a common architecture. Increasingly, such systems are being implemented using nanotechnology.

Keywords: microsystems, implantable biosystems, neural prostheses, chromatography

1. INTRODUCTION

The use of silicon micromachining for the formation of integrated sensors is now forty years old. It began with neural probes, pressure sensors, and miniature gas analysis systems in the late 1960s [1] and during the 70s expanded to accelerometers, inkjet and thermal print heads, flowmeters, and other devices as technologies such as wafer bonding and bulk etch-stops were developed [2]. The automotive industry took silicon sensors out of the laboratory and put them in high-volume production for electronic engine control, and during the 80s surface micromachining was introduced [3] and applied to accelerometers, micromotors, and a variety of other microstructures. Integrated sensors became known as microelectromechanical systems (MEMS) and became the focal point of major programs worldwide. In the 90s, MEMS proliferated into a number of sub-fields representing different application areas, including optical MEMS, inertial-MEMS, bio-MEMS, RF-MEMS, and microfluidics [4]. Today, many of these areas are evolving into microsystems, where MEMS is joining with micropower circuits and wireless interfaces to realize very small electronic modules capable of measuring a variety of physical parameters, interpreting the data, and communicating the resulting information over a bi-directional wireless link. During the next two decades, such systems will become pervasive in society. They will make the automated gathering of information a reality, extending the electronic connectivity represented by personal communications and the worldwide web to information provided directly by the environment. They will provide button-sized information-gathering nodes for measuring air and water quality, controlling adaptive process tools, improving transportation systems, and revolutionizing health care. Linking microelectronics to the non-electronic world, they will address a wide range of critical societal needs. Figure 1 shows a block diagram of a typical microsystem. Such systems will consist of two or three chips, implemented in novel stacking arrangements or embedded in silicon platforms.

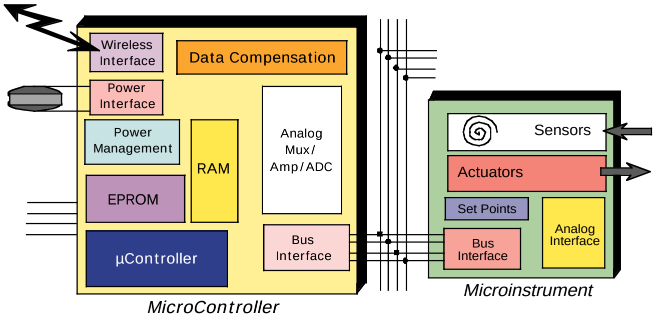

Fig. 1: Block diagram of a typical microsystem.

Wireless integrated microsystems (WIMS) will consist of a power source, an embedded microcontroller, a wireless interface, and front-end sensors/microinstruments. Operating from a generic platform, WIMS will differ primarily in the front-end sensors chosen and in their software. They will pack the sophistication of several major laboratory instruments in the space of a wristwatch, dissipating less than 1mW and communicating over distances from a few inches to a mile or more. This paper will highlight recent developments in microsystems intended for biomedical and environmental applications. Such systems employ a mix of micro- and nano-technology and must balance the conflicting constraints imposed by power sources, process technology, materials, circuit power-speed limits, wireless tradeoffs, and wafer-level packaging.

MICROSYSTEM EXAMPLES

Figure 2 shows one example of a microsystem recently developed for remote data collection [5]. Although this system began as a system for the studying gait dynamics of insects, it has a wide variety of applications in biology and other fields. The system consists of an 8b embedded micro-controller (Xemics XE88LC05), a 16Mb flash memory (Atmel AT45DB161), a custom sensor interface chip, capacitive sensors for pressure, temperature, and humidity, and connectors for off-board silicon neural recording electrodes, EMG electrodes, and piezoresistive strain gauges for neurological and physiological monitoring. These components allow the acquisition and storage of multi-domain data at low power levels (<50μW reading the sensors at 1Hz). The system is programmable in gain (0.4-3.2mV/fF), offset (10b), accuracy (14b), and sampling rate (0.1Hz-10kHz), and is integrated in a silicon platform containing through-wafer interconnects, solder-based microconnectors, and recessed cavities for chip-stacking as shown in Fig. 3. The microsystem measures 9.5mm x 7.6mmx 2.0mm in size (0.15cc).

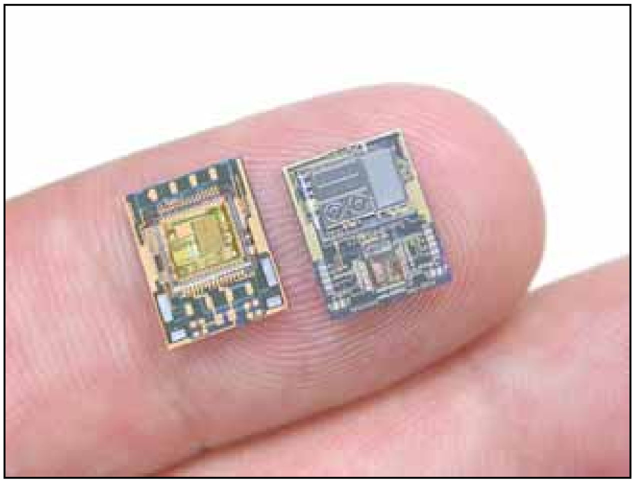

Fig. 2: Top and back views of a microsystem formed from a commercial microprocessor and flash memory together with capacitive sensors for pressure, temperature, and humidity. The microsystem occupies less than 0.5cc, including a 3V coin cell that mounts behind the platform.

Two other examples of multi-chip microsystems can be found in prosthetic devices being developed for improved health care. The first, shown in Fig. 4, is a microsystem for recording control signals from the motor cortex of the brain for possible use in a prosthesis for quadriplegics, activating paralyzed muscles using these signals in conjunction with functional neuromuscular stimulation. In this implementation, the microsystem consists of two- and three-dimensional electrode arrays [6] implanted in the cortex and connected to a subcutaneous electronics package (mounted above the skull) via polymeric cables. The entire system receives power from an external 10MHz RF carrier and system command signals from the modulation of that carrier. Neural signals are recorded by 64 IrO electrodes, amplified by a factor of 1000, and presented to a neural spike processor that separates the spikes from background noise and forms the results in digital data packets that record spike place of origin. These data packets are Manchester encoded and sent to a wireless interface for transmission to the outside world at a data rate of 2Mb/sec on a 100MHz output carrier. The system is programmable for use with either active or passive probes, and spike thresholds can be set positive, negative, or biphasic as desired. In addition to operating in scan mode, the system can also be used in monitor mode, where the signal from any site can be monitored at high resolution. A digital signal processor has also been reported [7] that operates on the multiplexed data from active probes and provides 5b spike shape information to the outside world. Figure 5 shows an 8-channel version of the cortical microsystem along with an input neural spike train, the output of the spike detector, and the on-off keyed output carrier.

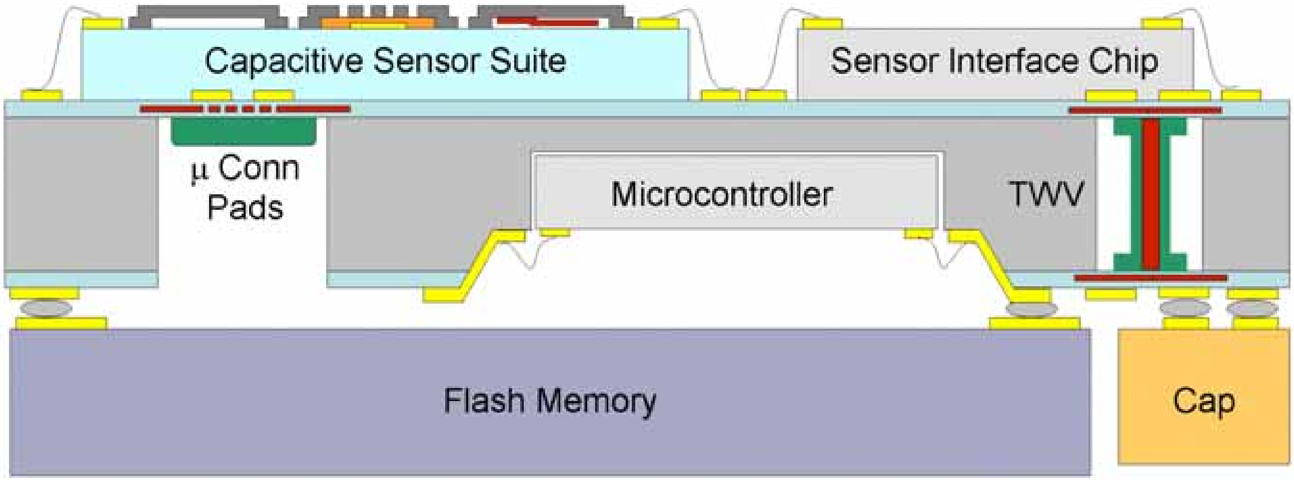

Fig. 3: Cross-section of the microsystem shown in Fig. 2. The silicon platform contains microconnector pads for off-board sensors (left), a cavity that allows the microcontroller to be embedded within the platform (middle), and air-isolated through-wafer vias that carry signals from the sensor interface to the controller (right).

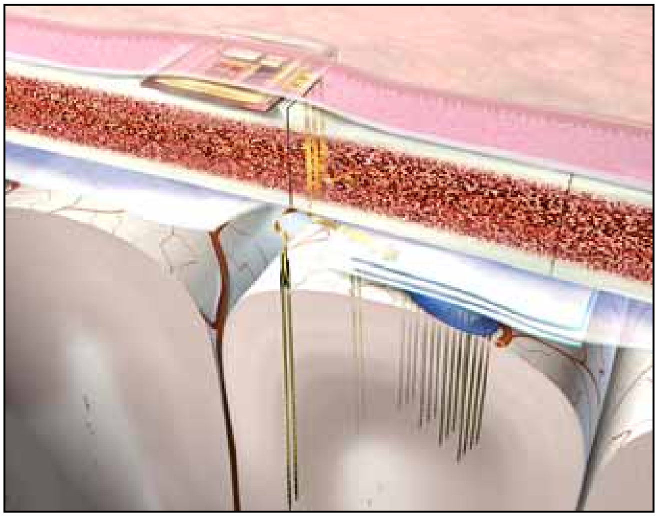

Fig. 4: Diagram of a neural microsystem. The circuit package is subcutaneous, connected to the implanted cortical electrodes by polymeric cables.

The second biomedical example, shown in Fig. 6, has a similar implementation, with an electrode array connected to a hermetically-sealed circuit package using a polymeric cable; however, in this case the system is an advanced cochlear prosthesis for the deaf [8]. The electrode array here consists of 32 IrO stimulating sites supported on a flexible silicon-dielectric-parylene substrate. The probe shown here is 8mm long, sized for use in guinea pig animal trials. A human array would have 128 sites spanning a 32mm length. The sites are on 250μm centers. The array substrate also includes position and wall-contact sensors to minimize insertion damage and facilitate deep insertions in order to span a wide range of perceived frequencies. Hybrid circuitry is mounted on the rear of the array and is used for position sensing, command verification and stimulus current generation. Stimulating currents are generated between 0 and ±500μA on four parallel channels with a biphasic current match of better than one percent and a power dissipation of less than 2.5mW per channel. The minimum pulse width is 4μsec. The electrode connects to the circuit package using an 8-line SPI bus. The circuit package contains a custom microprocessor running the CIS speech-processing algorithm along with a wireless interface similar to that used in the cortical implant. This system represents the first use of thin-film electrodes in a cochlear prosthesis and the first realization of embedded position sensing in such devices.

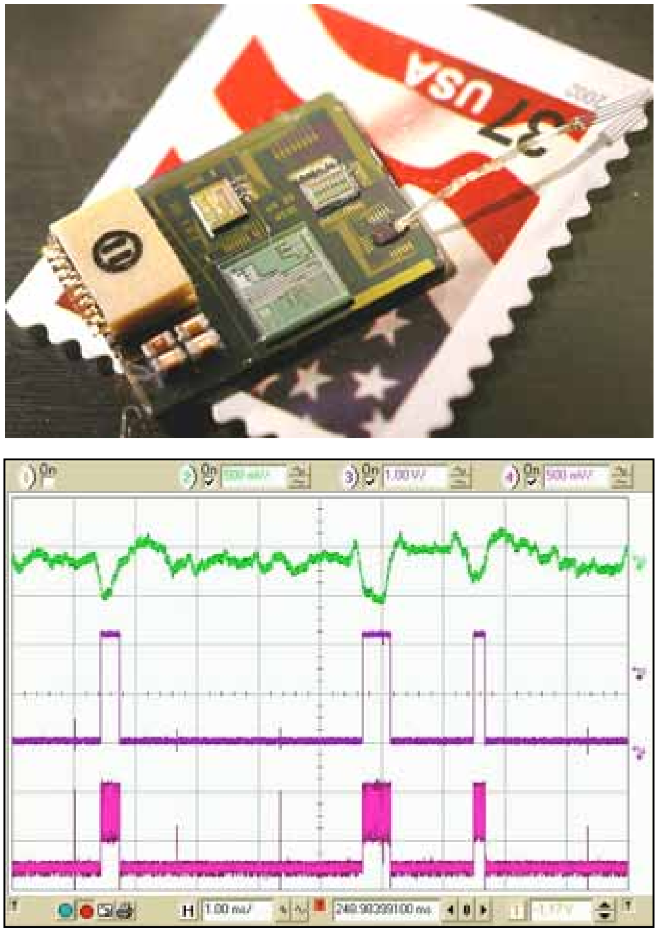

Fig. 5: Top view of an 8-channel cortical microsystem composed of a 2D electrode array, cable, amplifiers, an integrated spike detector, and a wireless interface. A connector is included at the back of the platform for testing here. A low-level neural recording (top trace, at 1msec/div), detected spikes, and on-off-keyed output signal is shown in the lower part of the figure.

Fig. 6: A 32-site 4-channel cochlear microsystem.

A final example is an environmental microsystem for measuring pressure, temperature, humidity, air quality, and other variables. The heart of this system is the integrated gas chromatograph (μGC) shown in Fig. 7 [9]. This microsystem contains two 3m-long separation columns, a pre-concentrator, commercial minivalves, a calibration source, and an output detector, all integrated on an electro-fluidic substrate. It has a footprint similar to that of a credit card. Electrostatic peristaltic pumps and integrated thermo-pneumatic microvalves have been demonstrated for a future version of the system. While initially viewed as a smaller and more portable but perhaps low-performance alternative to commercial devices, we now believe that such systems can perform better in many respects than their than their table-top ancestors. Since the integrated separation columns are ultra-low mass, they can be temperature programmed very rapidly at low power. This can drastically shorten analysis times. C_5-C_{16} alkanes and chemical warfare simulants have been separated in less than 8sec using temperature-programmed 25cm-long columns [10], and ultra-low-mass columns formed using chemical-vapor-deposited dielectrics have shown the ability to operate at 100°C in vacuum.

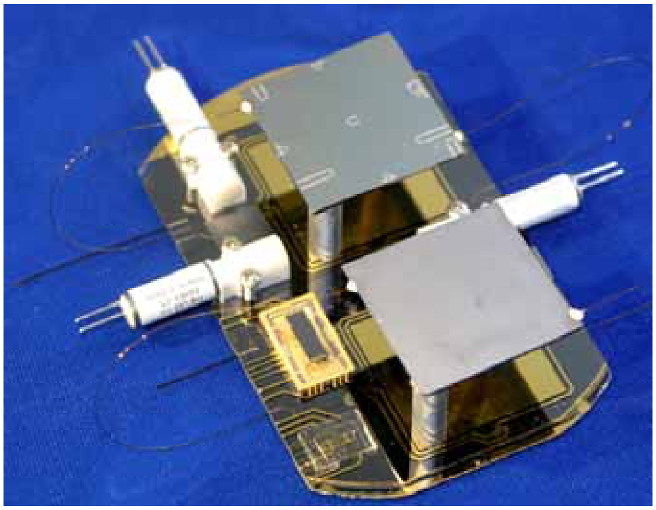

Fig. 7: A prototype gas chromatograph based on temperature-programmed silicon separation columns.

NANOTECHNOLOGY

There is a very fuzzy boundary between micro- and nano-technology; many of the devices reported today as nano are really micro, just as many microdevices have overall dimensions measured in millimeters. However, increasing amounts of nanotechnology are finding their way into microsystems, even excluding the submicron dimensions of the microelectronics itself. The microelectrode arrays described above depend critically on interfacing with tissue at the cellular level, and those interfaces depend on a variety of nanoscale phenomena, including coatings capable of preventing protein encapsulation of the sites. The electrodes themselves may eventually shrink to submicron dimensions in order to minimize tissue displacement, even though the sites themselves will likely continue to have larger dimensions. In the µGC, carbon nanotubes are being explored for very high surface area absorbers in the preconcentrator and gold-thiol nanoparticles are the basis for the detectors being used today. This trend toward microsystems based on nanotechnology will only continue to expand in the years ahead.

Acknowledgments

The author wishes to thank the many faculty, staff, and students at the University of Michigan that contributed to the microsystems described here, including. K. Najafi, E. T. Zellers, M. P. Flynn, R. B. Brown, R. Sacks, D. Kipke, A. Sodagar, J. F. Hetke, M. N. Gulari, R. Gordenker, D. F. Lemmerhirt, R. Olsson, G. Perlin, Y. Yao, J. Potkay, M. Agah, G. R. Lambertus, K. Beach, P. T. Bhatti, and J. Wang. This work was supported primarily by the Engineering Research Centers Program of the National Science Foundation under Award Number EEC-9986866 and by the Neural Prosthesis Program of the National Institute of Neurological Disorders and Stroke under Contract HHSN265200423631C.

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