INTEGRATED SENSORS: INTERFACING ELECTRONICS TO A NON-ELECTRONIC WORLD

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Abstract

This paper considers the rapidly-developing field of integrated sensors, in which one or more transducers are joined with custom interface circuitry on a single chip Many of the issues confronting continued development in this area are discussed, including process compatibility and circuit partitioning Backed by an increasingly powerful array of solid-state process technologies, integrated sensors are expected to be widely applied to extend microcomputer-based control in a variety of areas

Introduction

It has been less than twenty-five years since the first monolithic solid-state devices were realized using the planar process, but the tremendous progress shown by the emerging field of microelectronics is well known The functional sophistication of monolithic circuits has gone from a single device to literally hundreds of thousands of devices per chip Photolithographic dimensions have decreased more than an order of magnitude, and the speed of individual devices is now pushing below 100 ps These developments, when combined with rapidly-decreasing functional cost and greatly improved reliability, have sparked the application of electronics in a wide number of areas, including those in transportation, industrial automation, robotics, health care and information processing Most forecasts anticipate a continuation of recent progress for at least another decade [1]

For many applications, even the present state of the art in logic and memory presents no barrier to the practicality of new systems Microcomputers are already fast enough, powerful enough and inexpensive enough to allow considerable progress, and combined with monolithic data converters at the 12-bit level and beyond, they offer sufficient accuracy for most applications For many systems the principal barrier to the application of electronic instrumentation lies not in the control area but rather in the periphery, where sensors and actuators are critically needed to couple the microcomputer to a non-electronic world Present sensors frequently lack the accuracy, resolution, speed, reliability and low cost necessary to allow full advantage

to be taken of the increasing performance levels of microcomputers and are not adequate for many electronic applications Unless activity in the sensor/actuator area increases rapidly, this situation will only become more evident as intensive efforts to develop more sophisticated microcomputers continue

Activity in the sensor area is now expanding, and this paper will comment on a segment of the sensor field where many of the new efforts are being focused — the area of integrated sensors We define an integrated sensor as one or more transducers joined with appropriate interface circuitry on a single monolithic chip The transducers can be formed from a variety of materials, although in most cases the substrate will be silicon The goal of this approach is clearly to take advantage of the broad array of process technologies available for silicon integrated circuits, extending this technology where needed to realize the required sensor The development of integrated sensors in many respects can be expected to parallel that of integrated circuits, and integrated sensors offer many of the same advantages, including high reliability, small size, low cost, high performance and system compatibility Of these, high reliability may be the most important — at least for many applications — and it is achieved for sensors in the same way as for integrated circuits (reliable devices, a stable process, no moving parts, few off-chip interconnections) Since the processes are batch, small device size is coupled to low cost but is additionally important in many applications such as those in biomedicine, where size may be paramount Finally, the ability to amplify and pre-process the transducer signals before presenting them to the cables leading to the microcomputer reinforces low cost, high-performance and high reliability Not only can less expensive multiplexed leads be used, but the correction of secondary-parameter sensitivities is also facilitated

Some of the integrated sensors now under development are listed in Table 1 Work on most of these dates back to the mid-1960s, when planar technology first began to be applied to the sensing area Visible imagers are the most highly-developed integrated sensors at present, offering color imaging of excellent quality [2, 3] While cost is still very high for large arrays, these structures are the focus of intense development efforts aimed at penetrating the home-photography market and cost should decline rapidly over the next few years Pressure transducers are in high-volume production at several companies for applications in industrial automation and automotive engine control On-chip electronics has been used for at least one commercial pressure sensor and other manufacturers are expected to follow suit Most of the other transducer types are in various stages of exploratory development or low-volume production Several collections of papers in this area have recently been published [4]

Integrated sensor challenges

There are many goals on which to focus continued development efforts in the sensor area These may be looked on as challenges or opportunities, depending on one's perspective Some of these goals are listed in Table 2 In

TABLE 1

Integrated sensors under development

Visible imaging	Temperature
Infrared imaging	Moisture/humidity
Pressure	Gas composition
Acceleration	Ionic concentration
Position	Magnetic field
Flow	Potential distribution

TABLE 2

Challenges and issues in the continued development of integrated sensors

Process compatibility
Synergistic transducers and circuits
Appropriate circuit partitioning
Environmental factors
New transduction mechanisms

order to ensure high reliability and acceptable production yields, it is essential that any integrated sensor be based on a sequence of fabrication steps which are compatible In general, this will mean defining processes which depart from the conventional integrated-circuit processes as little as possible Visible imagers are an example of sensors which do this (and one where packaging is relatively simple) and which have consequently developed rapidly Lack of a truly suitable process has been an important factor in keeping many devices in the laboratory and away from production in the past

As transducers and circuits are merged into single structures, process compatibility will remain important and the need for synergism among the various system elements will grow For example, one approach to correcting for non-linearity or secondary-parameter sensitivity in a transducer is to build-in a compensating effect in the interface circuit Since temperature is the most troublesome secondary parameter and can be measured independently, the design of a circuit for such compensation on- or off-chip is possible [5]

The amount of electronics to be added to a transducer chip is now being debated, and the results will certainly be strongly application dependent But we are apt to see increasing amounts used, just as has occurred in integrated circuits The difference in cost or reliability between a six-transistor circuit on-chip and a six-hundred-transistor circuit on-chip is not likely to be significant, so that if the additional hardware buys anything in terms of performance or system compatibility, it will be likely to evolve Many, and probably most, applications will benefit from some on-chip circuitry in the form of amplification and conditioning

Physical parameters such as radiation, temperature, acceleration and magnetic field strength are relatively easy to couple to integrated sensors without significant extensions of current packaging technology For other parameters such as ion concentration, gas composition and flow, packaging may be more difficult, and while progress is being made, packaging remains a major area of concern for many devices [6] In some areas, packaging can dominate both cost and reliability, however, the use of on-chip circuitry can be expected to ease the packaging requirements in many areas [7] In some cases, this may be the principal reason for its initial adoption

An environmental factor capable of imposing a more fundamental barrier is temperature For bulk silicon circuits, 200 °C is a practical upper limit

on operating temperature Silicon-on-insulator technologies may push this to 300 °C [8], and still higher temperatures may be achieved using other semiconducting films Alternatively, the search for alternative transducers, measurement approaches or measurement sites can also be productive The search for new and more stable transduction mechanisms is very important and may be facilitated by the recent development of material growth techniques such as molecular-beam epitaxy and metallo-organic chemical vapor deposition

The challenges facing the development of integrated sensors promise some interesting design choices, and each evolution in the resulting devices can be expected to open significant new application areas for electronics or allow significantly improved performance As VLSI technology continues to expand, it will probably offer increasingly exciting challenges for integrated sensors and work on the interdisciplinary materials, processes and circuits needed for sensors may well result in technology spin-offs back into more traditional areas of logic and memory as well

Some examples

Process compatibility

There are two principal areas where present integrated sensors have extended standard integrated-circuit processes significantly These deserve special mention The first is in the area of silicon etching (i e , micromachining) to shape the silicon substrate in a particular way [9, 10] Many sensors require such procedures, and the most common structure is that of a thin silicon diaphragm formed selectively in a much thicker wafer by chemical etching Typical diaphragm thicknesses range from 30 μm or so down to less than 1 μm Since these must be formed in a batch process with high yield from wafers 200 - 400 μm thick, some form of etch control is typically required Such structures are required for reverse-illuminated imagers, thermal detectors, accelerometers, pressure sensors and several other devices

Silicon may well have unique capabilities for precision chemical etching Early work with isotropic etchants has largely given way to the use of anisotropic etchants in order to escape the agitation sensitivity of the former solutions Increasingly practical methods for monitoring and/or controlling the diaphragm thickness have evolved using infrared transmittance, V-groove and etch-stop techniques [11] The last technique is illustrated in Fig 1 Here, a selectively-diffused boron buried layer is used to stop the etch This technique relies on the fact that a concentration of boron in the silicon lattice above about 5×10^{19} cm^{-3} is sufficient to completely stop dissolution in ethylene-diamine-based etchants [12] This makes the accurate control of diaphragm thickness a matter of controlling the thickness of the epitaxial layer, which is far more tractable than trying to stop on a thin layer using etch rate alone

p- TYPE SENSING RESISTORS

n SUBSTRATE

p⁺ BORON BURIED LAYER

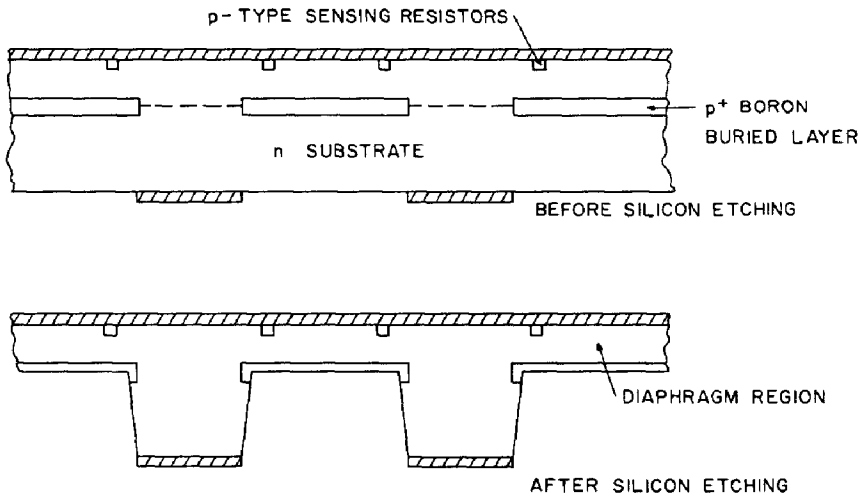BEFORE SILICON ETCHING

DIAPHRAGM REGION

AFTER SILICON ETCHING

Fig 1 Diaphragm thickness control using boron buried-layer techniques

While the boron etch-stop has many advantages, it has a few drawbacks as well If the boron doping level is too low, the etch will not stop, however, if the boron concentration is too high, it may be difficult to maintain high epitaxial layer quality in the face of outdiffusion and dislocations/stacking faults over the buried layer The electrochemical etch-stop [13] uses a voltage applied across a p-n junction to induce a stop, eliminating the need for a highly-doped buried layer and its associated problems Using this technique, uniform diaphragms can be formed reproducibly with high yields

A second area where it has been necessary to extend conventional silicon processing has been in the use of non-silicon transducer materials, usually in thin-film form The use of thin-film resistors on silicon has been common for several years in the data converter area, and thin-films have recently been used to realize infrared detectors [14], piezoelectric accelerometers [15] and a variety of other devices [3, 4] Figure 2 shows a portion of a bismuth-antimony thermocouple array used as an infrared detector It is likely that the utilization of thin-film transducer arrays has only just begun, and that it will become increasingly common over the next few years Again, these efforts will be heavily reinforced by processes such as vacuum evaporation, sputtering, ion-beam deposition and chemical vapor deposition, which were primarily developed for integrated circuits In both silicon shaping and thin-film transducer formation, we have evolved to the point where compatible processes are possible

Interface circuit functions

Most integrated transducers appear either resistive or capacitive to their interface circuitry, and this circuitry may take quite different forms in the two cases While aimed at the same physical parameter and having similar structures, resistive and capacitive sensors can exhibit quite different performance characteristics Such structures now offer competing alternatives

Fig 2 A monolithic thin-film thermocouple array [14] Alternating leads of bismuth and antimony are photolithographically defined on a 1 μm-thick silicon membrane The leads are 10 μm wide and are interconnected by Cr–Au tabs The membrane is formed by a diffused boron etch-stop and selective chemical etching Membrane texture is thought to be due to dislocation-induced diffusion spikes (Shown in transmitted and reflected light)

for the measurement of pressure [7, 11], acceleration [16, 17] and other parameters Capacitive pressure sensors, for example, offer approximately an order of magnitude more pressure sensitivity for a similar die size [7, 18] when compared to their piezoresistive counterparts with nearly two orders of magnitude less temperature sensitivity, however, they are also more non-linear and the full-scale capacitance changes (a few picofarads) demand on-chip circuitry capable of reliably detecting capacitance shifts of a few femto-farads Such sensors are only now becoming practical and depend critically on the development of temperature-stable synergistic interface circuits

In general, interface circuitry can do much more than signal condi-tioning, and some of the possible functions are shown in Table 3 Reducing the number of leads can be critically important in terms of cost and system practicality While visible imaging arrays are again the most highly-developed example, there are many others involving fewer transducers A system-campatible output format is very important, and where operating bandwidths permit, there appears to be an evolution from analog-amplitude formats to variable pulse-rate schemes (e g , FM) and perhaps toward the use of on-chip data converters Secondary parameter compensation can be on-chip (using circuitry designed for a particular temperature as well as electrical response) or off-chip (using independent transducers and a multiplexer to an external processor) While few present sensors now allow remote testing, it is certainly possible and underscores the fact that we are increasingly concerned with

TABLE 3

Interface circuit functions in integrated sensors

Reduce external leads
Compatible output format
Signal conditioning
Secondary parameter compensation
Remote testing

sensing systems While physically small, these systems will grow in sophistication to include many features once restricted to large electronic systems, provided that system performance improves as a result

Conclusions

Integrated sensors hold the key to the application of microcomputer-based electronic control in a variety of areas, and the development of sensors for a wide variety of physical parameters has been intensifying recently on a world-wide basis The issues in the continued development of such devices are many, several of which have been discussed in this paper There is a continuing need for process compatibility, involving better materials and techniques Synergistic transducers and circuits must be developed to optimize overall system performance, and in many cases this will demand on-chip circuitry How much electronics to put on the chip will depend on the applica-ation, but the amount is expected to grow as transducer arrays are increasingly employed Some efforts at output standardization are needed as well as work to allow increased versatility and dynamic range from known transducers Better packaging is a continuing need, as are improved transduction mechanisms and device structures In many areas, the use of better models will be necessary both to allow design optimization and to increase our understanding of the complex interactions present in many sensing structures Finally, sensors must be regarded as sensing systems which are an extension of a central processor Optimal system partitioning and a designed-in testability will be important

The sensor area is interdisciplinary and in the past has been highly proprietary Both aspects have undoubtedly held back its evolution While there are certainly many other segments of sensor research in addition to the approach discussed here, solid-state process technology is so highly developed that integrated sensors are likely to receive increasing attention and are expected to be used more and more widely As this occurs and as sensors become a more integral part of the overall microelectronic scene, the free interchange of ideas and approaches will become more common, accelerating the development process It is hoped that some of the ideas presented here will serve to stimulate thought and discussion during this process While the broad sensor area is likely to remain interdisciplinary, it is through such broad-based research in new materials, processes and circuits that we can expect not only progress in sensors but in VLSI itself

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Biography

Kensall D Wise received the BSEE degree from Purdue University in 1963, and the M S and Ph D degrees in electrical engineering from Stanford University, Stanford, California, in 1964 and 1969, respectively From 1963 to 1965 (on leave 1965 - 1969) and from 1972 to 1974, he was a Member of Technical Staff at Bell Telephone Laboratories, where his work was concerned with the exploratory development of integrated electronics for use in

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