Sensors
A Comprehensive Survey

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1 Introduction

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1.1 Definition of Mechanical Sensors

Mechanical sensors can loosely be defined as sensors which measure mechanical quantities. Some examples of "mechanical quantities" are given in the box below.

| force, torque, power, stress, displacement, rotation, strain, acceleration, pressure, flow rate, velocity, rotational speed, weight, mass, liquid level, density, viscosity, sound, and composition of nonreacting mixtures. |

Typically these mechanical quantities are measured indirectly through their effect on sensor parameters which are often, but not always, mechanical in nature. For example, pressure, force, and acceleration sensors may include a thin membrane which is deflected by the action of the pressure, force or acceleration. The magnitude of the deflection is proportional to the stimulus or measurand (the quantity we wish to measure) and is usually determined by measuring strain, capacitance, or optical interference. When one measures these, the mechanical signal is typically converted to an electronic one. Sensors, then, can be classified either according to the measurand (i.e., pressure sensor) or according to the method of signal conversion (i.e., a capacitance sensor).

The first part of this volume (chapters 2-8) emphasizes conversion devices such as strain gages, capacitors, piezoresistors, hall effect units, and thermoelectric units. The second part of the book (chapters 9-16) describes sensors used for the measurement of such variables as acceleration, force, torque, density, viscosity, flow rate, pressure, and sound and vibrations.

1.2 From Antiquity to Now

Mechanical sensors are among the oldest measurement devices around. The Romans, for example, monitored the water supply to private customers for the purpose of tax assessment. Frontinius (approximately, 35 AD-103 AD) describes the use of officially certified bronze nozzles (Calix, in Latin) with various internal diameters to control the rate of water flow to customers [1]. The Romans were careful to choose appropriate materials for their nozzles. They selected bronze, for instance, rather than lead because the bronze, being a harder material, was less likely to be tampered with. The nozzles were available only in certain specified and carefully measured diameters. This represents an early attempt at standardization. Another mechanical sensor described by Frontinius is the odometer (road measure) which was used to measure distances. The odometer consisted of a series of worm gears which were activated by the chariot wheel and turned pointers indicating the distance traveled by the chariot up to about a hundred miles. The principles of density measurement were discovered by Archimedes, who is also credited with the discovery of buoyancy.

Throughout the years, mechanical measurement devices have undergone a continuous evolution and they have become an important part of many industries, ranging from manufac-
uring to process, chemicals, machinery, health-care, environmental monitoring, automotive, avionics, as well as household appliances (see, for example, [2], Chapters 14–22, and [3]).

Given this long history and the widespread use of mechanical sensors, one might be tempted to assume that "Mechanical Sensors" is a mature field with very little room for innovation. However, nothing could be further from the truth.

The last two decades have seen an explosion of new sensors with new capabilities and this trend is likely to continue. Many factors have conspired to keep "Mechanical Sensors" an active and evolving field. There is continuing interest in improving sensor precision. For instance, like the Romans, we are still concerned with improving the precision of flow metering in order to assure that customers pay for what they actually consume. Given the high cost of fossil fuels, small inaccuracies in gas or fuel flow measurements quickly translate into megadollars.

An increased emphasis on product quality and process efficiency (i.e., reduction in energy and materials consumption) as well as the manufacturing of sophisticated products which require narrow process tolerances and tight control of process parameters has generated a huge demand for networks of high precision, maintenance-free, reliable sensors capable of operating in hostile environments. The accommodation of large numbers of sensors is facilitated by our increasing ability to process large amounts of information in real time and at a reasonable cost.

Increased concerns about the environment and safety have prompted government legislation requiring monitoring of pollutants discharged to the environment. For example, power plant operators are now required to monitor the flow rate and composition of flue gases. This, in turn, has created new applications for existing sensors and a demand for new types of sensors.

Likewise, advances in medical technology have resulted in the use of various mechanical sensors in closed-loop medical systems such as drug delivery systems, respirators, dialysis machines, blood oxygenators, and fetal monitors. Doctors are using sensor-based diagnostic equipment for applications ranging from blood pressure measurement to the detection of glaucoma.

The microelectronics revolution has made available low cost, abundant computational power. This computational power allows us to process efficiently vast amounts of information and determine the appropriate control parameters for various processes. Sensors and actuators are needed to interface between the computers and the physical world. Many technologies, ranging from transportation to health care to manufacturing to consumer goods, are likely to benefit if better sensors and actuators are made available.

Finally, advances in microfabrication technology during the last two decades have provided us with the means of satisfying the increasing demand for high precision, inexpensive, intelligent sensors. In turn, the availability of inexpensive, micro-sensors has promoted new applications which in the past would have been either impossible or economically infeasible. Here we mention only a few examples. For instance, large numbers of sensors have been incorporated into the automotive power plant [4]. Pressure transducers are used, for example, to measure intake manifold pressure for real time electronic engine control in order to achieve high performance and fuel economy. Walters [5] reports on the potential use of pressure sensors mounted on car wheel rims to detect when a tire is over or underinflated. The pressure reading is transmitted via radio to an electronic package installed under the hood and the information is, in turn, displayed on the dashboard, thus enabling the driver to observe the pressure of all four tires. Micro-accelerators may eventually be incorporated into the automotive suspension to monitor road conditions and adjust the suspension to maintain a smooth ride and constant handling conditions.
Finally, in the future, it may be possible to use large numbers of inexpensive, small sensors and actuators to affect macroscopic phenomena. For instance, such sensors and actuators might be installed on the solid surface of an aircraft to render turbulent flows laminar and thereby achieve drag reduction and savings in fuel cost.

1.3 "Smart" or "Intelligent" Sensors

The most salient feature of the last two decades' evolution in sensor technology has been the development of "smart" or "intelligent" sensors. For a definition and description of "smart sensors", see [6]. The development of such sensors has been facilitated by advances in microfabrication technology. This technology allows one to micromachine electromechanical components and systems (MEMS) which convert thermo-mechanical quantities such as deformation or heat into electronic signals. These devices are typically fabricated using modern integrated circuit, semiconductor technology. Since the microfabrication process is similar to the one used for the production of electronic components, electronic circuitry such as analog to digital converters and microprocessors can be produced on the same chip, resulting in integrated electro-mechanical elements and the requisite circuitry for power supply, control, signal conditioning and processing, calibration, and communications [7].

Microfabrication technology allows one to machine very complicated structures through a combination of material removal and deposition. The microfabrication process is a batch process. Hundreds of micro-sensors can be produced in one process from a single wafer of about five inches in diameter. This obviously leads to large economies of scale and a lower price per unit. The process is accurate and results in uniform devices. Moreover, the technology allows one to incorporate a number of different measuring devices on a single wafer, a significant advantage when the measurement of diverse quantities may be desirable either for correcting sensor measurement for unwanted effects or for measuring simultaneously diverse physical quantities of interest.

Microfabricated sensors often offer better performance, sensitivity, accuracy, dynamic response, reliability, and user-friendliness at lower cost, lower power dissipation, and much smaller physical dimensions than their larger counterparts. Accordingly, there has been a great increase in demand for them. It has been reported that $750 million worth of silicon micro-sensors were sold in the US in 1989 and it has been forecasted that the market will keep growing at a rate of between 10% to 15% per year [8]. Similar tendencies are observed in Europe and Japan. Not surprisingly, a large part of this book is devoted to this type of sensor.

Micromachining is often classified into "bulk" and "surface" machining. Bulk processes consist of sculpting structures such as beams and diaphragms onto a single crystalline silicon wafer. These structures are formed using either isotropic or anisotropic wet chemical etchants, such as ethylene-diamine-pyrocatechol (EDP) and KOH, together with several etch-stop techniques. Isotropic etchants remove material uniformly in all directions. Anisotropic etchants etch at different rates in different directions in the crystal lattice. Areas where no silicon is to be removed must be protected by masking them with chemically inert layers. The silicon's properties can be modified by adding dopants by diffusion or ion implementation. Material can be added to the silicon surface through thin film deposition, metal plating, epitaxial growth,
or bonding. Bulk machining has been applied mostly to silicon, but other materials, such as GaAs, glass, quartz, and ceramic, have been used. Silicon is the preferred material for micromachining because of its good mechanical and electrical properties and its widespread use in the electronics industry.

Surface machining refers to the deposition of thin structures on sacrificial layers that are later removed. This results in free-standing or completely detached structures. Mechanical devices which have been formed using this technique include: pin joints, gears, linkages, springs, micro-tongs, and electrical motors. For additional information on micromachining, see [9].

A recently developed micromachining technique is the LIGA (Lithographie, Galvanof ormung, Abformung) process. This process utilizes high energy X rays which can penetrate through an exposed area into a polymer layer. The polymer layer can be attached to a metallic or ceramic substrate or to a silicon wafer. The exposed areas of the polymer are then removed with a developing chemical, leaving behind a template or mold which can be filled up with another material (e.g., nickel) by electrodeposition. The remaining polymer can then be removed, leaving behind an attached or detached structure. The use of laser beams for material removal is also being explored.

Most micro-sensors are currently mass produced using bulk micromachining. Thin diaphragms form the basis for pressure sensors, pressure switches, load cells, and displacement sensors. Suspended mass structures are used to make vibration sensors, accelerometers and flow sensors. The mechanical deformation is converted into an electrical signal through a variety of methods such as utilizing the effect of the mechanical deformation on structure capacitance or electrical resistance or by measuring the deformation directly using optical techniques. Temperature-sensitive resistance films deposited on thermally isolated, dielectric material are used in mass flow rate and wall shear stress sensors.

Bulk produced, silicon-based, pressure sensors were first developed in the sixties for the aerospace industry, where wind tunnel experiments on airframes and the testing of jet engines created a demand for large numbers of exceedingly small sensors which pose minimal intrusion [5]. Since then, these sensors have conquered a major fraction of the pressure-sensor market, replacing older technologies such as transducers based on flexing Bourdon tubes and manometers. In addition to the aerospace industry, silicon based sensors have been adopted by the military, automotive industry, and household goods manufacturers. Witness the use of silicon based sensors in microwave ovens and vacuum cleaners. Currently, microfabricated sensors are being used to measure such diverse physical quantities as pressure, acceleration, fluid flow, chemical composition, density, viscosity, humidity, and tactile forces, among other things.

1.4 Future Trends

Modern technology continually requires increasing numbers of sensors and actuators with better performance characteristics. Batch processing allows the production of large numbers of sensors with on-chip conditioning circuitry at a reasonable cost. Microfabricated sensors are likely, therefore, to play an increasingly important role in the future and their market share is likely to keep increasing. They will continue to replace older technologies and will enable
new applications which heretofore were not feasible. In line with Feynman’s prophecy that there is “plenty of room at the bottom” [10], the trend towards reduction in the physical size of sensors is likely to continue; and the ability to manufacture smaller and smaller sensors, no doubt, will spur the development of new applications which were not previously thought possible.

Hybrid sensors and systems capable of measuring simultaneously a few physical quantities, such as flowrate, pressure, and temperature, are likely to experience an increase in demand. An interest in simultaneous measurement of various quantities may arise either because all these quantities are needed for process control or because of a need to improve a sensor’s precision by compensating for unwanted effects either in software or hardware. For example, pressure sensors are often sensitive to both temperature variations and accelerations and vibrations. Accordingly, one might wish to integrate temperature, acceleration, and pressure sensors on a single unit in order to provide for adequate compensation.

We are also likely to see the use of larger and larger networks of sensors in plants and processing lines. This will pose the problem of how to transmit and process huge amounts of information. A possible solution is to use several microprocessors operating in tandem, each of which will communicate with a cluster of sensors and actuators and with each other. Such communication networks may mimic neural nets and may be programmed to operate in a learning mode. To facilitate this type of development, new software tools and communications protocols will need to be developed.

It is likely that in the near future, traditional electronic communication lines will be replaced with fiber-optic cables, which will allow the transmission of larger amounts of information than is currently possible and will be free from electromagnetic interference. This, in turn, will help eliminate noise which often compromises sensor accuracy.

Mechanical sensors are playing an increasing role in medical applications as parts of medical instrumentation, diagnostic equipment, and prostheses. Our ability to manufacture sensors which can pass through the “eye of a needle” has resulted in sensors mounted on the tip of a catheter. Such sensors are inserted into various organs (eg, the heart) for diagnostic purposes. One day, micro-pressure sensor arrays might be implanted into the human ear canal to form an “artificial ear”. Moreover, the low cost of microfabricated sensors will allow their use as disposable devices, thereby eliminating the need for sterilization.

Researchers are also developing arrays of sensors for robots. Such robots may one day be equipped with tactile sensing pads with the sensitivity of the human finger.
1.4 Future Trends

Figure 1. The critical Reynolds number $R_{cr}$, the wave number $k_e$, and the wave speed at linear loss of stability are depicted as functions of the proportional controller's gain for laminar, Poiseuille flow of water between two parallel plates. The control strategy consists of measuring the deviation of the wall shear stress from its laminar value and changing the local wall temperature in proportion to this deviation with $K$ being the proportionality constant. The temperature alteration affects the adjacent fluid's viscosity. When the fluid decelerates, the temperature increases and the viscosity decreases, thereby counteracting the effect of flow disturbances. Witness that the critical Reynolds number increases/decreases as the controller's gain $(K)$ increases/decreases. It is hoped that this scheme can be used to delay or advance the transition to turbulence. (From [11].)

Sensors capable of operating in harsh environments are also sorely needed. For example, the material processing industry requires sensors to monitor transport processes in the melt during welding and casting and silicon crystal growers need better control of transport processes in the melt of the Czochralski crystal grower.

Some day, of course, other materials may replace silicon as the major construction material for micro-sensors. Optical fiber-based sensors are currently under development [12], for instance. Such sensors may take advantage of the piezoelectric effect of the optical fibers, the influence of the environment on the phase angle, or the polarization of the light transmitted in the fibers. Other classes of materials which may see increased use in the mechanical sensor community are ceramics and oxides [13] and piezoelectric polymers such as polyvinylidene fluoride (PVDF). PVDF materials can convert mechanical stimuli into electrical signals and can be used for manufacturing pressure or wall shear sensors.

A continuous discussion in sensor technology is whether or not to integrate electronic circuitry on the same chip as the sensor device. Most sensor processes are compatible with IC
processes, but still the total process is more complicated, which has its impact on the fabrication yield. For bulk-micromachined sensors, it is generally felt unwise to integrate more than a resistive network on-chip. However, surface micromachining offers better process compatibility, and sensors with complete electronic circuits may be expected. Complex integrated circuits with micromechanical components which take less chip surface than the electronic components have been demonstrated.

At present, 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. In the future, we might even see the appearance of monolithic microsystems.

In conclusion, sensor technology has developed tremendously in a relatively short period of time. But we have only scratched the surface. Many application areas stand to benefit from additional developments. The field of sensor technology is an active and evolving one.

1.5 Comments on Sensor Selection

This book describes a wide range of sensors which can be used for measuring the same physical quantities. In selecting the appropriate sensor, the user must consider a number of factors such as frequency response, precision, sensitivity to extraneous factors, calibration, size, safety, reliability, durability, compatibility with the working environment, and cost. In this section, we elaborate briefly on some of these factors.

Generally speaking, a sensor cannot be regarded in isolation. Typically, one is acquiring a "sensing system" which includes, in addition to the sensor itself, packaging, local signal processing electronics, transmission lines, and interfacing protocols. All of which should be consistent with the intended application.

Sensors in general, and mechanical sensors are no exception, almost never measure directly the quantity of interest (referred to as the desired input, see [14]). For example, pressure sensors often measure the deflection of a thin membrane. However, such a deflection can also be caused by temperature variations in the medium adjacent to the sensor and/or by acceleration and vibrations, in which case the pressure readings will be erroneous. Sensors are always sensitive to extraneous effects (interfering input). For this reason, it is important for the sensor user to be familiar with the principles of operation of the sensor and aware what secondary effects may influence the sensor's output. This knowledge will enable the user to select the sensor which is least sensitive to the extraneous effect present in his/her specific application or, alternatively, to decide on means to measure the interfering factors so as to correct for the undesired effects (i.e., modify the input). Compensation for interference can be integrated into the sensor design (compensation in hardware) or implemented into the signal processing algorithm (software compensation).

The user must also assure that the sensor and packaging materials are compatible with the working environment. Manufacturers typically will specify the range of temperature, pressures, accelerations, and other environmental conditions over which the sensor will function within stated specifications. In addition, the effect of a changing ambient temperature on the sensitivity and zero shift must be specified. Some sensors include internal temperature
compensation as well as (in special circumstances) compensation for other factors such as accelerations. The manufacturer will also specify the sensor’s sensitivity to factors such as temperature, vibrations, and accelerations. Some applications involve a corrosive, high temperature, toxic, dusty or otherwise hostile environment, and one has to assure that the sensor’s packaging is compatible with such an environment. In certain situations, the transducer must be isolated from its environment. For example, when silicon sensors are required to measure high pressures in a high temperature fluid, an additional diaphragm, usually made out of stainless steel, may be added between the silicon membrane and the measured fluid to isolate the silicon sensor. The space between the diaphragm is filled with an incompressible transmission fluid such as silicon oil. In the food and medical industries, it is important that the sensor’s surface is mounted flush with the container’s or instrument’s walls to facilitate cleaning and/or sterilization.

All sensors are invasive to some degree. By conducting a measurement, the sensor always perturbs the quantity it measures. For example, by positioning a flow or pressure sensor in the bulk of the fluid, one is likely to perturb the flow field and thus affect the measurand. The degree of flow modification caused by such a sensor is usually referred to as the “blockage factor”. On occasion, the disturbance is negligible such as in the case of optical measurements. On other occasions, the disturbance may not be readily apparent such as in the case of wall mounted hot films. These sensors alter the temperature and thus the viscosity of the adjacent fluid, sometimes significantly disturbing the flow. In short, the user must determine the extent to which the sensor’s presence will affect the phenomenon being measured and whether this disturbance is tolerable.

Calibration is another important factor in choosing a sensor. Calibration procedures include a comparison of the sensor’s reading with either a primary or a secondary standard. The calibration of the standard should be traceable to a standards organization. Various institutions such as the US National Institute of Standards and Technology (NIST) and the German Physikalisch-Technische Bundesanstalt (PTB) offer calibration services. The standard should preferably have a higher precision than the sensor to be calibrated. However, sensor technology has advanced very rapidly in recent years, leading to a situation in which the sensors to be calibrated often have a higher precision than the standards against which they are tested. This situation will change, no doubt, as standard organizations adopt new standards. Ideally, a sensor should be calibrated in situ under the same conditions in which it will operate. Unfortunately, this is rarely practical. Typically, the customer has to rely on “factory” calibration. Accordingly, it is imperative that the sensor have appropriate calibration documentation.

Other factors of concern are the static and dynamic responses of the sensor. The concepts of static and dynamic response are described in great detail in standard textbooks such as the one by Doeblin [15] and in the introductory volume to the Sensors series [16]. Briefly, the static response is specified, among other things, by the sensor’s accuracy and precision. The term “accuracy” refers to how close the sensor’s response is to the true value. The term “precision” refers to the reproducibility of the sensor’s readings. Dynamic response is of interest when the phenomena being measured is time-dependent. Dynamic response disclosure often will provide information about the sensor’s response when it is subjected to well defined, time-dependent variations of the measurand. These variations may be periodic or impulsive (e.g., step function). In the first case, a chart known as a frequency response may be given. In the latter case, the time constant is specified.
1.6 Remarks on Further Reading

The book at hand focuses on modern developments. For a description of more traditional sensors, the interested reader is referred to books such as those by Bekwith and Maran-goni [17], Doebelin [16], and Holman [18]. To keep up with newer developments, the reader is referred to such publications as the Journal of Sensors and Actuators, IEEE/ASME Journal of Microelectromechanical Systems, the Proceedings of the IEEE Solid-State Sensors and Actuator Workshops, J. of the Instrument Society of America, J. of Scientific Instruments, the Review of Scientific Instruments, Proceedings of the IEEE Micro Electro Mechanical Systems Workshop, and the journal, Sensors and Materials (newcomer, published in Japan). The above list is by no means all inclusive.

For general information on the fundamental aspects of sensors, their modeling, design and packaging, materials, fabrication techniques, signal processing, and interfacing, the reader is referred to the first volume in this series, Sensors Vol I: Fundamental and General Aspects, edited by Grandke and Ko [2].

1.7 References

2.1 Introduction

This chapter reviews current attempts to make mechanical microsensor prototypes, notably for gas flow measurement, using integrated circuit (IC) technologies such as CMOS (complementary metal oxide semiconductor) or bipolar technology, in combination with post-processing micromachining. This approach comes with the promise of batch fabrication and on-chip signal conditioning circuitry leading to cost-effective integrated microsystems.

A number of mechanical sensors are based on thermal effects, such as resistive heating and resistive or thermoelectric temperature detection. Classical resistance thermometers, thermocouples and related thermal mass flow meters are covered in Volume 4 in this series [1-3] and the book by Pollock [4], whereas this chapter aims at integrated thermomechanical sensors based on IC technologies with thermal insulation achieved by a final micromachining step.

The recent demonstration of thermopiles fabricated by using the materials inherent in bipolar [5, 6] or CMOS [6, 7] IC technology is of particular interest. Theory and materials of thermoelectric microsensors are therefore reviewed in Section 2.2-4. Section 2.5 is dedicated to the pertinent combination of IC technologies with micromachining. Section 2.6 presents selected IC compatible thermomechanical devices. Not all the sensors described here are for mechanical measurands, but all use micromechanical structures such as cantilever beams, bridges, or membranes.

2.2 Thermoelectric Effects

The thermoelectric effects discovered and analyzed by Seebeck in 1826 [8], Peltier in 1834 [9] and Thomson (Lord Kelvin) in 1857 [10] are widely used for sensors and actuators. The first theoretical treatment of thermoelectricity was given by Lord Kelvin in the framework of thermodynamics. Although based on a questionable assumption, his theory has the advantage of simplicity and gives correct results. It was not until the development of irreversible thermodynamics by Onsager in 1931 [11, 12] that the theory could be put on a firm foundation.

One of the first applications of thermoelectricity was the infrared detector, developed by Melloni in 1833 [13]. Meanwhile, thermoelectric generators have become important constituents of power supply systems in space and thermoelectric refrigerators are used for cooling. Seebeck’s discovery has become an important sensor effect: thermoelements are “active” or “self-generating” transducers converting temperature differences directly into electrical voltages without an external power supply. Wherever a measurand causes temperature changes, the thermoelectric sensor principle can be applied.

During the last decade, thermoelectric microsensors and actuators have been developed for the following purposes (see Section 2.6):

- measurement of radiation (radiometry, pyrometry);
- determination of electrical voltage, current, or power in a wide frequency range (Hz to GHz);
- flow measurements of gases and fluids;
2.2 Thermoelectric Effects

- vacuum and pressure gauges and thermal conductivity measurement;
- thermoelectric generation with power output in the mW range.

Thermoelectric devices compatible with standard IC technologies have been attempted recently [5-7, 14, 15], where sensor elements and circuitry can be co-integrated on the same chip. In situ signal conditioning brings about temperature compensation, low-noise sensor signals, and "smart" sensors. The small size of the resulting devices favors response speed and low consumption. Whenever large numbers of sensors are required, IC-style batch fabrication allows their production with a high performance-to-price ratio. These benefits can outweigh the disadvantage that IC processes may exclude certain sensor materials preferable from the point of view of thermoelectric efficiency.

2.2.1 The Seebeck Effect

A thermoelement or thermocouple is a junction of two electrically conducting materials (metal or semiconductor) A and B electrically connected at a "hot" point of temperature \( T_1 \) (see Figure 2-1). The nonconnected ends of both legs are kept at another temperature \( T_0 \) ("cold" point). In the open circuit case the net current flow through the thermoelement is zero and a thermoelectric or Seebeck voltage:

\[
U_S = \int_{T_0}^{T_1} \alpha_A (T) dT + \int_{T_1}^{T_0} \alpha_B (T) dT
\]

(2-1)

can be observed between the thermocouple leads at the "cold" point. For small temperature differences, \( (T_1 - T_0)/T_0 \ll 1 \), the Seebeck voltage can be approximated by

\[
U_S = (\alpha_A - \alpha_B) (T_1 - T_0) = \alpha_{A/B} (T_1 - T_0)
\]

(2-2)

where \( \alpha_A \) and \( \alpha_B \) denote the Seebeck coefficients (or thermopower or thermoelectric power) of materials A and B. They are specific transport properties, determined by the band structure and the carrier transport mechanisms of the materials. \( U_s \) is always created in electrically conducting material when a temperature gradient is maintained along the sample, but the Seebeck voltage cannot be observed with two legs of the same material for reasons of symmetry. The Seebeck coefficient is negative for charge transport mainly by electrons (n-type materials) and positive for conduction dominated by holes (p-type materials). Legs of p- and n-type should be combined in order to achieve large voltages, since then the absolute value of the resulting Seebeck coefficient \( \alpha_{A/B} = \alpha_A - \alpha_B \) is the sum of the absolute values of \( \alpha_A \) and \( \alpha_B \).

Figure 2-1.
The Seebeck effect: generation of a thermoelectric voltage \( U_S \) due to a temperature difference \( (T_1 - T_0) \).
The Seebeck voltage arises from the carrier drift caused by the applied temperature gradient. This drift induces a carrier concentration gradient and hence an electrical potential difference. The Seebeck coefficient relates the applied temperature gradient to the induced carrier gradient or to the gradient of the Fermi level \( E_F \), viz 
\[
\text{grad}(T) = \frac{1}{q} \text{grad}(E_F),
\]
where \( q \) denotes the elementary charge. The thermoelement can be connected with a load resistance \( R_L \) (see Figure 2-1) for thermoelectric energy conversion, which can be used in thermoelectric generators with up to 10% conversion efficiency in e.g., space vehicles.

### 2.2.2 The Peltier Effect

Peltier [9] discovered that heat is transferred from, or to, the ambient when an electrical current \( J \) flows through the junction of two materials (see Figure 2-2). Absorption or emission of heat depends on the direction of the current flow. The transported heat per unit charge depends on the band structure and the carrier scattering mechanisms of the materials. The absorbed or emitted "Peltier heat" \( Q_p \) is proportional to the number of charge carriers through the junction, i.e., the current flow \( I : Q_p = \Pi_{A/B} I \), where \( \Pi_{A/B} \) is the Peltier coefficient. In Figure 2-3 the situation is illustrated for a metal/n-type semiconductor transition. The energy difference \( E_C - E_F \) between semiconductor and metal electrons causes this effect.

![Figure 2-2. The Peltier effect: absorption or emission of heat \( Q_p \) at a junction due to electrical current \( I \). The Thomson effect: absorption or emission of heat \( Q_T \) due to carrier movement up or down a temperature gradient.](image)

![Figure 2-3. Illustration of Peltier effect for metal-semiconductor junction. \( E_F \): Fermi energy.](image)
2.2.3 The Thomson Effect

When the junctions of a Peltier element are at different temperatures $T_1$ and $T_0$ (see Figure 2-2), heat must be absorbed or released by the legs because of energy conservation [10]. Heat absorption or emission depends on the direction of current and temperature gradient. The "Thomson heat" $Q_{TV}$ per unit volume is $Q_{TV} = \tau_T j \text{ grad}(T)$, where $j$ is the current density and $\tau_T$ the Thomson coefficient. For a thermoelectric leg with constant cross section the total Thomson heat $Q_T$ is

$$Q_T = \int_{T_0}^{T_1} \frac{\tau_T}{T_0} j dT .$$ (2-3)

The three thermoelectric coefficients are connected by relationships discovered by Thomson [10] and derived by Onsager [11, 12], viz, $\Pi = \alpha T$ and $\tau_T = (d\alpha/dT) T$.

2.3 Thermoelectric Sensor Parameters

The characteristic sensor parameters are derived in two steps. From the energy balance of the system we determine the temperature rise caused by the absorbed heat. From this temperature rise we derive the generated thermoelectric voltage $U_S$, which is the detector output. The voltage $U_S$ per unit incoming heat or internal sensor noise characterizes the sensor responsivity or detectivity, respectively.

2.3.1 The Ideal Thermoelectric Sensor

Figure 2-4 illustrates a thermoelectric sensor and the corresponding heat balance. The sensor consists of a sensitive area $F$ (with radiation conductance $G_F$) coupled via two thermoelectric legs (thermal conductance $G_L$) to a heat sink of constant ambient temperature $T_0$. Without thermal input the average temperature of $F$ is $T_0$, but the temperature fluctuates...
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around this value. This fluctuation causes the "temperature noise", which ultimately limits the minimum signal detectable. When a heating power $N$ (which can arise from radiation, electrical heating or other sources) is absorbed by $F$, the temperature increases to $T_i$. The power $N$ is dissipated by thermal conduction via $G_L$ and by radiation via $G_F$. The corresponding heat fluxes are $N_T$ and $N_F$, respectively. For small temperature differences $(T_i - T_0)/T_0 \ll 1$, the heat fluxes $N_T$ and $N_F$ can be expressed in terms of the conductances $G_L$ and $G_F$. Assuming zero convection heat losses (operation in high vacuum) and negligible radiation losses of the thermoelectric legs in comparison with $G_L$, we obtain the heat balance equation:

$$N = N_T + N_F = G_L (T_i - T_0) + G_F (T_i - T_0)$$  \hspace{1cm} (2-4)

and hence the steady-state temperature increase of the sensor:

$$(T_i - T_0) = N/(G_L + G_F) = R_T N$$  \hspace{1cm} (2-5)

where $R_T$ denotes the thermal resistance, $G_L$ is determined by the dimensions (length $l$, cross sectional areas $A_1$, $A_2$) and the thermal conductivities $\lambda_1$, $\lambda_2$, of the legs, $G_L = \lambda_1 A_1/l + \lambda_2 A_2/l$, and $G_F$ by the Stefan–Boltzmann law, $G_F = 4 \varepsilon \sigma_s T_0^3 F$, where $\varepsilon$ is the emissivity of $F$ and $\sigma_s$ is the Stefan–Boltzmann constant.

Analyzing the transient behavior in terms of a harmonic time-dependent power input $N(t) = N + N_0 \exp(i\omega t)$ leads to a response time (time constant) $t = R_T C$, where $C$ is the heat capacitance of the sensor, and the thermoelectric voltage

$$U_s = \alpha_{A/B} [(T_i - T_0) + T_0(t)]$$  \hspace{1cm} (2-6)

with $T_0(t) = N_0 (G^2 + \omega^2 C^2)^{-1/2} \exp(i\omega t + \phi)$, $G = G_L + G_F$ and the phase $\phi = \tan^{-1}(\omega C/G)$. Clearly, $T_i - T_0$ and $N_0 (G^2 + \omega^2 C^2)^{-1/2}$ should be as large as possible. To this end, $G$ should be small and $\omega C$ should obey $\omega C \ll G$, i.e., the thermal capacitance of the detector and its thermal coupling should be as small as possible. These requirements can best be met by microsensors using thin-film techniques and micromachining.

The steady-state sensitivity (responsivity) $S$ is the ratio of the signal voltage $U_s$ and the incoming power $N$:

$$S = U_s/N = \alpha_{A/B} R_T$$  \hspace{1cm} (2-7)

The noise equivalent power (NEP) relates the sensitivity $S$ to the noise voltage $U_N$. For our ideal sensor we assume only thermal noise (Nyquist noise) arising from the resistance $R = \rho_1/A_1 + \rho_2 /A_2$, where $\rho_1$ and $\rho_2$ denote the electric resistivities of the legs, hence

$$\text{NEP} = U_N/S = \sqrt{4k T_0 R \Delta f}/\alpha_{A/B} R_T$$  \hspace{1cm} (2-8)

where $\Delta f$ is the amplified noise band width and $k$ is the Boltzmann constant. The detectivity $D = 1/\text{NEP}$ is usually referred to the sensitive area $F$ and $\Delta f = 1$ Hz, resulting in the specific detectivity:

$$D^* = S\sqrt{F}/U_N = \alpha_{A/B} R_T \sqrt{F}/\sqrt{4k T_0 R}$$  \hspace{1cm} (2-9)