Foreword

THE RAPID ADVANCES made by integrated electronics during the past decade are now having significant and far-reaching impacts on many areas of society. Led by increasingly sophisticated low-cost microcomputers, microelectronics is stimulating rapid progress in data processing, telecommunications, consumer products, industrial process control, transportation, and health care. Many of the most important new applications for electronics, particularly in the last three areas, involve the development of instrumentation and control systems. For many such systems, the signal-processing needs can already be met using existing microcomputers. The greatest challenges for present and future systems are not the processor or its memory, but instead are associated with the system periphery and, in particular, with the sensors and actuators needed to interface the electronic system to a nonelectronic world. In terms of performance, reliability, and even cost, sensors and actuators are the weak link in many systems and determine the feasibility of extending electronics into new areas. This Special Issue on Solid-State Sensors, Actuators, and Interface Electronics is intended to highlight the present state of the art in solid-state sensors and, it is hoped, to stimulate further work in an area of increasing importance to a wide variety of applications for microcomputer-based electronic systems.

Until very recently, solid-state sensors and actuators were, for the most part, neglected by the bulk of the electronics industry, and no particular pressure existed for increased development efforts in this area. Even in systems where such components were needed, only a few were generally required, and since the cost of the control electronics was relatively high, the high cost of a few sensors did not significantly impact the system. Sensors, therefore, tended to remain low-volume, high-cost, individually calibrated devices, fabricated using structures and techniques which were not very compatible with high-volume batch processing. With the development of the microcomputer, however, this situation has changed drastically. First, the cost of signal-processing electronics has plunged and its sophistication has rapidly increased. Second, the number of systems requiring sensors has soared as electronics has pervaded many new areas. These two factors have suddenly forced the sensor area into a position of primary importance in the development of next-generation systems. Although many of the comments here are directed to sensors, in most cases they are valid for actuators as well.

The application of silicon integrated-circuit technology to the development of high-performance, low-cost sensors has been the focus of many recent efforts. Silicon is known to be a highly effective material for transducing many physical effects, including light levels, force, and temperature. Silicon process technology is highly developed and well suited to high-volume production. Work on high-performance linear circuits such as data converters has shown the technology to be capable of the high precision required for many sensing applications. Since transducers are typically devices producing low-level analog outputs, some signal conditioning (e.g., amplification or encoding) is often required before transmission to the digital world of the microprocessor. With silicon sensors, the designer has an additional degree of freedom created by the ability to integrate signal-conditioning circuitry into the transducer chip itself. This Special Issue illustrates the results of many innovative efforts in the area of silicon sensors and underscores the enormous versatility of silicon technology for a wide variety of applications.

The use of microcomputers in virtually all new instrumentation systems has not only increased the need for high-performance sensors, it has also changed the emphasis in sensor design. When the system control electronics were relatively simple, it was essential that the sensor output be a simple function of the variable to be measured. This meant that sensitivity to secondary variables such as temperature had to be eliminated and a linear response to the primary variable was very important. With the advent of the microcomputer, design emphasis has shifted from linearity and secondary parameter compensation to predictability and stability. Nonlinearity and sensitivity to secondary variables can be corrected by the processor so long as the response characteristics are known and stable and so long as the secondary variables can be independently measured. Thus some present and many future sensing chips can be expected to incorporate several transducers, measuring the secondary as well as the primary parameters and either compensating the primary variable on-chip or passing all the results to the external processor. No longer an isolated component, sensors are now being designed from the start to work in concert with a microcomputer to achieve the best in overall system performance. The importance of viewing the sensor, which includes both the transducers and some signal-conditioning electronics, as a system element is emphasized. Two-way communication between the sensor and the microcomputer is now being explored for many systems, and with it the possibilities of remote testing, autocalibration, and multiparameter measurements. Thus the sensing area is evolving rapidly to incorporate a variety of system concepts.

This issue begins with an invited paper which highlights many of the tradeoffs facing future sensor development. The important automotive area is discussed, and several approaches to implementing real-time engine control are examined. In the following paper, a new NO_x sensor needed for engine control is discussed.

The use of anisotropic etching to shape silicon microstructures is a key element in many sensor designs, and the next six papers make use of it for a variety of applications. The first paper, which is an example of innovative sensor design in silicon, describes a complete gas chromatographic air analyzer

0018-9383/79/1200-1861$00.75

(including the separator column, valves, and detector) integrated on a single wafer. The next three papers deal with pressure sensors. The first paper analyzes the pressure sensitivity of anisotropically etched piezoresistive and capacitive pressure sensors and examines the sources of device-to-device variability in these structures. The second paper presents a piezoresistive device intended for chronic biomedical applications, focusing on long-term stability and its relationship to device design and packaging. In the third paper, the integration of active signal conditioning circuitry on a piezoresistive pressure sensor is considered for a multisensor catheter application requiring a device of minimum size with multiplexed outputs. Package design is also critical for accelerometers, and the next paper describes a miniature accelerometer which employs a silicon cantilever in a cavity sealed using silicon-glass electrostatic bonding techniques. Anisotropic etching and electrostatic sealing are again illustrated in the next paper, which deals with the batch fabrication of ink-jet printing devices.

The issue continues with a paper examining acoustic transducer arrays using integrated silicon PVF_2 structures, and this is followed by a paper in which the precise lithographic capabilities developed for integrated circuits are applied to another sensing array: microelectrodes designed to interface with the nervous system at the cellular level and fabricated using tantalum-on-sapphire technology.

The use of solid-state electrode structures for the direct measurement of ion concentrations in solution is the subject of the next several papers. Ion-sensitive field-effect transistor structures, in which the solution is allowed to contact the gate dielectric, are explored in the first paper, which reports results for *p*H measurement with several inorganic gate dielectrics. The following papers report a gate-controlled diode structure for similar measurements, examine capacitive electrode structures, and discuss some of the electrochemical effects which occur at the dielectric–solution boundary. There is high interest now in ion-concentration monitors using silicon-based structures, and these papers illustrate some of the present thinking and results which have been achieved.

The issue concludes with two papers in the area of photodetection. The first paper examines the use of silicon p-n junction photodiodes for sensing in the ultraviolet, while the second paper discusses imaging sensors using static induction transistor structures.

We would like to extend our sincere thanks to the many individuals who contributed to this Special Issue. First, our appreciation goes out to the authors, who worked hard to meet the publication deadlines and who provided a set of innovative papers which well represent both the depth and the breadth of the silicon sensor area. Secondly, we would like to thank the many reviewers for this issue, who gave unselfishly of their time and contributed a great deal to the accuracy and clarity of the papers presented here. Finally, as editors we hope that this issue will provide its readers with a greater appreciation for the problems and potential of solid-state sensors and perhaps will stimulate increased work on the new structures and designs which will be needed to meet the needs of next-generation electronic systems.

James D. Meindl
Kensall D. Wise
Guest Editors

James D. Meindl (M'56–SM'66–F'68) received the Ph.D. degree in electrical engineering from Carnegie-Mellon University, Pittsburgh, PA, in 1958.

He was initially employed by the Westinghouse Electric Corporation and the Autonetics Division of North American Aviation. On military duty with the U.S. Army Electronics Command he was Head of the Microelectronics Section and subsequently as a civilian became Director of the Integrated Electronics Division. From 1960 to 1967 he was also concurrently a Lecturer on Solid-State Electronics at Monmouth College, West Long Branch, NJ. He was recognized by the Arthur S. Fleming Commission in 1967 as one of the ten outstanding young scientists working for the Government. He is a Professor of electrical engineering, Director of the Integrated Circuits Laboratory and Center for Integrated Electronics in Medicine, and Director of the Stanford Electronics Laboratories at Stanford University, Stanford, CA. He is the author of a book on micropower circuits and over 150 technical papers on integrated circuits, micropower circuits, and medical electronics. His current research interests focus on the application of integrated-circuit technology in medical electronics.

Dr. Meindl is a Fellow of the American Association for the Advancement of Science, was Editor of the IEEE Journal of Solid-State Circuits from 1966 to 1971, Chairman of the 1969 International Solid-State Circuits Conference, recipient of the IEEE Solid-State Circuits Council in 1972, and General Chairman of the 28th Annual Conference on Engineering in Medicine and Biology (1975). He is a member of Tau Beta Pi, Eta Kappa Nu, Sigma Xi, and Phi Kappa Phi, as well as the AAAS, The Electrochemical Society, The Biomedical Engineering Society, the American Institute of Ultrasound in Medicine, and the National Academy of Engineering.

Kensall D. Wise (S'61-M'69) received the B.S.E.E. degree from Purdue University, Lafayette, IN, in 1963, and the M.S. and Ph.D. degrees in electrical engineering from Stanford University, Stanford, CA, in 1964 and 1969, respectively.

From 1963 to 1965 (on leave 1965-1969) and from 1972 to 1974, he was a Member of the Technical Staff of Bell Telephone Laboratories, where his work was concerned with the exploratory development of integrated electronics for use in telephone communications. From 1965 to 1972 he was a Research Assistant and then a Research Associate and Lecturer in the Department of Electrical Engineering at Stanford, working on the development of integrated-circuit technology and its application to solid-state sensors. In 1974 he joined the Department of Electrical and Computer Engineering at The University of Michigan, Ann Arbor, where he is now serving as Director of the Electron Physics Laboratory. His present research interests focus on integrated circuits and the application of integrated-circuit technology to solid-state sensors and microcomputer-controlled instrumentation.

Dr. Wise is a member of the Electrochemical Society, Tau Beta Pi, Eta Kappa Nu, and Sigma Xi.