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ADVANCED SENSORS : AN EMERGING TECHNOLOGY

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INTRODUCTION

The economic realities of productivity, quality and reliability for the industrial societies of the 21^{st} century are placing major demands on existing manufacturing technologies [1]. To meet the present and emerging requirements new and improved sensing devices are being developed. The sensors can be broadly divides into five categories, namely :

- magnetic sensors
- thermal sensors
- optical sensors
- chemical sensors
- biochemical sensors, and
- multiattribute sensors

Sensors are substitutes for the five human senses. Sensors could also be classified according to their applications. Intensive efforts to develop sensors with electronic compatible signals began in the mid 1970's [2]. As microprocessors and very large scale integrated circuits became generally available, the field of measurement and instrumentation has undergone a major change because of the advent of solid state sensors or semiconductor sensors. The advanced sensors are those which intelligent functions. This paper provide an overview of the evolution of advanced sensor technology and its emerging applications.

The advanced sensors are the critical elements for building intelligent devices. The importance of sensors is likely to increase and they have been identified the world over as one of the critical technologies for the future. Advanced sensors constitute a generic technology which form the basis of intelligent instruments, intelligent manufacturing systems, intelligent buildings, intelligent cities and environmentally conscious manufacturing technology systems. The use of other enabling technologies such as fuzzy logic and neural networks has opened up a whole range of new control capabilities [3]. Semiconductor sensors that combine integrated circuits and micromachining technologies as well as new high purity materials or polymeric materials have opened up new avenues for integrating sensors and process controls. With the converging developments in large scale integration, micromachining, lithographic fabrication etc many families of advanced sensors are emerging to meet new demands in performance, size and cost.

WHAT ARE ADVANCED SENSORS ?

Advanced sensors are smart or intelligent sensors. These are devices in which signal processing have been harnessed to improve the performance of particular sensing devices. Smart sensor systems with intelligence capabilities are being used in many equipments. Smart sensors are the ones that modify their internal behaviour to optimize its ability to collect data from the physical world and communicate them in a responsive manner to a host system or a computer system [4]. Smart sensors have integration, self correction, self compensation and memory capabilities. Smart sensors are schematically represented in **Fig.1**. The sensors are made intelligent through the development of intelligent sensing devices. Intelligence is achieved through

- sensors using new materials
- sensors based on new processes, and
- sensors based on new measurement systems.

New sensing materials currently being used include amorphous semiconductors, amorphous materials, fine ceramics, superlattice semiconductors, shape memorizing metals, enzymes, antibodies, microorganisms, superconducting materials etc. Advanced integrated sensors uses either hybrid integration or monolithic integration. These use advanced manufacturing technology such as microlithography, micromachining, surface mounting and chemical vapour deposition etc. Advanced sensors require ultra pure materials and ultra clean conditions for manufacturing. Another class of sensors are the biotechnology based molecular and supramolecular systems capable of measuring physical, chemical and biological parameters.

Advanced sensors represent a critical technology needed for sustaining high productivity in manufacturing systems, high reliability in industrial control processes and high levels of quality. They are also needed for maintaining high levels of environmental quality and industrial safety.

TYPES OF ADVANCED SENSORS

The advanced sensors [5]can be categorized as :

- semiconductor sensors, and
- integrated sensors

Semiconductor sensors are transducers that convert mechanical signals into electrical signals. These are widely used for the measurement and control of physical variables. The various types of semiconductor sensors are :

- acoustic sensors
- mechanical sensors
- magnetic sensors
- radiation sensors
- thermal sensors
- chemical sensors
- biosensors
- integrated sensors

The acoustic sensors use mostly piezo electric effect. The trend is use microfabricated micromechanical devices, mainly involving piezo electric thin films. Mechanical semiconductor sensors use either capacitive or piezoresistive transduction. The main varieties of mechanical sensors used today include pressure sensors, accelerometers and flow sensors as well as tactile sensors. Tactile sensors rely on touch to detect the presence of an object. Advanced mechanical sensors are micromachined in bulk silicon. Recently sensors fabricated using surface micromachining have been developed. Surface micromachined sensors offer better process compatibility and small size. Polisilicon microstructures have been used for pressure sensors, accelerometers and flow sensors. Research and development are slowly moving into the age of microsystems which requires the integration of different technologies such as sensors, electronics actuators and optics in miniature hybrid systems. Magnetic sensors cover a range of sensors capable of measuring weak biomagnetic fields to high magnetic field strengths. Integrated silicon magnetic sensors used widely in consumer electronic devices, computers etc. Proximity sensors are a class of magnetic sensors which can sense the presence of a nearby object by inductance, capacitance, light reflection or eddy currents. Magnetic sensors are fairly inexpensive to manufacture and are reliable. Radiation sensors cover sensing devices for both electromagnetic and nuclear particle radiation. The advances in semiconductor fabrication technology has revolutionized solid state imaging technology. Most of the solid state image sensors are based on the internal photoelectric effect for the conversion of photons into electronically detectable charge. Charge couple device (CCD) image sensors are the most advanced ones. The CDD image sensors with 5120 x 5120 pixels, manufactures in 1992 with its 26 million pixels covering an area of 61.4 x 61.4 mm^2 is the largest image sensors. In 1995, CCDs with 65 million pixels in 8000x8000 pixels format are available. Advanced thermal sensors are made with silicon technology. Silicon based thermal sensors are manufactured using micromachining. The recent development is the integration of sensors on the same chip as the electronic processing circuitry, thus forming smart systems. Smart sensor systems can be implemented at relatively low costs, because they eliminate or reduce the external circuitry, wiring and printed circuit boards and because they reduce the calibration and assembling effort. The major silicon based sensors are summarized in **Table.1** along with the major parameters which they can sense [2].

Integrated sensors take full advantage of the world's of semiconductor sensors and integrated circuitry by combining best features they have to offer. In integrated sensors the microprocessor based system operates on the sensed signals and offers a standard digital data stream to the user making the entire sensing module behave like a smart system peripheral rather than a passive component. The recent development is to integrate sensors and actuators so that when a sensor is connected to an electronic device the output of the sensor drives the actuator. Micromachine technology is applied for integrating sensors and actuators. This is the emerging technology today, but is a complex one needing both microlithography and micromachining technology. To sum up intelligent, integrated and multifunctional sensors are being developed are used.

Biosensors are devices which measure the concentration of specific biological substances of interest exploiting the molecular recognition capability of certain biological materials as shown in **Fig.2**. A biosensor generally consists of a biological sensing element such as an antibody, enzyme or cell in close contact with a physicochemical transducer such as an electrode or optical fibre. The various elements of a biosensor is given in **Fig.3.** The various types of biosensors are

- enzyme sensors
- microbial sensors use a micro-organism for detecting a metabolite. This uses immobilization of micro-organisms on transducer
- ion sensitive field effect transistor based sensors, and
- optical biosensors based on fluorescence using confined and coenzymes are being used for sensing antibodies, enzymes or cells.

The development of biosensors and semiconductor sensors along with the use artificial neural network technology and pattern recognition technology is facilitating the objective measurement of physical, chemical and biochemical parameters.

APPLICATIONS

Advanced sensors will be used in every segment of human endeavour covering agriculture, advanced manufacturing systems, advanced avionics, optical communications, remote surveillance systems, space satellites, medical diagnostics, super smart highways, pollution monitoring and so on. Advanced sensors is a generic technology which will have applications across the board in many segments. A schematic representation of the range of advanced sensors in relationship to the market size is given in **Fig.4.** Advanced sensors are the key elements in the architecture of process controllers and process monitors in manufacturing as well as in services. Machine vision systems that process over a billion pieces of information per second and measure species at atom level makes the sensors a wonderful element of the emerging information technology revolution. Selected applications of some classes of sensors are given below, for illustrative purposes :

1. ***Humidity sensors*** : These sensors use advanced molecular substances, ceramic materials or semiconductors. Semiconductor based humidity sensors use silicon semiconductor known as charge flow transistors. These sensors can monitor and control temperature as well as humidity. Humidity sensors using ceramics or ogano polymer electrolytes are useful in food processing industry, air-conditioning, sensitive warehousing, drug manufacturing, precision electronics manufacturing etc.

2. ***Rotation sensors*** : Rotation sensors are the basic sensing devices behind shake compensation mechanism in camcorders, auto-focus cameras, antilock braking systems for automobiles, throttle positioning devices and electronics controls for engines and motors.

3. ***Gas sensors*** : Gas sensors are solid state sensors or acoustic wave sensing devices used for detecting gaseous components. Semiconductor gas sensors using metal oxides which detect inflammable gas in air such as methane, liquefied petroleum gas and hydrogen are widely used in gas leakage alarms. Oxygen sensors using stablizied zirconia is used in car emission control and in metallurgical process control. Apart from these, gases, ammonia, hydrogen sulphide, ethanol vapours, chlorine, nitrogen oxides and carbon di oxide can also be monitored. Gas sensors are the most rapidly growing category of sensors. These new sensors will revolutionize the industrial controls, safety and operational reliability in industrial manufacturing operations, transportation of chemicals, storage and handling of fuels.

4. ***Photo sensors*** : Photo sensors are discrete light detecting devices. Photo conductive devices, photodiodes, photo transistors, photo Ics, pyroelectric infrared sensors are the major ones. They are used in copiers faxes, dot matrix printers, laser printers, video cameras, electronic and control equipments, robots, laser discs, and large capacity memory devices.

5. ***Thermal sensors*** : This sensor segment constitutes the largest segment of the sensor market. Thermals sensors are those that sense changes in temperatures. They are used extensively in a variety of products ranging from office automation equipment and air conditioners to heaters and home cooking equipment. Leadless thermistors, soft touch sensors, hermetic thermistors etc are the emerging ones. Recently, leadless parts have been directly soldered to

printed circuit boards by surface mount technologies. In portable electronic devices, temperature correction is carried out through smart sensors. Thermal sensors are used in non contact switches, overheat protection circuits and fixed temperature heating elements.

6. ***Acceleration sensors*** : Mechanical quantity sensors are one of the emerging technologies since their applications are many and varied. Semiconductor pressure sensors are now used in acceleration sensors and flow rate sensors. The manufacturing process used for fabricating micromechanical silicon sensors is similar to that used for manufacturing integrated circuits and hence the technology has reached maturity.

7. ***Biosensors*** : Biosensor is a fast developing area. Various biosensors which are emerging are identified in **Fig.5**. Sensors based on small transducer or thinner protein immobolized membrane are emerging. Miniature biosensors are currently under development Enzyme sensors and immunosensors are the thrust areas. These are used in diagnostics, food processing industry, etc.

RELEVANCE TO DEVELOPING COUNTRIES

Sensors are the fundamental building blocks of the emerging industrial revolution [6]. Advanced sensors are semiconductor based. Evolution of multifunctional smart sensors will change the industrial, transport, health as the services sectors. Sensors allow precision in manufacturing and improve the measurement reliability in quality control operations. Developing countries have to export quality products and this will require a higher level of sensing and monitoring capability with respect to manufacturing processes as ell as products. This will require extensive use of advanced sensors. Some of the major segments in which advanced sensors will play a major role in developing countries are :

- sensors for industrial process control
- sensors for toxic and hazardous chemicals
- sensors for supporting advanced manufacturing
- sensors for food processing and quality sensing
- sensors for medical diagnostics
- sensors for environmental monitoring, and
- sensors for agricultural operations.

Sensors can help in monitoring humidity as well as micronutrients in soils. On-line monitoring of soil quality is possible at low cost. Similarly, on line quality monitoring in food processing industry is a high growth area of relevance to developing countries. Some of the major applications of advanced sensors in developing countries are presented in **Table.2.** The special significance of advanced sensor technology is that it allows low cost automation and quality monitoring in small scale operations. This makes it a relevant and cost effective technology for small and medium enterprises for improving productivity as well as quality conformance. This has special significance to developing countries since SMEs are the ones which have to be modernized rapidly so that they can get effectively integrated with the global economy. This will be possible only through productivity improvement and quality management. Advanced sensors is an enabling technology for this.

TECHNOLOGY TRENDS

A vast array of possible sensor technologies which were considered to be in the realm of the impossible have become a reality. Some of the recently developed sensors include :

- pathogens in the blood
- explosives in luggage
- toxic gases in enclosed atmospheres
- road roughness
- engine torque
- decomposition products in food
- intruder motion in closed premises
- pollution in the atmosphere
- wear products in lubricant
- sounds from microcracks in pressure vessels

These sensors promise a new era of health, safely, security, quality of products, reliability in controls and comfort for mankind. The increase in capability of electronic systems, the decrease in size and cost have all proceeded exponentially over a number of years and there is no indication that this trend is about to change [4]. One of the most noteworthy development which will change the sensing technology is the emergence of electronic noses.

Electronic noses **:** The human nose is capable of detecting around 2000 different smells and a trained one can differentiate upto 10,000 aromas. Analysis of the mechanism underlying mammalian olfaction has led to the concept and realization of electronic analogues of the human nose.

Such systems consist of an array of broadly selective chemical sensors coupled to microprocessor based pattern recognition systems. These are termed electronic noses or olfactory sensors array systems. Electronic noses permit the mapping of olfactory images, thereby, providing a powerful tool for characterizing multicomponent mixtures, which was rather cumbersome prior to this development [7]. Chemical sensing and odour identification systems have enormous commercial potential. Electronic nose technology [8] has a number of advantages, namely :

- real time measurement of a wide range of chemicals and mixtures is possible
- can rapidly analyze complex multicomponent samples or atomosphere
- high levels of discrimination can be achieved
- can detect small amounts of impurities or contaminants
- suitable for on-line analysis, and
- can be very application specific.

Electric noses have tremendous market potential and some of the emerging applications are :

- fire and smoke detection
- environmental monitoring
- petrochemical industry
- building management
- food, drink and breweries
- fragrance and flavour industry

- detection of toxic or hazardous chemicals
- medical diagnostics
- aerospace applications, and
- military applications.

Portable electronic noses have been developed by GEC-Marconi Lab of UK [8]. Electronic noses can be used for analysis of complex mixture such as foods, drinks, fragrances, petrochemicals etc will revolutionize the industrial process control, contamination testing as well as quality assurance systems. Food, drink and perfume companies are keen to use the electronic noses to increase the objectivity and consistency of their quality assurance systems. General Motors is using electronic noses to build a more sensitive air conditioning system for its cars and Ford Motor Co is using them to test exhaust emissions. Electronic noses makes it easier to trademark smells since a written description can be backed up by an electronic smell print, similar to the finger print. Electronic noses along with intelligent or smart sensors will revolutionize the automatic sensory perception. Advanced sensor technology is rapidly emerging to meet both the present and future requirements of industrial instrumentation, industrial process control, quality measurement, manufacturing automation and reliability.

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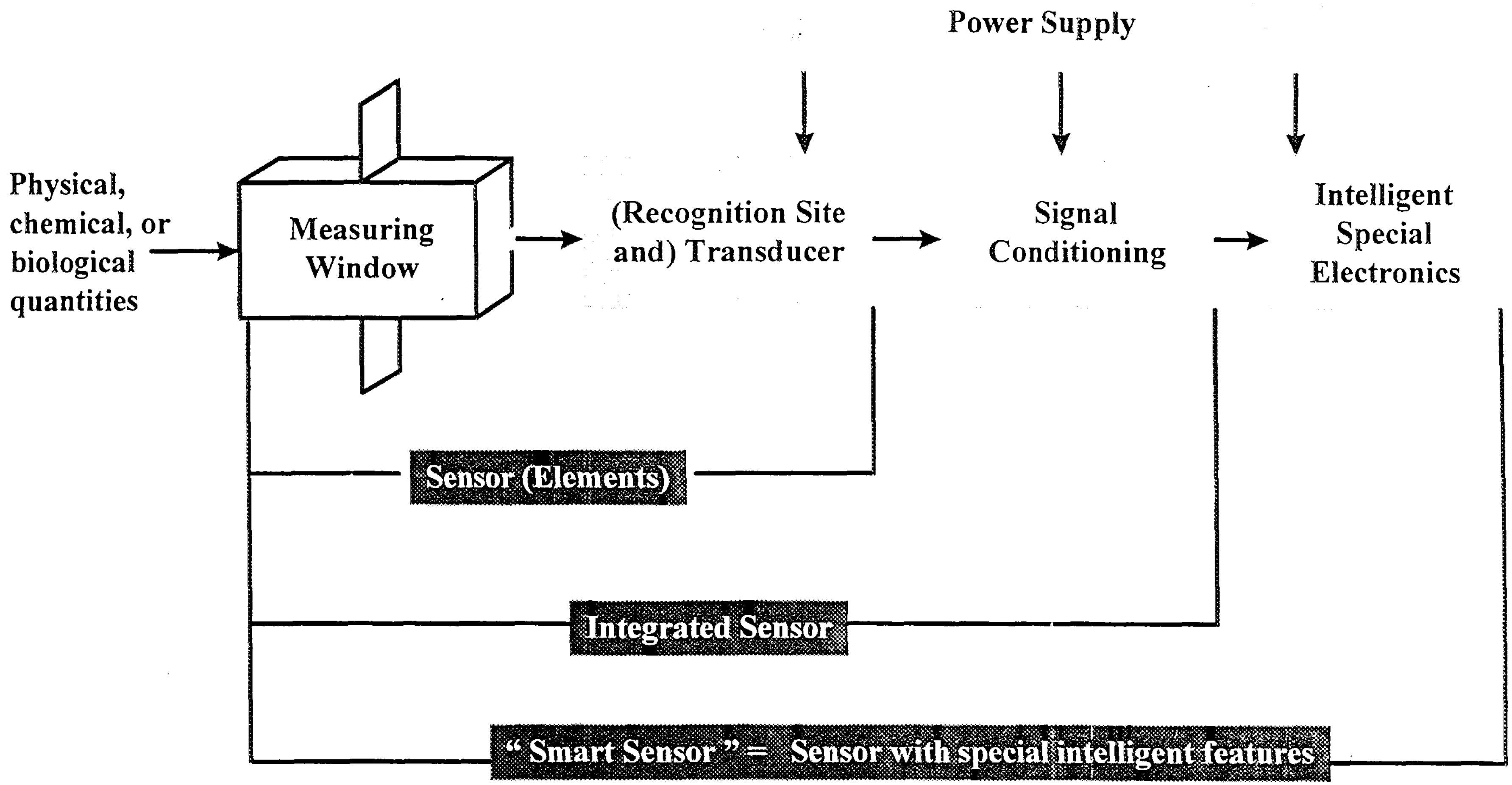

Fig. 1 SMART SENSOR

B-bioactive layer, containing "recognition molecules" (enzymes, antibodies, receptor proteins) T - transducer, a probe sensitive to the primary signal produced by the recognition process (potentiometric or amperometric electrode, FET (Field- effect transistor), piezoelectric crystal); A-amplifier, R-recorder.

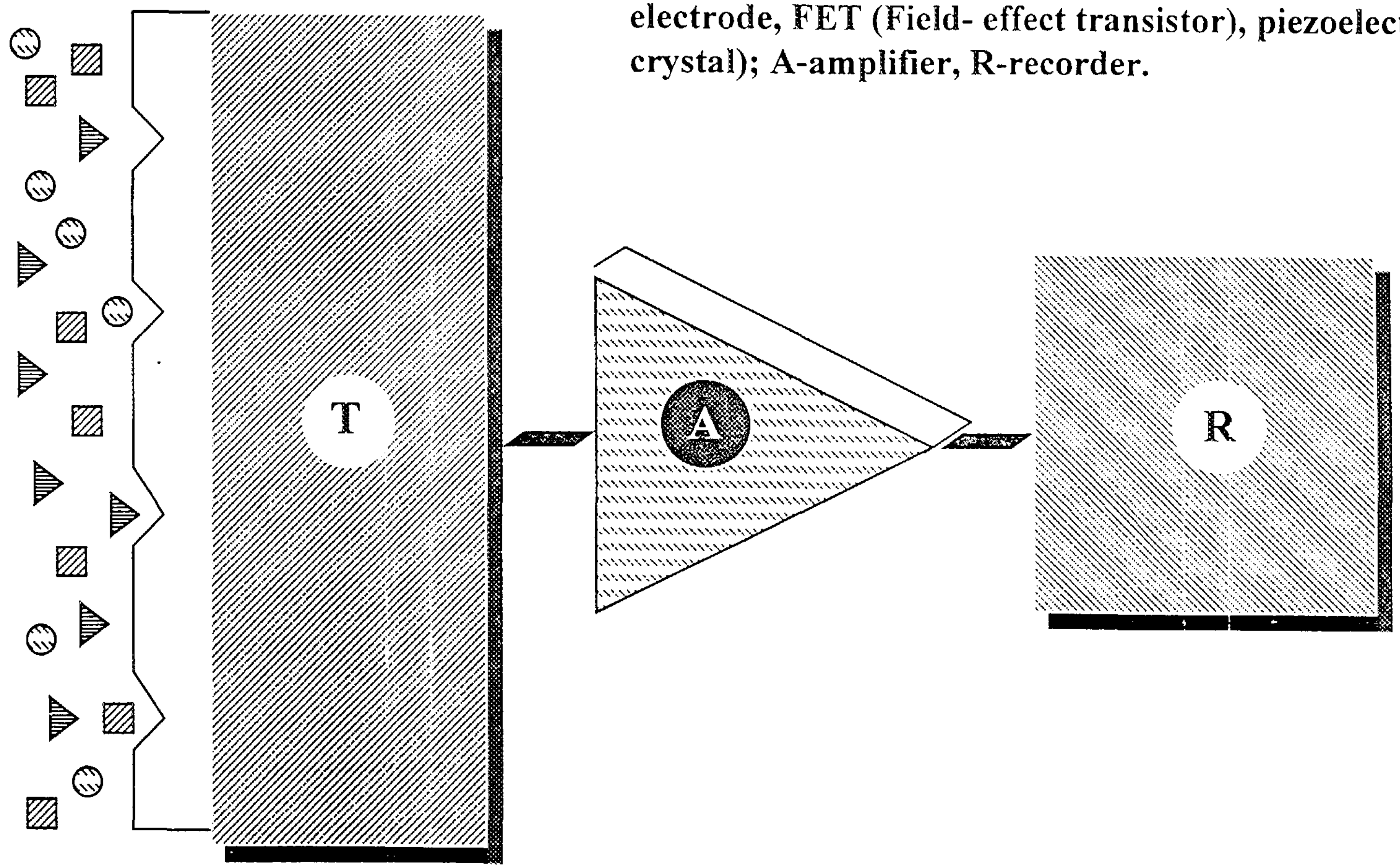

Fig.2 PRINCIPLE OF SETUP OF A BIOSENSOR

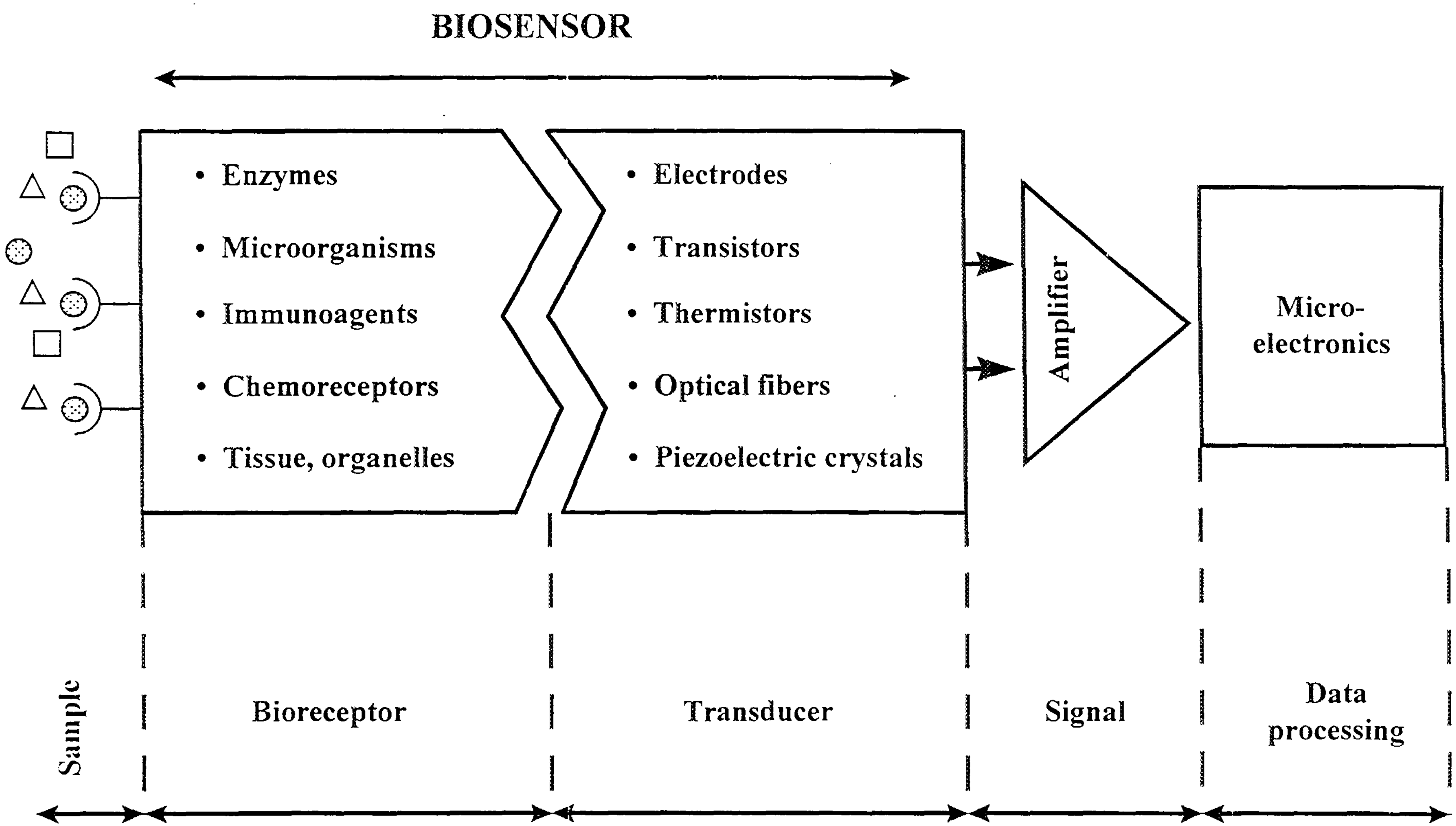

Fig.3 THE VARIOUS STAGES OF DETERMINATION WITH A BIOSENSOR

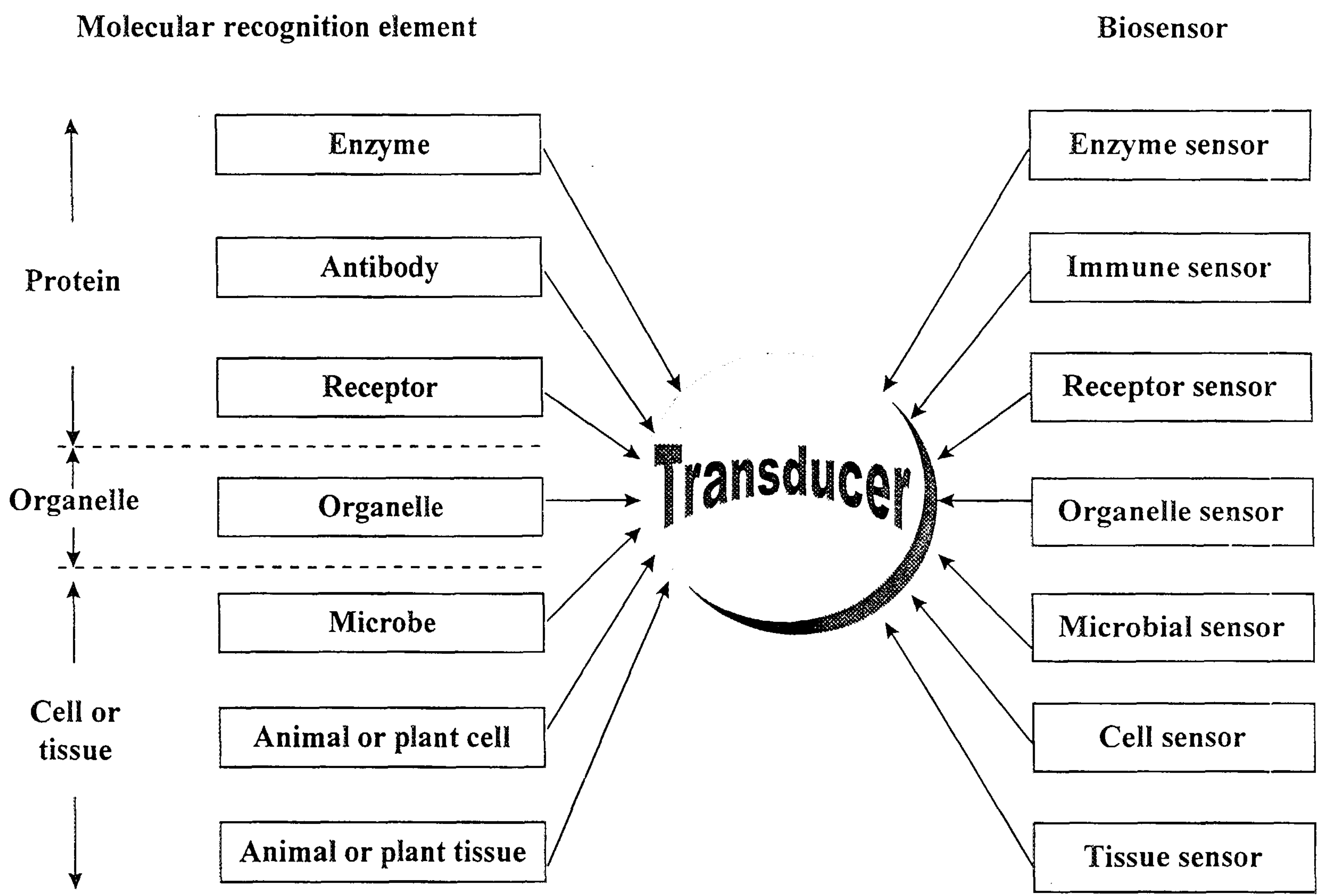

Fig.4 MOLECULAR RECOGNITION ELEMENT AND BIOSENSOR

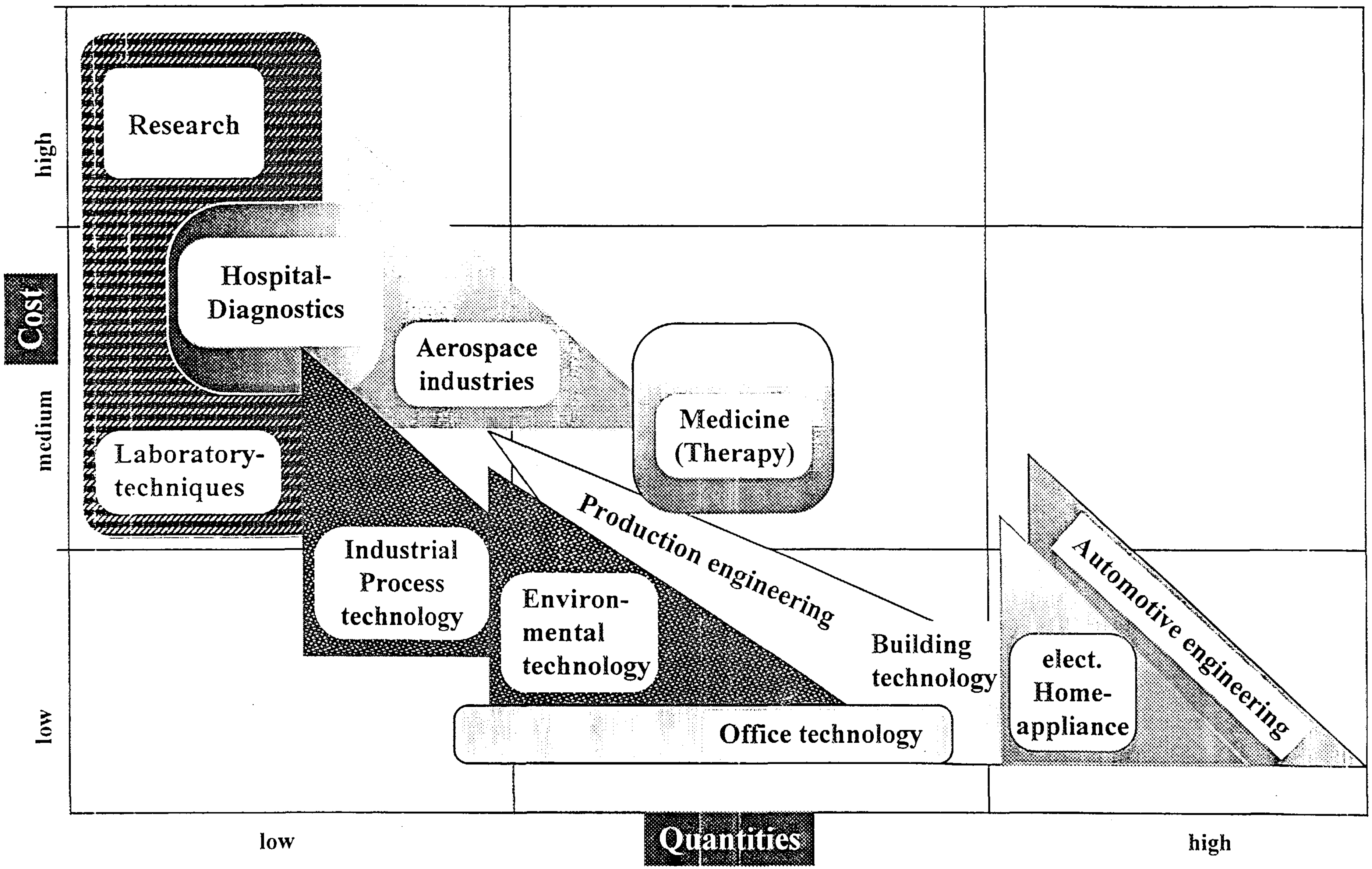

Fig.5 ADVANCED SENSOR MARKET

Table 1

SILICON BASED SENSORS

ELEMENT TO BE MEASURED	SENSORS
Radiation	Photoconductor, photodiode, phototransistor, avalanche photodiode Schottky photodiode, diode array, diode matrix, color sensor, thermal infrared sensor, charge couple devices, micro strip detector, X-ray detector
Mechanical signals	Stress gauge, piezoresistive and capacitive pressure sensor, vacuum sensor, acceleration sensor, scanning-picture sensor, positioning sensor, inclination sensor, angle measurement device, position sensitive device, piezojunction force sensor, pressure-metal oxide semiconductor field effect transistor, gas-and liquid-flow sensor, optical and magnetical distance sensors
Thermal signals	Thermo - resistor, temperature - sensitive diode and transistor, thermopile, micro-calorimeter, PTAT temperature sensor
Magnetical signals	Hall - element, bipolar and metal oxide semiconductor field effect transistor -magnetotransistor, magneto-resistive field sensor, magnetodiode, magnetic head
Chemical signals	Chemoresistor, chemical capacitor, micro-calorimeter, surface acoustic wave gas sensor, chemodiode, ion sensitive field effect transistor , hydrogen sensor, moisture sensor, biosensor,

Table 2

ADVANCED SENSORS OF RELEVANCE TO DEVELOPING COUNTRIES

Sensor Type	Application
Chemical sensors	Detection of explosives
Humidity sensors	For process control, food preservation and soil analysis
Laser sensors	Position detectors
Enzyme sensors	Food processing
Microbial sensors	Medical diagnostics for AIDS
Temperature sensors	Food processing, industrial process control
Gas sensors	Environmental monitoring
Biosensors	Non-invasive detection of blood glucose
Chemical sensors	Soil nutrient analysis
Acoustic wave sensors	Pollution control and sewage treatment