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SMART SENSORS

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Abstract

This report discusses general architecture of smart sensor and the usefulness of silicon technology in smart sensor. This report also pays attention to the importance and adoption of smart sensors. In addition to this an effort is made to present the design consideration of smart sensor as per the functions performed. The discussion will conclude with some examples of smart sensor.

1. Introduction

The advent of integrated circuits, which became possible because of the tremendous progress in semiconductor technology, resulted in the low cost microprocessor. Thus if it is possible to design a low cost sensor which is silicon based then the overall cost of the control system can be reduced .We can have integrated sensors which has electronics and the transduction element together on one silicon chip. This complete system can be called as system-on-chip .The main aim of integrating the electronics and the sensor is to make an intelligent sensor, which can be called as smart sensor. Smart sensors then have the ability to make some decision. Physically a smart sensor consists of transduction element, signal conditioning electronic and controller/processor that support some intelligence in a single package [1]. In this report the usefulness of silicon technology as a smart sensor, physical phenomena of conversion to electrical output using silicon sensors, characteristics of smart sensors. A general architecture of smart sensor is presented.

2. Definition [1]

Smart sensors are sensors with integrated electronics that can perform one or more of the following function

logic functions,
two-way communication,
make decisions.

3. Usefulness of Silicon Technology in Smart Sensor

There are very convincing advantages of using silicon technology in the construction of smart sensor. All integrated circuits employ silicon technology. A smart sensor is made with the same technology as integrated circuits. A smart sensor utilizes the transduction properties of one class of materials and electronic properties of silicon (GaAs). A transduction element either includes thin metal films, zinc oxide and polymeric films. Integrating electronics circuits on the sensor chip makes it possible to have single chip solution. Integrated sensors provide significant advantages in terms of overall size and the ability to use small signals from the transduction element [1]. The IC industry will get involved in smart sensor if a very large market can be captured and the production of smart sensor does not require non-standard processing steps.

3.1 Signal conversion effects

We know that silicon shows a suitable physical signal conversion effect. Many of the physical effects of silicon can be used in making sensors. Based on these effects, different types of sensors can be constructed which can be used for measuring different physical and chemical measurand.
Table1 below shows how different non electrical signal in which we can classify different measurand and Table 2 shows the physical effects for sensors in silicon [2].

Table 1

Signal Domain	Examples
Radiant Signals	Light intensity,polarization,phase,wavelength
Mechanical Signals	Force ,pressure,flow,vaccum,thickness
Thermal Signals	Temperature , Temperature gradient,heat
Chemical Signals	Concentration,pH,toxicity
Magnetic Signals	Field intensity ,flux density,permeability

Table 2

Signal Domain	Examples
Radiant Signals	Photovoltaic effect, photoelectric effect, photoconductivity, and photo magneto-electric effect.
Mechanical Signals	piezoresistivity
Thermal Signals	Seebeck effect,temperature dependence of conductivity
Chemical Signals	Ion sensitive field effect
Magnetic Signals	Hall effect,magnetoresistance

One problem with silicon is that its sensitivities to strain, light and magnetic field show a large cross-sensitivity to temperature. When it is not possible to have silicon with proper effect, it is possible to deposit layers of materials with desired sensitivity on the top of a silicon substrate. Thus we can have a magnetic field sensor by depositing Ni-Fe layer on the top of a silicon substrate.

3.2 Different Silicon Sensors Employing Above Effects

Radiant Signal Domain

Silicon can be used to construct a sensor for sensing wide range of radiant signal from gamma rays to infrared. Silicon can be used for the fabrication of photoconductors, photodiode, and phototransistor or to detect nuclear radiation [2].

Mechanical Signal Domain

Silicon can be used for measuring force and pressure because of the piezo-resistance effect. This effect is large because the average mobility of electrons and holes in silicon is strongly affected by the application of strain. Silicon can also be used for the measurement of air or gas velocities. If we slightly heat a silicon structure having two temperature measuring devices, and is brought into airflow then the resulting a temperature difference is proportional to the square root of the flow velocity. Combining a piezoresistor, diffused in a cantilevered beam or a piezoelectric layer with silicon can make a miniature accelerometer [2]. By photoelectric principle one can find angular position by employing two photodiodes (i.e. one for X co-ordinate and other for Y) [2].

Thermal Signal Domain

We know that all electron devices in silicon show temperature dependence, this property of silicon can be used for the measurement of temperature. This can be achieved by using two bipolar transistors with a constant ratio of emitter current. Another way of measuring temperature is to integrate thermocouples consisting of evaporated aluminium films and diffused p-type and n-type layers. This is possible because Seebeck in silicon is very large [2].

Magnetic Signal Domain

Silicon is a non –magnetic material but it can be used for the construction of Hall plates and transistor structures that are sensitive to magnetic fields. These sensors are constructed by depositing a thin magnetic Ni-Fe film on top of silicon chip that also contains electronic circuits.

Chemical Signal Domain

The demand for the better process control for bio-medical, automotive and environmental applications has encouraged many laboratories to undertake silicon chemical sensor. The ion-sensitive FET (ISFET) is best suitable for such application. When an ISFET with properly chosen ion-sensitive gate insulators is immersed in an electrolyte,the change of the drain current is a measure of the concentration of the ions or the pH.Chemical sensors can be used as humidity sensor or gas sensor[2].

3.3 Suitable Silicon Processing Circuit Using Silicon

The silicon sensor can produce output as voltage, current, resistance or capacitance, output format can be analog or digital. Suitable signal conditioning circuits along with processor can easily designed using silicon technology.

4. Importance and Adoption of Smart Sensor

The presence of controller/processor in smart sensor has led to corrections for different undesirable sensor characteristics which include input offset and span variation, non-linearity and cross-sensitivity. As these are carried in software, no additional hardware is required and thus calibration becomes an electronic process. Thus it is possible to calibrate the batches of sensor during production without the need to remove the sensor from its current environment or test fixture [5].

4.1 Cost improvement

In case of smart sensor inside hardware is more complex in the sensor on the other hand it is simpler outside the sensor. Thus the cost of the sensor is in its setup, which can be reduced by reducing the effort of setup, and by removing repetitive testing.

4.2 Reduced cost of bulk cables and connectors

Use of smart sensor has significantly reduced the cost of bulk cables and connectors needed to connect different blocks (i.e. electronic circuits).

4.3 Remote Diagnostics [5]

Due to the existence of the processor with in the package, it is possible to have digital communication via a standard bus and a built in self-test (BIST). This is very helpful in production test of integrated circuits. This diagnostic can be a set of rules based program running in the sensor.

4.4 Enhancement of application [1]

Smart sensor also enhances the following applications:

- Self calibration
- Computation
- Communication
- Multisensing

Self calibration:
Self-calibration means adjusting some parameter of sensor during fabrication, this can be either gain or offset or both. Self-calibration is to adjust the deviation of the output of sensor from the desired value when the input is at minimum or it can be an initial adjustment of gain. Calibration is needed because their adjustments usually change with time that needs the device to be removed and recalibrated. If it is difficult to recalibrate the units once they are in service, the manufacturer over-designs, which ensure that device, will operate within specification during its service life. These problems are solved by smart sensor as it has built in microprocessor that has the correction functions in its memory.

Computation:
Computation also allows one to obtain the average, variance and standard deviation for the set of measurements. This can easily be done using smart sensor. Computational ability allows to compensate for the environmental changes such as temperature and also to correct for changes in offset and gain

Communication:
Communication is the means of exchanging or conveying information, which can be easily accomplished by smart sensor. This is very helpful as sensor can broadcast information about its own status and measurement uncertainty.

Multisensing:
Some smart sensor also has ability to measure more than one physical or chemical variable simultaneously. A single smart sensor can measure pressure, temperature, humidity gas flow, and infrared, chemical reaction surface acoustic vapor etc [1].

4.5 System Reliability [1]

System reliability is significantly improved due to the utilization of smart sensors. One is due to the reduction in system wiring and second is the ability of the sensor to diagnose its own faults and their effect.

4.6 Better Signal to Noise Ratio

The electrical output of most of the sensors is very weak and if this transmitted through long wires at lot of noise may get coupled. But by employing smart sensor this problem can be avoided.

4.7 Improvement in characteristics [2]

Non-linearity: Many of the sensors show some non-linearity, by using on-chip feedback systems or look up tables we can improve linearity.

Cross-sensitivity: Most of the sensors show an undesirable sensitivity to strain and temperature. Incorporating relevant sensing elements and circuits on the same chip can reduce the cross-sensitivity.

Offset: Offset adjustment requires expensive trimming procedures and even this offsets tend to drift. This is very well reduced by sensitivity reduction method.

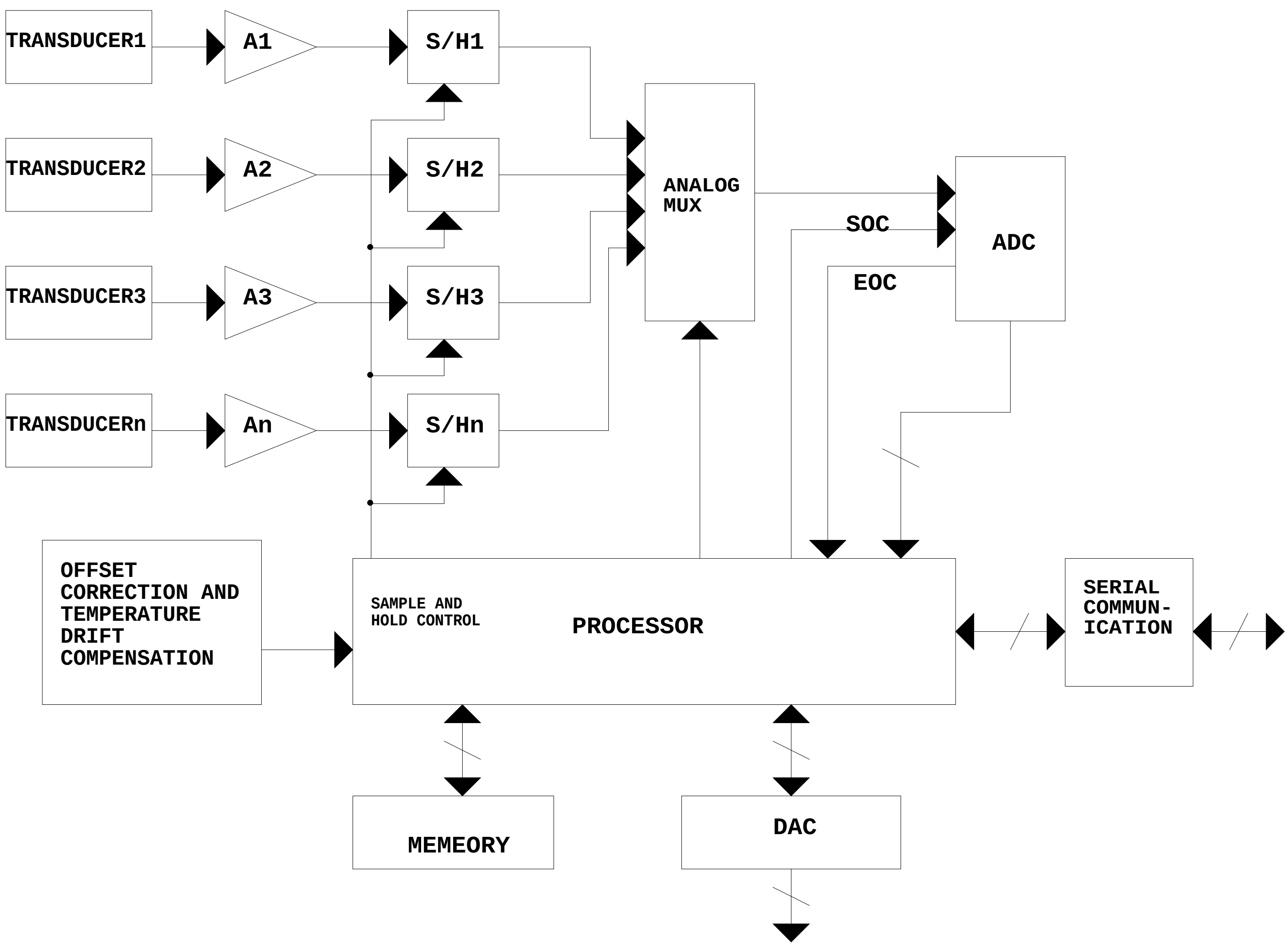
Parameter drift and component values: These are functions of time. This can be solved by automatic calibration.

5. General Architecture of smart sensor:

One can easily propose a general architecture of smart sensor from its definition, functions. From the definition of smart sensor it seems that it is similar to a data acquisition system, the only difference being the presence of complete system on a single silicon chip. In addition to this it has on–chip offset and temperature compensation. A general architecture of smart sensor consists of following important components:

Sensing element/transduction element,
Amplifier,
Sample and hold,
Analog multiplexer,
Analog to digital converter (ADC),
Offset and temperature compensation,
Digital to analog converter (DAC),
Memory,
Serial communication and
Processor

The generalized architecture of smart sensor is shown below:



GENERAL ARCHITECTURE OF SMART SENSOR

5.1 Description of Smart Sensor Architecture

Architecture of smart sensor is shown. In the architecture shown A1, A2…An and S/H1, S/H2…S/Hn are the amplifiers and sample and hold circuit corresponding to different sensing element respectively. So as to get a digital form of an analog signal the analog signal is periodically sampled (its instantaneous value is acquired by circuit), and that constant value is held and is converted into a digital words. Any type of ADC must contain or proceeded by, a circuit that holds the voltage at the input to the ADC converter constant during the entire conversion time. Conversion times vary widely, from nanoseconds (for flash ADCs) to microseconds (successive approximation ADC) to hundreds of microseconds (for dual slope integrator ADCs). ADC starts conversion when it receives start of conversion signal (SOC) from the processor and after conversion is over it gives end of conversion signal to the processor. Outputs of all the sample and hold circuits are multiplexed together so that we can use a single ADC, which will reduce the cost of the chip. Offset compensation and correction comprises of an ADC for measuring a reference voltage and other for the zero. Dedicating two channels of the multiplexer and using only one ADC for whole system can avoid the addition of ADC for this. This is helpful in offset correction and zero compensation of gain due to temperature drifts of acquisition chain. In addition to this smart sensor also include internal memory so that we can store the data and program required.

6. Block Level Design Considerations for Smart Sensor [3]

Design choice of smart sensor depends on the specific application for which the sensor is required and also related to specific industry. Normally a smart sensor will utilize inputs form one or more sensor elements either to generate an output signal or to generate a correction signals which are applied to the primary output. This includes design of circuitry to take output of raw sensor elements and generate compensated and linearized sensor output.

6.1 Functions within electronics:

The smart sensor contains some or all of the following functions

Sensor Excitation:
Many a times it is required to alter the sensor excitation over the operating range of a sensor. An example of this is a silicon wheatstone bridge, where the drive voltage is increased with increasing temperature. This is done to compensate for the reduction in sensitivity of the piezoresistors with increase in temperature. A drive stage with temperature dependence can be used which is control by a microprocessor. This will also reduce the calibration time.

Analogue Input:
Multiplexing of inputs can be done to avoid duplication of circuit. In multiplexing inputs of same type and range are switched to a common front end. The outputs of sensors are normalized before they are switched and a variable gain stage is included after the multiplexer. This allows the sensitivity variations between the different sensors to be accounted for by a common front-end .In addition to this an offset adjustment is also included in the common front end.
The variable gain stage also offers an additional advantage where the input signals are to be sampled by analog to digital converter (ADC) with fixed reference points. Under such situation gain can be increased at the lower end to increase the sensitivity.

Data Conversion:
In case of smart sensor most of the signal processing is done in digital form. This is possible only when we have an ADC along with an anti-aliasing filter. This is because most of the sensor output is in the analog form. Choice of ADC depends on the resolution, bandwidth and complexity of anti-aliasing filter.

Digital data bus interface:
The controller embedded in the smart sensor supports communications by digital data bus. The advantages of this are:

Wiring is reduced considerably
Automatic calibration at production can be simplified.

Monitoring and diagnostic functions:
In many applications self-test is required. This self-test includes connectivity checking and long-term offset correction.

Control processor:
To provide greater flexibility and reduced complexity, a control processor can be used. Control processor can do digital filtering. Another important point is software development. Processor must allow writing codes in higher language as it reduces the development time.

6.2 Level of integration:

Though it is possible to integrate smart sensor on a single piece of silicon it is unattractive due to cost and performance. Analog processing, digital logic and non-volatile memory (NVRAM), can all be done on same piece of silicon. But compromise must be made that limit the performance of at least one of these functions.

7. Summary of different smart sensors:

Some of the smart sensors developed at different research institutes are as follow:

Optical sensor: Optical sensor is one of the examples of smart sensor, which are used for measuring exposure in cameras, optical angle encoders and optical arrays. Similar examples are load cells silicon based pressure sensors [1].

Infrared detector array: Integrated sensor is the infrared detector array developed at the solid laboratory of the University of Michigan. The Infrared-sensing element was developed using polysilicon –Au thermocouples and thin film dielectric diaphragm to support the thermocouples. On-chip multiplexer was fabricated by using silicon gate MOS processing. This detector operates over a temperature range of 0 to 100 degree centigrade with a 10msec response time. It has a responsiveness of 12V/W.It is a 16*2 element staggered linear array with one lead of each detector connected to a common ground line and other connected to one of the input of 16*1 analog multiplexer. This chip also contains a separate calibration thermopile, polysilicon resistors, and diodes and MOS transistors to allow direct measurements of the cold junction temperature both and the thermoelectric power of the polysilicon lines [1].

Accelerometer: Accelerometer fabricated at the IBM Research laboratory at San Jose California, which consists of the sensing element and electronics on silicon. The accelerometer itself is a metal-coated SiO2 cantilever beam that is fabricated on silicon chip where the capacitance between the beam and the substrate provides the output signal [1].

Integrated multisensor: Integrated multisensor chip developed at the electronics research Laboratory University of California. This chip contains MOS devices for signal conditioning with on chip sensor, a gas flow sensor, an infrared sensing array, a chemical reaction sensor, a cantilever beam, accelerometer, surface acoustic wave vapor sensor, a tactile sensor array and an infrared charge coupled device imager. This chip was fabricated using conventional silicon planer processing, silicon micromachining and thin deposition techniques [1].

8. Conclusions

In conclusion, silicon is very suitable material for fabrication of smart sensors. But still a lot of research is required to get benefits of the smart sensor, but from the experience of already existing devices, we can expect that in the coming decade a large number of successful smart sensors will emerge.

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References

1. J. M. Giachino, "Smart sensors," *Sensors and actuators*, 10(1986) 239-248.
2. S. Middelhoer and A.C. Hoogerwerf, "Smart sensors when and where," *Sensors and Actuators*, 8(1985) 39-48.
3. M. Bowen, G. Smith, "Considerations for the design of smart sensors," *Sensors and Actuators*, A 46-47(1995) 516-520.
4. J.M. Riviere, D. Luttenbacher, M. Robert, J.P. Jouanet, "Design of smart sensors: towards an integration of design tools," *Sensors and Actuators* A46-47 (1995) 509-515.
5. G. Smith, M. Bowen, "Considerations for the utilization of smart sensors," *Sensors and Actuators* A 46-47(1995) 521-524.
6. J.G.Rocha, C. Couto, J.H. Corria, "Smart load cells: an industrial application," *Sensors and Actuators*, 85 (2000) 262 –266.
7. G.D. Graaf, R.F. Wolffanbuttel, "Smart optical sensor systems in CMOS for measuring light intensity and color," *Sensors and Actuators*, A67 (1998) 115-119.
8. Wai-chi Fang , "A low power high speed smart sensor design for space exploration missions," *Sensors and Actuators(small satellite for space exploration missions)*,Vol. 46,pp 241-250(2000)
9. D. Martinez, D. Esteve, "Adaptive quantization and fault detection in smart sensors," *Sensors and Actuators*, 46-47(1995)530-533.