Chapter 1
Introduction

Abstract This chapter introduces the state-of-the-art in the main topics covered in the book: energy harvesting, with special interest in the body energy harvesting sources, biosensors, and finally the electronics for them. These are the main aspects to consider in the envisaged conception of the Self-Powered architecture for subcutaneous detector device.

Keywords Low-power instrumentation · Miniaturized biomedical system · Wireless implanted devices · Self-Powered devices · Event detector implantable devices

The integration of medicine and electronic technologies allows the development of biomedical devices able to diagnose and/or treat pathologies by detecting and/or monitoring pathogens, multiple ions, PH changes, and so on. Moreover, the advances in different areas such microelectronics, microfluidics, microsensors and biocompatible materials open the door to develop human body Lab-on-Chip Implantable Devices and Point-of-Care in-vitro devices.

The key aspect on the development of subcutaneous applications consists on combining the powering and the instrumentation in the same device, hence two main problems should be overcome. The first one consists on the integration of the necessary instrumentation and communication electronics to control the sensors/Biosensors and to send the information through human skin, whereas the second one resides in the way to transfer enough energy to power the device.

Some examples of implantable telemetry electronics integration can be found in the literature like in [1, 2] or [3] and in [4] and [5] where two integrated electronics for in-vivo monitoring are introduced. Although many efforts have been focused on developing robust electronics for in-vivo monitoring, that is continuously sensing, recording and data transmission, not all the in-vivo subcutaneous applications require these circuits. There are other less studied applications more focused on the detection of presence or absence of a certain levels of proteins, antibodies, ions, oxygen, glucose, etc...

These in-vivo subcutaneous event detection circuits or True/False applications [4] work as an alarm; when the analyzed concentration level exceed, under or over,

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a threshold value or the system detects the presence of zero tolerance pathogens like salmonella [4], the systems send to an external reader a signal indicating the fault or showing the value as in some pregnancy tests.

For instance, in the case of glucose monitoring, the detection of a threshold decrease in the glucose level it is mandatory to avoid critic situations like the hypoglycaemia [6]. In that case, the True/False implantable device could check the glucose levels to manage an automatic method to inject insulin to regulate the glucose level on blood.

The second question to be considered is how supply energy to the subcutaneous or implantable devices. Since it is quite difficult to use the classical bulky batteries or other more modern type of batteries under the human skin, the device is not a pacemaker that is inserted into the chest, this is implanted just under the skin, a smart solution consists in harvesting the energy from the environment and, in that particular case, to recollect the energy coming from the human being to self-power the implanted device.

In application areas as diverse as aircraft construction, personal health care systems or burglary detection systems, energy harvesting is on the verge of developing a market with a multibillion dollar potential. For instance, an electronic device including a semiconductor-based thermo electric generator (TEG) that transforms temperature differences into electrical energy could be worn on the body using the human body heat as an energy source for medical monitoring. Furthermore, the total amount of energy demanded to the energy suppliers could be strongly reduced just walking around while carrying on the body or on the clothes several autonomous portable devices in which energy harvesting from vibrations has been included.

The benefits of this green local actuation could get a huge impact in the global energy demand. In the particular case of personal healthcare, the combination of harvesting sources and/or thin-film batteries opens new fields of interest, like Patient Monitoring & Tracking, Transdermal Drug Delivery, Accelerated Healing Devices and Pharmaceutical Compliance in the conception of a Body Sensor Network (BSN).

The miniaturization of electronics and the combination with solutions like the thin-film batteries by Silicore [7] are interesting options in the development of new Transdermal Drug Delivery (TDD) methods [8, 9] with the idea to eliminate needles, Fig. 1.1, and to ensure proper dosage control, closing the feedback of an artificial pancreas.

Moreover, an inductive coupling RF power harvesting is a growing alternative method to transmit energy transcutaneously instead of batteries or wires [10–12], and for the particular case of subcutaneous devices it seems a good approach.

Furthermore, this alternative permits to establish a bidirectional communication between the implanted device and an external base or reader. Some implantable RF circuits based on inductively coupling can be found in the literature like in [13, 14]. Several energy sources as well as the state of the art in energy harvesting are introduced later on in this chapter, whereas on Chapter 2 is developed our approach to Multi-Harvesting Power Chip (MHPC) applicable to generic developments.

A the end of this work, on Chapter 4, it is presented a generic implantable front-end architecture based on an inductive coupling for in-vivo presence or absence

Fig. 1.1 Patch example from [8]

detection of pathogens, ions, oxygen concentration, etc... for a generic amperometric Biosensors application. The proposed architecture includes the on-chip biasing, the potentiostat to drive the sensor, and the modulation and communication block.

The final step of this book is the conception of a first capsule prototype with an ideal size less than 4.5 cm long and 2.5 cm in diameter following the same philosophy like some contraceptives subcutaneous implantable devices like Norplant®, Jadelle® or Implanon® [15, 16].

All circuits in this work have been developed with the 130 nm technology from ST Microelectronics available through the CMP Tima. This tech. gives a nice tradeoff between area and Analog/Digital performances for that type of applications.

1.1 Energy Harvesting in Human and Non-human Activities

1.1.1 Introduction

Nowadays, there is an enormous interest on renewable energy sources and its applications, especially for high-power levels [17, 18, 19]. There is also an increasing interest in using free available external energy sources for powering small electronic systems, a process known as energy harvesting [20]. However, the amount of energy that can be obtained from these external ambient sources like vibrations, heat gradients, light, radio waves [21–23, , , 14], or from human activity [25, 26] is limited regarding power consumption levels.

Some already published works show the design of self-powered systems based on MEMS micro-power sources like electromagnetic micro-power MEMS generators [27, 28], variable capacitors [29], piezoelectric-based generators [30, 31], or defining completely an integrated sensor node [32]. Examples of these technologies are the design of self-powered wireless networks [33] formed by distributed sensors which are capable of monitoring the real-time condition of motors, turbines, pumps, and gear boxes, or the design of heating or ventilation control systems for burglary alarms.

One of the most interesting application fields is biology where self-powered RFID bio tags can monitor the temperature, pressure [34, 35] or check animal's healthcare [36, 37].

The continuous advances in the semiconductor's integration technology related to the reduction of the transistor's size allow the industry to develop these new self-powered portable electronic devices which usually include in their System-in-Package (SiP) or System-on-Chip (SoC) a great variety of circuitry and functions like wireless sensor networks or biomedical electrical instrumentation. However, the main problem with these new devices resides in the power supply system, which is usually based on a typical bulky battery solution often with much larger size than the SiP or SoC itself.

The size, width, finite energy lifetime, and battery replacement are important drawbacks for those small and portable applications that need long lifetime energy supply systems [38–40]. So, novel and innovative energy supply alternatives must be explored to remove or replace the battery dependence and make feasible the deployment of these batteryless devices. Focusing on this field, a new trend in the research of energy sources for low-power applications is growing rapidly over the last years.

This approach consists in harvesting the available energy of the environment in order to supply enough power to the electronic applications instead of using a battery or other technologies with short lifetime and finite amount of energy.

1.1.2 State-of-the-Art of the Energy Harvesting

The first energy cell, the battery, was invented by Alessandro Volta 1799. His invention predated the first mechanical to electrical energy converter device discovered by Michael Faraday. At the beginning, batteries were the only way to generate electrical energy. It was at the end of nineteenth century when electricity arrives to the cities by wires and the batteries were relegated to mobile platforms.

Battery technology underwent a tremendous progress since it was first discovered. This progress enabled the explosion of a huge number of new applications such for mobile devices. However, new challenges in technology added to some intrinsic limitations of batteries have motivated the research to look for new smart energy generation solution systems.

These new smart energy systems are conceived to actively "monitor and optimize themselves". The requirements and expectations for these systems are: efficiency, sustainability, intelligence, autonomy, a high degree of integration, etc... These expectations rule out the use of batteries as energy sources because they have a limited life time, which is in contrast to the concept of "Smart". In addition, batteries produce pollutant residues. New energy solutions must have a very long life time and must be sustainable.

A very interesting publication to the "Economist Group" about future trends was presented in 2003 by the Microsoft chairman and chief software architect Bill Gates [41]. The publication was named "The Disappearing Computer". In that publication, he envisioned a future world where ubiquitous embedded systems will interact with people whether they know it or not. Those envisioned systems will have to run without batteries and use power harvesting systems to transform environmental energy into usable electrical energy.

> As people find more ways to incorporate these inexpensive, flexible and infinitely customizable devices into their lives, the computers themselves will gradually "disappear" into the fabric of our lives. We are still a long way from a world full of disembodied intelligent machines, but the computing experience of the coming decade will be so seamless and intuitive that–increasingly–we will barely notice it. At the same time, computing will become widespread enough that we will take it for granted–just as most people in the developed world today trust the telephone service.
>
> The pervasiveness and near–invisibility of computing will be helped along by new technologies such as cheap, flexible displays, fingernail-sized MEMs (microelectromechanical systems) chips capable of storing terabytes of data, or inductively powered computers that rely on heat and motion from their environment to run without batteries.

Thus, the solution for this energy problem seems to pass through the design of systems capable of continuously transform energy from the environment into electrical energy useful to supply an electronics device. This procedure is known as "power harvesting". Basically, four different power sources are available in the environment: mechanical vibrations, solar, thermal and Magnetically Induced.

1.1.2.1 Mechanical Vibrations

Mechanical vibrations can be found in many places. In floors and walls of a building caused by nearby machinery. In automobile chassis or tires, in jet engine housing, human walking, etc…

These vibrations present a wide range of amplitudes and frequencies. Medium frequency vibration appears in our daily life. For example, inside a building or inside a lab, there are different vibrations produced by different sources. Figure 1.2 shows typical vibration sources that act inside a laboratory [42].

Moreover, in our daily home life it is also used some machinery that also produces vibrations like a microwave oven or a milling machine. In general, we are submitted to vibrations from 1 to 100 Hz. Some other intermediate vibrations appear with higher accelerations in vehicles, i.e. it is possible to find vibration frequencies up to 1 kHz @ 10m/s^2 inside a car. Higher frequencies can be found in industrial applications. Some specific engines such as some turbines or motors generate frequencies > 1 kHz.

Researchers usually have long designed systems exploiting the oscillations of a proof mass to harvest mechanical vibration energy. These kinds of converters are also known as "Inertial Converters". There are different ways to convert this mechanical energy into electrical energy. In fact there exist three kinds of physical

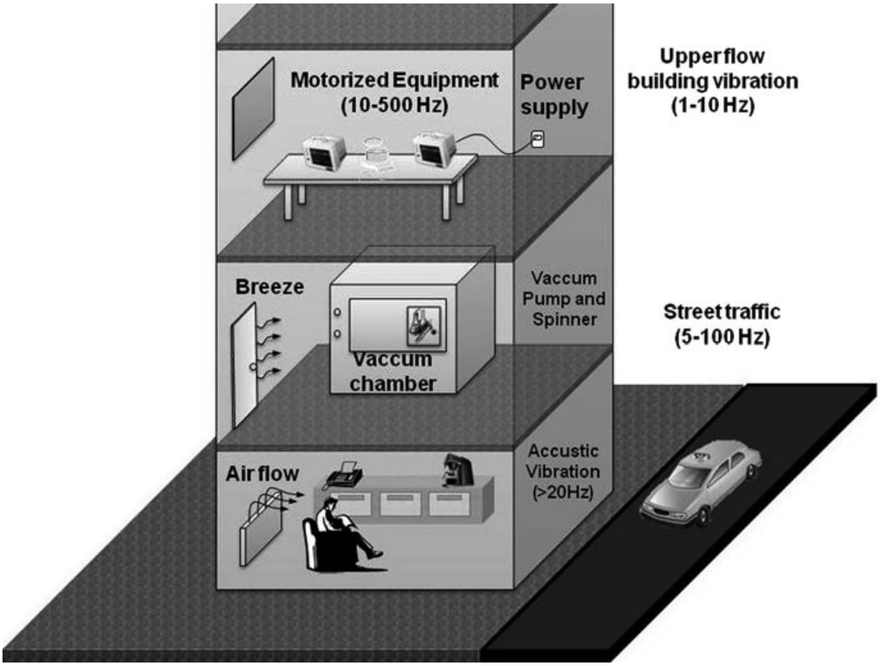

Fig. 1.2 Common environmental sources of noise in a laboratory [43]

principles that can be used: (1) magnetic induction converters, (2) electrostatic converters and (3) piezoelectric converters.

The magnetic induction transducer (1) is based on Faraday's law. It is based on the motion of an electric conductor through a magnetic field. Typically the conductor is wound in a coil to make an inductor. The relative motion between the coil and magnetic field causes a current flowing in the coil.

Some relevant research groups have been designing electromagnetic power generators. MIT researchers [44] developed a generator able to deliver 400 μW using the human walking activity as vibration source. On the other hand, other group from Sheffield, presented a 1 mm^3 size electromagnetic micro-generator, able to generate 0.3 μW from a 4 MHz input excitation.

Electrostatic generation (2) consists of two conductors separated by a dielectric (i.e. a capacitor), which moves relative to one another. As the conductors move, the energy stored in the capacitor changes, thus providing the mechanism for mechanical to electrical energy conversion. Menninger et al. of MIT presented an electrostatic generator that employs a variable micro machined capacitor to recollect ambient vibrations.

The third physical technique consists in using the well known piezoelectric materials. These materials generate an electric field or electric potential in response to a mechanical stress. Like the other techniques it is possible to find some examples of generator based on piezoelectric like in [42].

There are a lot of variables and trade-offs to take into account when designing systems for harvesting from vibrations. Some of the more important ones are: volume restrictions, specifications of the vibration source and environment of application, the available electronic and mechatronic technology, etc… Although all these aspects will influence the solution to be adopted, it is interesting to make a quantitative comparison in terms of energy density inherent to each type of converter.

Table 1.1 presented by Roundy et al. [45] shows the expressions for the three energy converters. Moreover, a computation of the theoretical and practical maximum values is shown. The piezoelectric energy density equation is obtained considering the energy density in a dielectric material and the electric field induced by a mechanical stress. The energy density equation for an electrostatic converter is directly computed as the energy density in a dielectric material and finally, the energy density in the electromagnetic generator is directly computed as the energy of a magnetic field.

Table 1.1 Summary of maximum energy density of three types of mechanical transducers

Type	Governing equation	Practical max. (mJ/cm^3)	Theoretical max.
Piezoelectric	$u = \sigma_y^2 k^2 \big/ 2Y$	17.7	335 mJ/cm^3
Electrostatic	$u = 0.5\varepsilon E^2$	4	44 mJ/cm^3
Electromagnetic	$u = B^2 \big/ 2\mu_0$	4	400 mJ/cm^3

The quantitative comparison is based on the evaluation of the maximum energy densities that these materials can sustain. In the case of the piezoelectric converter, the maximum energy density is achieved when the material sustains the maximum stress before breaking; this is named the “yield strength”.

Table 1.1 also shows that piezoelectric converters have higher practical energy densities than the other two options. Nevertheless, it is important to have in mind other qualitative and performance comparisons for these converters.

- *Electromagnetic* converters produce very low voltages. This is a serious problem because the signal generated from the converter is an AC signal so it needs to be rectified. In order to increase this signal a heavy transformer has to be used so the dimensions of the whole system increase. These converters have other problems intrinsically associated to them. The role of the magnetic fields in the transduction process can produce interferences with its associated electronic circuitry. These converters have the advantage of being easily micro-mechanized.
- *Electrostatic* converters have the disadvantage of requiring an external power source to charge the capacitor beforehand; moreover they need a mechanical stopper in order to avoid the contact between the two plates. This mechanical stopper will increase the damping of the system. On the other hand, these converters produce higher voltages than the electromagnetic ones, and can be directly rectified. A very interesting advantage of these converters is their easy integration

in micromechanics systems that allow the design of compact and specifically designed systems.

- *Piezoelectric* converters have the highest energy density. The voltage and current levels are in an acceptable range and are easily modified to fulfill the input specifications. These converters do not need any magnetic field or mechanical stopper.

1.1.2.2 Solar Energy

It consists on using the energy radiated by the sun and it is widely used as a power source in many applications. In fact, solar radiation varies around the world due to weather conditions, longitude and latitude, etc. However, it is possible to give an averaged value for a direct bright sun of about 100 mW/cm^2. It is also possible to use the emitted light inside a building; in this case an average value of about 100 μW/cm2 is expected [46].

The conversion principle for changing light into electrical energy is based on the photovoltaic effect. This effect is the result from the interaction between light and matter, the absorption of the photon energy by the photovoltaic cell generates electrical current. Silicon solar cells are a mature technology for a large scale.

Photovoltaic systems are found from the Megawatt to the milliwatt range, producing electricity for a wide range of applications with efficiencies from 12 to 25%. There are thousands of companies that supply silicon solar cells and spend millions of dollars to improve its efficiencies while reducing costs.

However, new materials with tremendous challenging potential applications are being used to form photovoltaic cells. Nanosolar [47], Konarka [48], and other companies are developing energy-producing material with solar cells embedded in thin sheets of plastic, which promises to drastically reduce solar power's cost. This "power plastic" can be laminated onto any surface, from rooftops to laptops to automobiles [49].

1.1.2.3 Thermoelectric Generators

The use of heat gradients to generate energy was one of the first ways to accomplish energy conversion. The classical "vapor machines" used the expansion of a gas, that when heated, moved a piston by pressure and generates a mechanical motion. However, since it would need to combust some kind of substance or material, this kind of systems could not be considered as an energy harvesting system,

On the other hand, in the environment, there are different constant sources of wasted heat that can be used to generate electrical power. The human body is always at the same temperature even the environmental temperature changes, this heat gradient can be used to generate electrical current.

There are different methods or principles to convert a heat gradient into electrical energy: 1) thermoelectric generators and 2) pyroelectric generators.

Thermoelectric generators (1), which have been of great interest in the recent years, are based on a junction of two dissimilar materials "n" and "p" semiconductors. These are connected by a metal conductor at the hot and at the cold side of the gradient. Temperature gradients across the thermoelectric material drives electron charge carriers from the hot to the cold junction and produce a voltage. Thermoelectric generators are a good choice since they can be microfabricated with classical microfabrication techniques.

In 1997, Stordeur et al. designed a micropower thermoelectric generator able to produce 20 μW with $\Lambda T = 20$ °K [50]. Nowadays, some companies are selling products based on thermoelectric generators. For example, Seiko placed for sale a thermal wristwatch that uses 10 thermoelectric modules to generate sufficient microwatts to run its mechanical clock [51]. Applied Digital Solution presented the Thermo Life that is a thermoelectric generator measuring 0.5 cm^2 and 1.6 mm thick, which can supply energy to a Biosensor when it contacts with the skin. It is able to supply 5 μA @ 3 V with a 5°C of gradient temperature, [52].

Pyroelectric solutions (2) are based on polar materials when they are subjected to temperature changes. The effect is similar to the piezoelectric effect but, instead of electric charges appearing when the material is deformed, superficial charges appear in a certain direction, when the material changes its temperature.

1.1.2.4 Mechanical, Thermoelectric and Solar Energy Comparison

A comparison of the different energy harvesting technologies is extracted from the analysis made by Shad Roundy in his dissertation submitted at the Virginia Polytechnique Inststute [53]. Table 1.2 shows the energy densities for a set of different environmental scavenged power sources and for some energy reservoirs.

The table is composed by three columns. The first one shows the energy density during the first year. The second column shows the energy density for the first year and up to the tenth year of life. This information is given to show the decrease in the performances of the energy reservoirs after several uses. The third column shows the source of information.

While this table of comparison is by no means exhaustive, it does provide a broad overview of potential methods to scavenge energy and energy storage systems. It is clearly seen that the energy reservoir undergoes to a considerable reduction of its energy density (one order of magnitude) after the first years of use, except for the nuclear uranium based sources.

This degradation in performance reduces the number of applications where this energy sources could be used. In contrast, the harvesting sources theoretically present the same performance after 1 year of life; therefore, it is possible to think in applications where the systems are completely autonomous for a long time.

Comparing the different sources, it is clear that the most energetic is the solar solution in a sunny day. This is the most widely used solution due to the ubiquitous of solar light. Mechanical vibrations are presented as the next more energetic solution because mechanical vibrations surround our daily life. Furthermore, some

Table 1.2 Comparison of energy scavenging and energy storage methods. Note that leakage effects are taken into consideration for batteries [53]

		Power density (μW / cm^3) 1 Year lifetime	Power density (μW / cm^3) 10 Year lifetime	Source
Scavenged power source	Solar (outdoors)	15,000 – direct sun 150 – cloudy day	15,000 – direct sun 150 – cloudy day	Commonly available
	Solar (indoors)	6 – office desk	6 – office desk	0
	Vibrations	200	200	Roundy 2002
	Acoustic noise	0.003 @ 75 dB 0.96 @ 100 dB	0.003 @ 75 dB 0.96 @ 100 dB	Theory
	Daily temp. variation	10	10	Theory
	Temp. gradient	15 @ 10 ªC gradient	15 @ 10 ªC gradient	Stordeur and Stark 1997
	Shoe inserts	330	330	Shenk and Paradiso 2001
Energy reservoirs	Batteries (non-recharge lithium)	45	3.5	Commonly available
	Batteries (rechargeable Lithium)	7	0	Commonly available
	Hydrocarbon fuel (micro heat engine)	333	33	Mehra 2000
	Fuel cells (methanol)	280	28	Commonly available
	Nuclear isotopes (uranium)	6×10^6	6×10^5	Commonly available

theoretical and experimental implementations demonstrate generations of about 200 μW/cm^2.

Big efforts are being done to accomplish designs for harvesting this energy. The last raw of the scavenged solutions shows the shoe insert solution. Some researchers have pointed out the possibility to use the energy damped in the sole of a shoe to drive some kind of wearable device. It is possible to harvest around 300 μW/cm^2 of power density, for normal walking conditions. The table shows other sources however the amount of energy these sources provide is very small.

1.1.2.5 Magnetically Induced Energy

Nowadays, wireless communications and transmissions are present in our daily activities generating lots of energy in electromagnetic form. Although, it is not strictly a power generator that can be easily and naturally found in the environment, the electromagnetic radiation can be used to power small devices such as energy transport media. Following that idea, terms like Witricity [54] or Wireless Power Transmission or Inductive Powering are becoming popular to power some equipment.

Wireless power transmission is basically based on the use of two electromagnetic resonant objects (i.e. one transmitter and one receiver antennas) tuned at the same frequency. In that way, the energy is transferred thanks to the electromagnetic coupling between both objects. Moreover, an electromagnetic field can be specifically designed to work at a specific frequency and orientation.

The possibility of industrial applications of this Wireless Power was demonstrated by MIT Researchers [55, 56]. They power a 60 W light bulb using two cooper coils of 60 cm diameter working at 9.9 MHz. The coils were inductively coupled achieving an efficiency of 45% for a separation of 2 m, one working as emitter and the other connected to the bulb.

Moreover, in the biomedical field, the use of an Inductive Link working at the appropriate frequency is a valuable option to transmit energy transcutaneously. Thus, the subcutaneous implantable devices can be designed avoiding the use of bulky batteries or even wires through the human skin. Other advantage is the possibility to establish a bidirectional data communication over the same Inductive link used for energy transmission.

This smart combination of power and transmission makes the use of Magnetic Induction highly valuable for sensitive applications like human subcutaneous implantable devices.

A widely used example of inductive links is a microchip implant for pet's identification. It is a Radio Frequency Identifier tag (RFID) with a unique chip number. This chip is implanted into the pet, cat, dog, etc... and the number is automatically associated to the owner after filling an enrolment form with the chip number, owner name and contact information. In that way, if the pet is lost or stolen, it can be scanned to obtain the owner information.

1.1.3 Body Harvesting

At that point, after study different environmental energy sources, it is time to analyze the energy harvesting sources available from the human body. Several studies and analysis have been reported that the human body can be used as a generator. Basically, the body could generate power in two ways, passively or actively.

Passive human generation of power for a product means that the person does not perform any special activity to drive the product. That is, passive powering takes place when the user does not have to do any task different to normal tasks associated with the product.

On the other side, active generation means that the person performs an activity that when using the same product not powered by a human would not have been performed. Generally speaking, more power can be generated actively than passively [21].

There are different available sources to harvest energy in the body, thermal, vibration or even magnetically induced thanks to the advances in portable local wireless systems. The human body is a tremendous storehouse of energy but, some key aspects must be taken into account.

The first source approach is related to the body heat. Since the human body emits energy as heat, it follows naturally to try to harness this energy. However, Carnot efficiency puts an upper limit on how well this waste heat can be recovered. Assuming normal body temperature and a relatively low room temperature (20°C), the Carnot efficiency is: (In a warmer environment (27°C) the Carnot efficiency drops to 3.2%)

$$\frac{T_{BODY} - T_{ambient}}{T_{BODY}} = \frac{310\,K - 293\,k}{310\,K} = 5.5\% \; 2.2$$

The energy that can be recovered using the Carnot engine is in the range of 2.4 W–4.8 W. Taking into account that the total amount of power that is wasted in the form of heat it is around 100 W, this represents a low efficiency.

While a full wetsuit or even a torso body suit is unsuitable for many applications, the neck offers a good location for a tight seal, access to major centres of blood flow, and easy removal by the user. The neck is approximately 1/15 of the surface area of the "core" region (those parts that the body tries to keep warm at all times). As a rough estimate, assuming even heat dissipation over the body, a maximum of 0.20–0.32 W could be recovered conveniently by such a neck braces.

The head may also be a convenient heat source for some applications where protective hoods are already in place. Furthermore, the head is also a very convenient spot for coupling sensory input to the user is some biomedical applications. The surface area of the head is approximately three times the neck area and could provide 0.60–0.96 W with an optimal conversion.

There are different approaches to recover this energy thanks to thermoelectric generators. Low-power thermoelectrically-driven products have appeared. Produced during the 1990s, the Seiko Thermal-wristwatch [51] uses ten thermoelectric modules to generate a microwatt from the small thermal gradient provided by body heat over ambient temperature to activate its mechanical clock movement.

Other company, Applied Digital Solutions, developed a thermoelectric generator called Thermo Life [57] with an area of 0.5 cm^2 and 1.6 mm thickness. It can generate 10 μA at 3 V (6 V open circuit) with only 5°C of temperature difference thank to its dense array of low-temperature thermopiles.

The ThermoLife is designed to power low-current Biosensor electronics working in contact with the skin. These systems typically come with batteries that store extra energy produced during periods of higher temperature differences, so they can work continuously during less efficient ambient temperatures.

The motion of the body is also a feasible power source for harvesting. Several normal movements of the human body can be used as energy sources as is depicted in the body map of Fig. 1.3

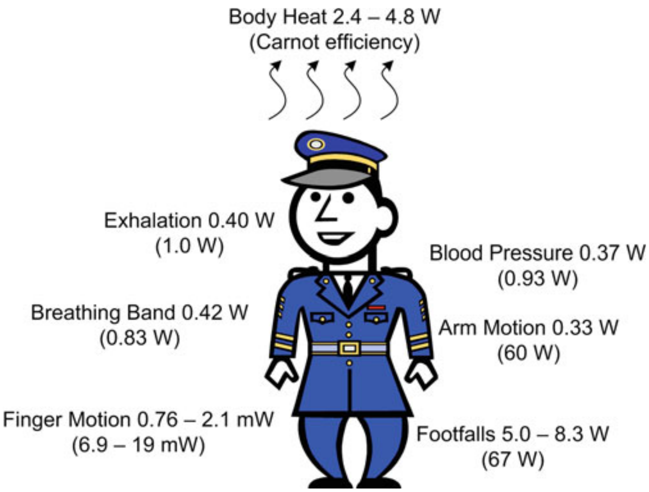

Fig. 1.3 Possible power recovery from body-centered sources. Total power for each action is included in parentheses [21]

Table 1.3 Some examples of active human generation by specific movements (Activity)

Activity	Power generation (W)
Finger (pushing pen)	0.3
Legs (cycling 25 km/h)	100
Hand and arm (freeplay)	21
Hand (aladdinpower)	3.6

Table 1.3 Presents some examples of generated energy with human movements. As can be seen, the amount of power generated depends on the activity and the moved limb

In [58] appears the idea of an energy fitness club where people could reload their portable device while getting in shape. The conception of the pedaling work could be used to supply different consumer electronics, Fig. 1.4 It is estimated that 10 min pedaling on a bicycle could generate 2 W and reload a mobile phone, which is described by the authors as HUMAN POWER.

Other foot-driven generators are not based on bicycles and use a small stationary pedal coupled to an embedded magnetic generator. A perfect example is the “Step charger” manufactured by Nissho Engineering able to generate up to 6 W when the pedal is vigorously pumped.

The Nissho Aladdinpower®, Fig. 1.4, is another product that uses human power. It is a hand-powered device that supplies power to electronic devices. IT is generated enough power to partially recharge a small battery when squeezing it for a minute.

Also, Freeplay [59] is a great example of an enterprise working in this field. This company is solely dedicated to human powered (also called free-powered) products.

Fig. 1.4 Power recovery from pedaling activity [58] and the Aladdinpower® charger

Fig. 1.5 Examples of Freeplay products. From left to right, the Indigo Self-Sufficient LED Lantern, a rechargeable FlashLigh and the ZipCharger ultra fast charger [59]

Some of their products are flashlights, lanterns, or portable zip-charger based on the movement like those shown in Fig. 1.5.

The walking activity is also a source of energy. The MIT Media Lab. has developed a full system able to harvest parasitic power in shoes employing piezoelectric materials [60, 61], Fig. 1.6. The low-frequency piezoelectric shoe signals are converted into a continuous electrical energy source. The first system consists in harvesting the energy dissipated in bending the ball of the foot by placing a multilaminar PVDF bimorph under the insole. The second one consists in harvesting the foot strike energy with a semi-flexible PZT under the heel. Both devices were excited under a 0.9 Hz walking activity.

Fig. 1.6 A pair of sneakers equipped with piezoelectric power-generating insoles and self-powered transmitter [60]

Industrial applications could also be developed using passive power harvesting. A nice example is the piezoelectric energy conversion at the Tokyo metro station [59]. They expect to obtain over 1,400 kW per day thanks to the walking of the passengers.

On the other hand, human harvesting could be also applied in biomedical and e-health monitoring. Figure 1.7 presents the conception of ubiquitous Body-Sensor network with external and implanted Biosensor powered by human harvesting [61].

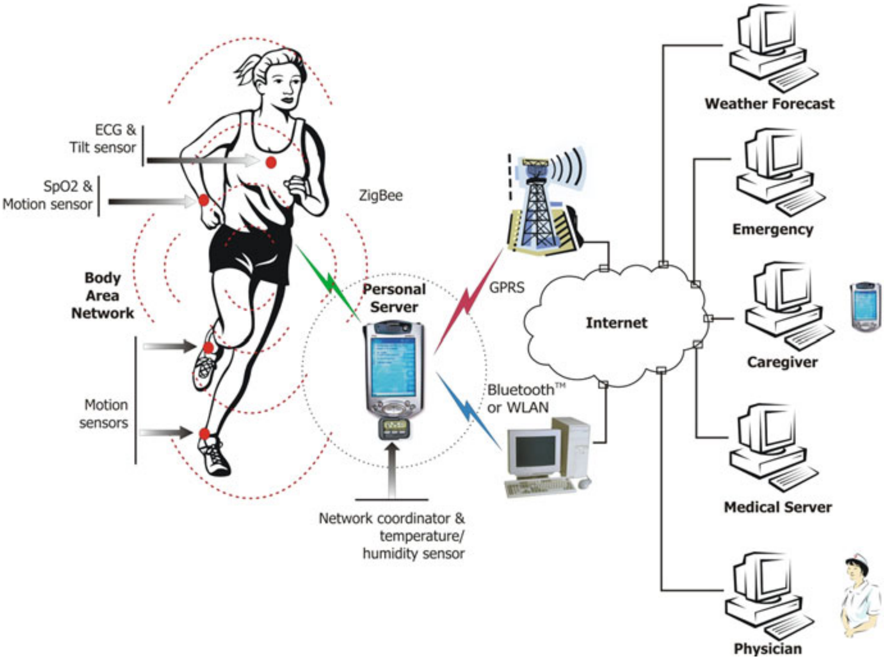

Fig. 1.7 Example of on-body sensor network [61]

Fig. 1.8 (*Right*) Smart T-shirt by Holst/IMEC [64] and (*Left*) RFID tag by Verichip [65]

Some examples of Body-Sensor areas can be found in the literature and from several companies like Toumaz [62]. An interesting one is the smart T-Shirt developed by IMEC [63] and depicted in Fig. 1.8. It is powered by the body heat and used to monitor the cardiac activity.

This IMEC [66] invention demonstrated the integration of a wireless autonomous sensor system in clothes. The system is fully autonomous for its entire life and requires no service – like replacing or recharging the battery – from the user. The shirt with integrated electronics can be washed in a regular washing machine.

The device is powered from a rechargeable battery. The battery is constantly recharged through thermoelectric conversion of the wearer's body heat. The Thermoelectric Generator (TEG) is divided into 14 modules to guarantee user comfort. It occupies less than 1.5% of the shirt area and typically generates a power of 0.8–1 mW @ 1 V at regular sedentary office activity. However, the power increases up to 2.7 mW at 22°C due to forced convection if the user walks indoors

Other alternative to recover energy on the body comes from the Radio Frequency (RF) or Magnetically Induced radiations. Power radiation is a potential power reservoir for on-body application because lots of RF and wireless transmissions are present in the urban environments. However, the development of electronic systems able to collect energy from radiation sources tends to be extremely power-limited and generally requires a large collection area or a close location to the radiating source [10, 36, 12, 67].

Some examples of magnetically induced power harvesting in health applications are the devices developed by VeryChip [65, 67] and Health Link [68]. Health Link utilizes a tiny, passive microchip and a private online database that links the user to the personal health record. It provides emergency room doctors and nurses with the vital medical and emergency contact information, allowing them to treat the human being rapidly, accurately and safely during an emergency. Meanwhile, Verichip has developed an implantable RFID Tag powered by an inductive link through the skin, Fig. 1.8.

1.2 Biosensors

A Biosensor is defined as a "device that uses specific biochemical reactions mediated by isolated enzymes, immunosystems, tissues, organelles or whole cells to detect chemical compounds usually by electrical, thermal or optical signals" [69]. A Biosensor that includes transducers based on integrated circuit microchips are often referred to as Biochip.

In recent years, many types of Biosensors have been developed and used in a wide range of biomedical and other applications. This is a fast-moving field and it is beyond the scope of this work to perform a long dissertation about Biosensors but it is here introduced the enormous importance and potential of these devices.

Basically, a Biosensor could be described as faradic and non-faradaic sensors. In faradaic Biosensors a Redox species is alternately oxidized and reduced by the transfer of an electron to and from the metal electrode; so, a Redox-active species is necessary. On the other hand, in non-faradic sensors no specific or additional reagent is required. Sometimes, a non-faradaic sensor used at a single frequency of operation is designated as capacitive Biosensor.

Thanks to the advances in Biosensors design, some of them are used in the analysis of trace substances in environmental science, pharmaceutical and food industries. However, the continuous monitoring mode is still a challenge for the sensors research.

One of the earliest references to the concept of a Biosensor is from Dr. Leland C. Clark who created many of the early Biosensors in the early 1960s [70]. He used an "enzyme electrode" for measuring glucose concentration with the enzyme Glucose Oxidase (GOD). The success of single analyte sensors was followed by the development of integrated multi-analyte sensors capable of more comprehensive analyses, such as a single instrument for glucose, lactate, and potassium detection.

Technical developments in manufacturing enabled the development of miniaturized integrated Biosensors for the determination of glucose, lactate, and urea in micro samples of undiluted whole blood or plasma. Miniaturization also allowed additional analytical tools to be added to the Biosensor, such as chromatography or capillary electrophoresis.

The newest generation of Biosensors includes miniaturized multi-analyte immunosensor devices with high-throughput capabilities and more than 1,000 individually addressable electrodes per square centimeter. These instruments can detect analytes present in the attomole range [71]. Furthermore, modern fabrication techniques such as ink-jet printing, photolithography and microcontact printing are contributing to the development of more advanced Biosensors that will allow the design of new miniaturized Biosensors with high-density ligands, self-contained lab-on-a-chip capabilities and in the nanoscale range.

Current, conductivity, capacitance variations, and impedance measurements are some of the reported ways to electrically monitor biochemical interactions. Current research in Biosensor technology has been toward developing better transducers to demonstrate superior sensitivity, portability, accuracy and throughput. Parallel, high-throughput monitoring of interactions between biomolecules is playing a significant role in the characterization of various protein functions.

Some interesting examples of health care Biosensors are lactate, urea, cholesterol, uric acid, DNA and inmunosensors. Lactate measurement is helpful in respiratory insufficiencies, shocks, heart failure and metabolic disorder and to monitoring the physical condition of athletes whereas urea estimation is important in monitoring kidney functions and disorders associated with it. Determination of cholesterol is clinically very important because abnormal concentrations of cholesterol are related with hypertension, hyperthyroidism, anemia and coronary artery diseases. Uric acid is one of the major products of purine breakdown in humans and therefore, its determination serves as a market for the detection of disorders associated with altered purine metabolism, notably gout, hyperuricaemia and Lesch–Nyhan Syndrome.

DNA Biosensors have an enormous application in clinical diagnostics for inherited diseases. Immunosensors are based on the specific interactions between antibodies and antigens agents, and are of great interest to analyze microorganisms, viruses, pesticides and industrial pollutants. The variations in the electronic signal to be measured are due to the antibody-antigen (Ab-Ag) interactions.

Other well known example of application is the glucose Biosensor [72–74] based on the electron transfer during the enzymatic reduction of glucose. In the last years, several works have been published regarding the Glucose Continuous Monitoring (GCM) sensor and the conception and implementation of artificial pancreas, like in [75] where it is presented an electro-enzymatic glucose sensor or in [76] where a capacitive based MEMS affinity sensor for continuous glucose monitoring applications is designed.

Rodrigues et al. [77] have developed a new cell-based biochip dedicated to real-time monitoring of transient effluxes of glucose and oxygen with arrays of amperometric microsensors integrated in the inlet and the outlet of a PDMS cell chamber. More advanced and complete sensor is presented in [78] where the design, microfabrication, packaging, surface functionalization and in-vitro testing of a complete electrochemical Cell-on-Chip for continuous amperometric monitoring of glucose is demonstrated performing some cyclic voltammetries, electrical impedance spectroscopy (EIS) and a microscopic examinations.

The use of smart new nanomaterials is of special interest. These materials are sensitive to chemical and biological interactions and they open the door to develop NanoBioSensors able to deal with molecules. They can be integrated into other technologies such as Lab-on-Chip to facilitate molecular diagnostics allowing a wide range of applications like the detection of microorganisms in various samples or in body fluids and detection of tissue pathology such as cancer. Their portability makes them ideal for pathogenesis of cancer (POC) applications.

Some examples related with glucose sensing and NanoBioSensors are presented in [79, 80] where electrodes based on carbon nanotubes and nanoporus of polypyrrole (PPy) respectively are reported to define amperometric glucose monitoring. ZnO nanowires directly connected to the gate of a standard low-threshold MOSFET are also used for Glucose Continuous Monitoring (GCM) as in [81].

All previous examples are focused on using amperometric signals to detect the desired reaction. On the other side, electro-inactive reactions like antibody-antigen affinity binding, where no direct amperometric signal are generated, the changes that occurs in the impedance of the bioactive film have to be measured [82–86]. In [87] is introduced an antiboby-based immunosensor that used Polyaniline nanowire bundles to transducer binding events between pathogens and their target antibodies into variations of the conductance. The variations in the concentration of antigens in the sample are captured as current variation across the electrodes, changing the measured impedance. A model of the variation of the impedance in terms of the concentration of the antigens then is used to analyze the performance of the sensor.

The electronics developed in this work is focused on low-frequency amperometric, and capacitive [88, 89] Biosensors. An amperometric sensor generates a current when a potential is applied on the electrochemical cell, which is proportional to the electrochemical reactions produced in the Bioreceptor. On the other hand, capacitive Biosensor produces a variation on its capacitance when a reaction takes place in the Bioreceptor. In that way, an impedance variation is produced in the electrode-solution interface when an AC signal is applied on the cell [90], which is impedance spectroscopy detection, at a fixed operating frequency.

This means that an amperometric sensors gives the electrochemical information by modulating the current through it, whereas, capacitive sensors gives the information by modifying the sensor impedance.

There are many examples of Biosensors and the interaction with the control and processing electronics. Some hybrid and monolithic integrations can be found in the literature for in-vivo or in-vitro applications like microelectronic pills [91], miniature wireless biopotential recording system [92], multichannel neurotransmitter sensing circuits [93], CMOS sensor interface arrays for DNA detection [94] or CMOS Lab-on-Chip [95].

The novel system presented further on is able to characterize the sensors thanks to a cyclic voltammetry and amperometric measurements in order to detect the variation of concentration of a specific agent. Also, the electronics explore the capability to define an impedance analysis (EIS) through an integrated lock-in amplifier.

1.2.1 Three Electrodes Biosensors

It is important to analyze the definition of the number of necessary electrodes when working with Biosensors. A basic electrode sensor is formed by two electrodes (Reference (R) and Working (W) electrode). The measurement is usually done by applying a voltage signal between them (V_{RW}) when they are inserted in a chemical environment. At the same time, the current across them is measured. The voltage V_{RW} must remain invariable during the measure to achieve a reliable measurement. Unfortunately, the polarization of the electrodes varies due to the current circulation across them, nullifying the measurement. This problem could be solved including an extra electrode (Auxiliary (A) or Counter (C) electrode), which provides the supply current to the working electrode, so no current flow through the reference electrode.

The three electrodes configuration is usually adopted. The three-electrodes are: a) the working electrode (W), which serves as a surface on with the electrochemical reaction takes place; b) the reference electrode (R), used to measure the potential at the W_E, and c) the counter electrode (C), or also called auxiliary electrode (A), has the role to supply the current required for the electrochemical reaction at the W.

The three electrodes topology provides greater stability and reliability than a two electrodes topology. It avoids the polarization of the reference electrode and hence, it is a constant voltage supply between the reference and work electrodes. It is very important that the voltage between the reference and working electrodes (V_{RW}) remains equal for every working conditions being independent of the environment in order to be able to do an accurate measurement and a correct study. A detailed introduction to 3 electrodes sensors is done in Chapter 3.

Several factors contribute to the current generated by the sensor [96], but the size of the working electrode is one of the most important ones. The amount of current generated takes considerable importance in how works with the sensor and the electronics. If the size of the electrodes is decreased, defining microsized electrodes, the current level could decrease to femtoamperes

1.3 Circuits for Three Electrodes Biosensors

Electronic measurement of the biochemical concentrations is essential for diseases diagnosis and study of biological systems. Taking into account that the conception of the system is based on the use of 3 electrodes sensors, the electronics are developed following this premise.

The electronics circuit known as “Potentiostat” is basically in charge to manage the sensor and the techniques used to characterize the sensor like the Electrochemical Impedance Spectroscopy (EIS) or Cyclic Voltammetry (CV)

1.3.1 Potentiostat

It is the key component when working with three electrodes Biosensors. It can be configured in two modes (a) the potentiometric configuration, where a fixed current is applied and the output voltage is measured, or (b) the amperometric configuration, where a fixed voltage is applied and the output current is measured through a current measuring system, for instance, a Transimpedance amplifier (TIA).

The design of a potentiostat varies from discrete to mixed and full-custom ASIC designs. The definition of the adopted solution is given by the size of the sensor and complexity of the system. For electrodes areas greater than 1 mm^2 just electronics based on low-cost surface mount components can be adopted but, for smaller and multiplexed solutions, full-custom ASIC solutions appears as a valid approach. Furthermore, the conception of an ASIC interface near the electrodes is motivated when very low current levels are derived from the sensors. Other key aspects to use an ASIC solution near the electrodes are, a part of the degree of miniaturization: a) EMI can be reduced; b) External disturbances like vibrations, moisture, sources of electrical noise, etc… are avoided.

Some references are described in Choi Myung-suk et al [89] in their work "Implantable Bio system design for displacement measurement of living life" or in the work by K. Kitamori [90], where he described micro and nano chemical sensors on-a-chip. Other interesting Biosensors are the piezoelectric immunosensors, like the one developed for the rapid diagnosis of M. tuberculosis by Eric Carnes et al [92].

Several references related the use of ASIC designs and Biosensors are presented in [97, 98] and [99], which introduces a low power readout circuit with a potentiostat amplifier for amperometric chemical sensors in Glucose Meter Application.

A basic potentiostat is divided in two parts: 1) the control and 2) the measure (TIA) and post-amplification circuitry. The control circuitry is used to maintain a constant voltage across the R and W electrodes. On the other hand, the TIA stage is in charge of detecting the current generated in the reaction.

One of the most used potentiostat architecture is depicted on Fig. 1.9 where it is also depicted one of the most usual electrical model for electrochemical cells [100], the Randles RC model. This simple and compact architecture is interesting for ASIC implementation [101–103] and to develop applications with multi-working sensors because the current is measured independently for each sensor with a dedicated read-out circuit.

This structure is based on four operational amplifiers (Opamp), and two resistors. OP4 is the Transimpedance (TIA) amplifier, which defines the virtual ground voltage of the W electrode and provides current-to-voltage conversion such that,

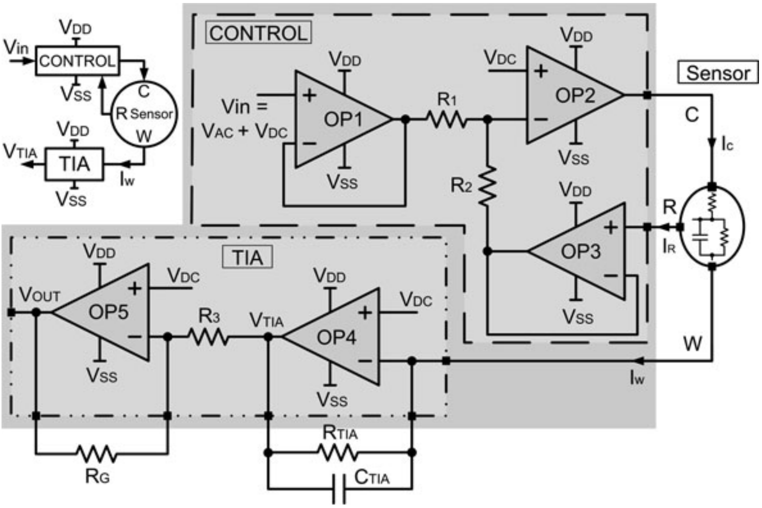

Fig. 1.9 Schematic view of the Biopotentiostat amplifier with the electrochemical electrical model

$$V_{TIA} = -I_W R_{TIA} \; 1.1$$

where I_W is the current through the cell and R_{TIA} the gain resistance defined in the Transimpedance amplifier.

OP3 is used to ensure minimal current flows through the reference electrode and to sense the voltage difference between the R and W electrodes. This difference is compared with the desired V_{in} by OP2 in order to drive properly the counter (C) electrode and to maintain controlled the V_{RW} voltage.

The architecture in Fig. 1.9 is the selected one to design the implantable electronics and it is explained in detail in Chapter 3.

The previous potentiostat architecture uses a classical Transimpedance amplifier configuration to detect the current. In order to solve the frequency bandwidth limitations associated with the standard TIA, other options could be studied for the analogue readout of the signal like the ones presented in Fig. 1.10. This converter is based on an integrator-differentiator scheme to combine low-noise and wide bandwidth with two simultaneous outputs.

A high speed output (V_{ac}) amplifies the input current by the capacitive ratio C_d/C_i and converts it into voltage by the resistor R_t. Differently from a standard Transimpedance amplifier, where the I – V conversion is set by a feedback resistor, whose value is necessarily large also for having low noise at the expense of a dramatic drop of the bandwidth, in this solution the current amplification is set by means of capacitors, noiseless components, and allows a small value of R_t, without affecting the overall noise performance.

The bandwidth is largely increased, and is set by the integrator loop-gain to the value $BW = GBP \cdot (C_i/(C_i + C_c))$ where GBP is the gain-bandwidth product of Opamp1 and C_s is the input capacitance on the input node.

Since a DC input current would saturate the integrator stage, an active feedback has been added to continuously convey the DC input current into a proper sink (resistor R_{dc}). The Low Pass Filter (LPF) in the feedback branch must be designed as an active filter with high gain in the very low frequencies and a very strong attenuation for higher frequencies.

The use of an Instrumentation Amplifier (IA) is also a widely used alternative if just one working electrode is going to be used. It adds an extra resistor (R_a) in

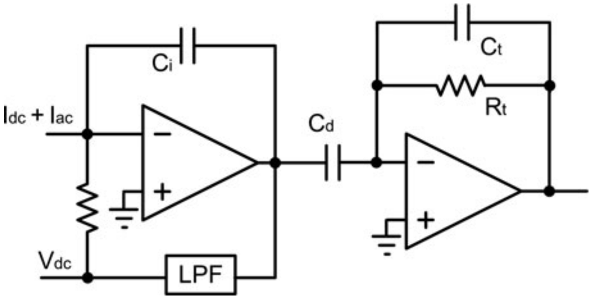

Fig. 1.10 Alternative transimpedance amplifier configuration

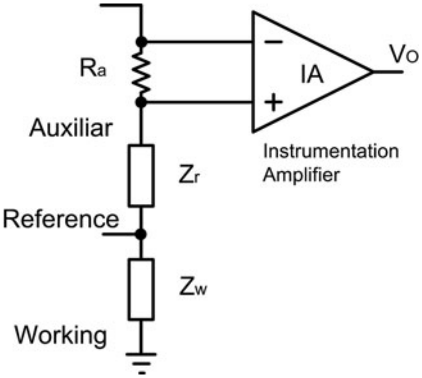

Fig. 1.11 Instrumentation amplifier stage

series with the Counter electrode to detect the current, Fig. 1.11. In that way, the Working electrode is physically connected to ground and not to a virtual ground as in the previous Transimpedance solution.

1.3.2 Discrete Potentiostat Approach

The architecture in Fig. 1.9 has been selected for developing the CMOS implantable instrumentation, although the structure has been previously validated and tested through a discrete implementation before the IC design. A first discrete prototype has been implemented for O_2 monitoring in environmental applications. The derived electronics were also used to validate the merge of these electronics with the electrodes in the conception of an encapsulated device.

This development combines a fluidic channel device integrated with the electrodes and the electronic system for oxygen monitoring in water to form a disposable device.

Dissolved oxygen concentration (DO) is an important index of water quality and the ability to measure the oxygen concentration and temperature at different positions and depths would be an important attribute to environmental analysis. The decrease of oxygen concentration in water is a clear indication of water pollution, which is one of the main concerns of the Water Framework directive in the European Union [104]. Moreover, in other topic, the detection of O2 concentration in blood plasma has several interesting applications including the oxygen monitoring during open-heart surgery [105].

This discrete system is based on sensors and electronics forming one module as is depicted in Fig. 1.12. The discrete PCB potentiostat amplifier is coated with PDMS and fully characterized through several Cyclic Voltammetries. The PCB was tested before and after its introduction into water

The custom electronics, which includes a small printed circuit board (PCB), has a size of 31 mm × 21 mm. The power consumption of this first implementation is

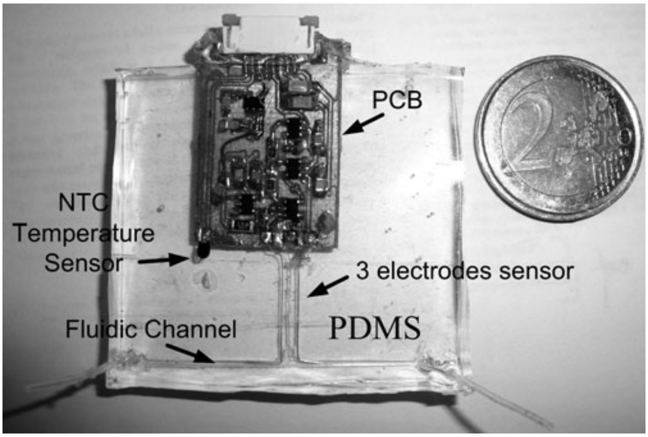

Fig. 1.12 PCB capture coated with PDMS

around 350 mW using the Texas Instrument commercial amplifiers OPA 656 and OPA 657, which acts as a Transimpedance amplifier. These amplifiers were selected for their good characteristics in terms of high input impedance, low bias and offset input currents and voltages.

The obtained results are compared with the ones obtained with the commercial instrument CH 1232A (CH Instruments ®). Figure 1.13 shows some voltammetries obtained analyzing tap water with high concentration (Region A) and low

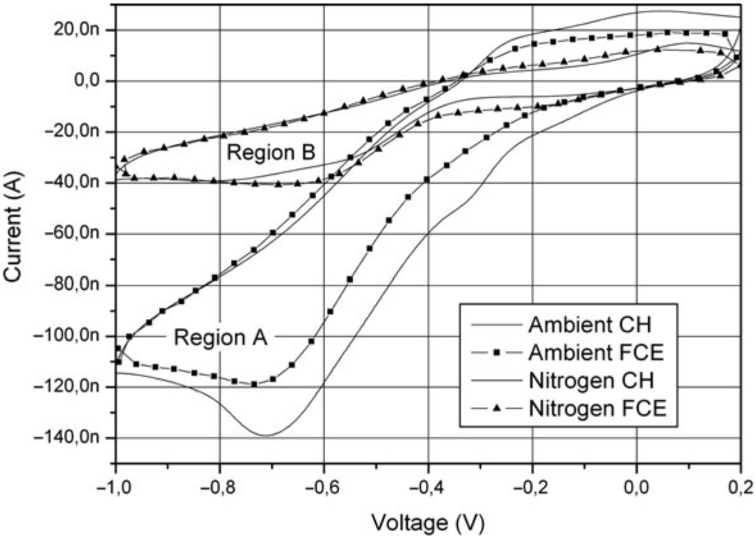

Fig. 1.13 Voltammograms obtained with the CH instrument and with the PCB for TAP water in ambient conditions and with nitrogen

concentration of O_2 (Region B). The more negative current peak around -1 V shown in Region A comes from a sample of water that has been exposed to ambient air.

On the other hand, the less negative peak on Region B is obtained for a water sample bubbled in nitrogen to remove the oxygen. As can be observed, the performance of the custom potentiostat is demonstrated obtaining measurements very close to the commercial one; hence, it is possible to detect several concentrations of O_2 with the discrete full-custom design.

The development of this discrete prototype has been used to acquire background knowledge and to observe problems when working with electrochemical sensors before proceeding with the design of implantable system presented in Chapter 4.

1.3.3 Lock-In Amplifier and Complex Impedance Detection

Regarding the electrochemical characterization of the Biosensors, the signal processing of the obtained measurements by the electrochemical impedance spectroscopy technique, defines a circuitry that has the role to obtain the real and imaginary components of the measurement of the Electrochemical Impedance.

EIS [106] is an AC method that describes the response of an electrochemical cell to a small amplitude sinusoidal voltage signal as a function of frequency. The resulting current sine wave differs in time (phase shift) with respect to the perturbing (voltage) wave, and the ratio V(t) / I(t) is defined as the impedance (Z), and accounts for the combined opposition of all the components within the electrochemical cell (resistors, capacitors, inductors) to the flow of electrons.

In an electrochemical cell, electrode kinetics, Redox reactions, diffusion phenomena and molecular interactions at the electrode surface can be considered analogous to the above components that impede the flow of electrons in an ac circuit. The simplest electrical model is based on an equivalent RC circuit so called a Randles circuit [100].

Based on the nature of the measured signal there are two main approaches:

- the Capacitive sensors where the surface of the electrode is completely covered by a dielectric layer and the whole electrode assembly behaves as an insulator. The variation of the capacitance is measured, in frequency ranges up to 100 kHz.
- and the faradaic sensors. In this case the surface of the electrode, which is partially or wholly covered by a non-insulating or insulating layer, is able to catalyse a Redox activity that exists in the solution. In this case, the measured parameter is the charge transfer resistance (the real component of impedance at low frequency values, typically 0.1–1.0 Hz).

In order to proceed with the signal processing there are mainly two approaches: (1) the Fast Fourier Transform (FFT), and (2) the Frequency Response Analyzer (FRA). In the case of the FFT, a pulse or a step is applied to the sample because it contains wide frequency content. Then, the response of the sample is digitized and processed in a digital processor and the different frequency components are obtained for their analysis using the FFT algorithm. Also, other possibility that could be followed is the logarithmic sampling in the DFFT calculus, reducing the data that must be required in the process.

A simpler solution is based on the FRA approach. In this case a sine and cosine signals are adopted and using two multipliers and a filter stage the real and imaginary components of the response are obtained. This measurement must be done for each frequency to obtain the full EIS characterization of the Biosensor. Working with just one sensor and in terms of the size of the final product, the FFT option could be adopted, because the response for several frequencies is obtained.

The FRA solution is more oriented to multi-sensor approaches but, also in the case of single sensors, it is a nice option in terms of complexity and speed for not too low frequencies. This FRA or Lock-In approach is more feasible and it is an interesting solution when just the impedance must be obtained at a fixed frequency of operation.

The perturbation signal provided by the instrumentation system – following the FRA approach – generally use a sinus wave as the input voltage. In this work a low-voltage integrated CMOS lock-in amplifier, Chapter 3, is analyzed as a method to measure the impedance value of the sensor. Typically, a Lock-In amplifier is used to increasing the Signal-to-Noise ratio of the system by synchronizing the output signal to the input signal at a known frequency; i.e., the frequency where the sensor has the best sensitivity response filtering the other frequencies and noise.

Some examples of FRA and Lock-In implementations can be found in the literature. In [107] a fully CMOS lock-in amplifier is proposed in the field of gas sensors that works at a fixed operating frequency. In [108] is derived a more complex lock-in amplifier for electrical bio-impedance analysis for implantable medical devices. There, the pulse signals used for the synchronous demodulation channels are modified by specific dead times so, the error in the magnitude and phase is reduced.

Reference [100] describes this technique as a very powerful tool for the analysis of complex electrochemical systems and how can provide a valuable and complete description of the electrode process. Following this idea, a theoretical analysis and design of a CMOS Lock-In amplifier for bio Impedance detection is carried out in Chapter 3.

1.4 Contribution of this Book

The main objective of this book is the conception of a generic Self-Powered CMOS Front-End Low-Voltage Low-Power integrated device that would be the main part of a subcutaneous device for biomedical applications [109–116]. At the end of this work, a prototype device would be implemented able to manage the information coming from a 3 electrodes amperometric sensor.

The devices, designed as a subcutaneous implant (small dimensions), will validate the conception of Implantable Biomedical event detector able to discriminate several specific concentration points of the analyzed substance for that reason the design and conception of the CMOS based implantable architecture has been divided into three parts:

1. the design of a powering system for the electronics,
2. the development of the integrated sensor instrumentation, post-processing and communications,
3. and the design and validation of the implantable detection prototype.

The powering scheme is an important aspect since the device is located under the human skin and the use and maintenance of batteries or conventional energy sources is a drawback. Moreover, to develop a self powered subcutaneous device, an appropriate alternative is to design a system that recovers energy from the environment.

Following this alternative, an specific novelty IC circuit called MHPC (Multi Harvesting Power Chip) has been designed to solve the power problem regarding the subcutaneous ambient of application. It is able to recollect energy from several ambient sources (vibrations, light, EM waves) in the range of mW and to power some low power applications focused on on-body applications. However the MHPC is originally oriented to on-body applications, it could be also used in different type of applications such as main power source in distributed sensor networks.

Basically, the designed MHPC power management is designed to

- assure a high efficiency low-power energy conversion,
- combine several energy sources with the same power management unit,
- low-power consumption,
- and occupy a small size and package.

The second part develops a "BioChip" with the necessary instrumentation and post-processing circuits to work with the three electrodes sensors. This IC integrates the potentiostat to drive and obtain the information from the sensor and the post-processing electronics to detect several values of concentrations.

Low-power circuits have been implemented to design the instrumentation and to avoid power consumption higher than 1.5 mW. In that way, it is possible to reduce damages under the human skin due hot spots. Furthermore, the theoretical and simulated design of a lock-in amplifier to detect complex impedance in Biosensors is also described as a part of the post-processing.

Finally, an ASIC based Self-Powered implantable device prototype is fabricated to validate the novel generic architecture for In-Vivo even detection with amperometric Biosensors. The prototype is based on two IC's sharing the same PCB substrate.

The MHPC chip will harvest the energy from an inductive link through the human skin and will generate the necessary on-chip voltages to drive the BioChip circuits. On the other side, the BioChip will drive the sensor and will deal with the post-processing to detect the desired concentrations. Moreover, the inductive link is also used to transmit the detected concentrations to an external receiver in the other side of the skin.

The design of the MHPC can be also oriented to work as a main power source to develop a Global (implantable) Application where the external device (or receptor) is also powered through harvesting sources [117, 118]. Figure 4.14 shows the conception of a Global Implantable Application where all the involved electronics (external and internal) are fully self-powered using the MHCP. Furthermore, in the future, the MHPC could use newer implantable power sources (Mecatronics, Fig. 4.14) to drive the subcutaneous device.

In short, this book presents novel low-power architecture for portable subcutaneous detection device powered through the energy harvesting concept. Thereby, the development of this kind of implantable and portable detectors represent a step forward in the biomedical diagnosis and detection devices evolution as it is illustrated in Fig. 1.15. Moreover, this work is the perfect link between the development of biomedical subcutaneous devices and the use of alternative energies, two of the major emerging research fields, and demonstrates that the development of complex biomedical detection systems could be completely self-powered.

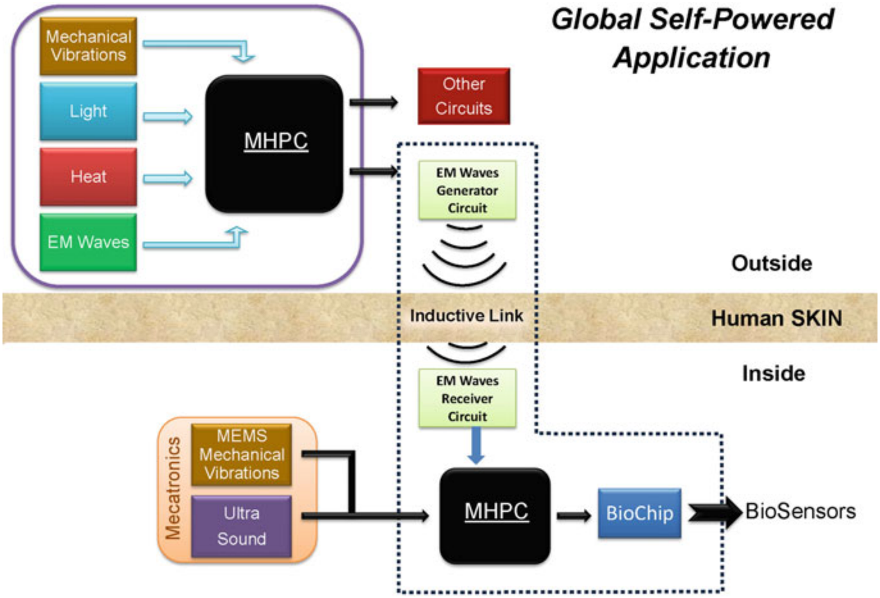

Fig. 1.14 Conception of the proposed global implantable subcutaneous application where implanted and external electronics are self-powered (autonomous). The *dotted line* represents the work covered in this book

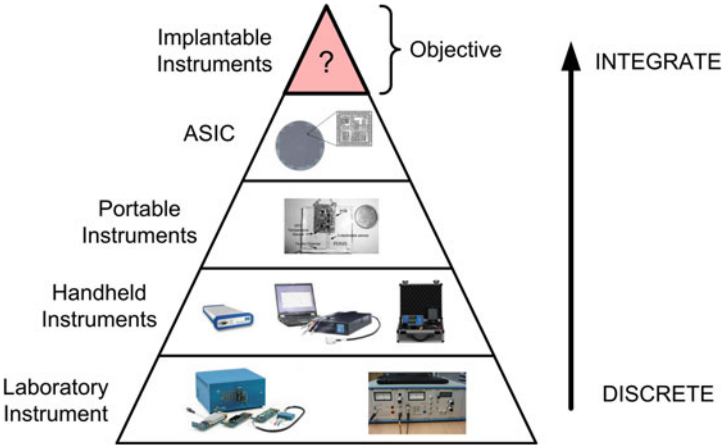

Fig. 1.15 Pyramid with the evolution of biomedical diagnosis equipment

1.5 Outline of the Book

This book is divided in three main chapters. The first one, Chapter 2, develops the Multi Harvesting Power Chip (MHPC). On it, all circuits used to recollect energy from several ambient sources are theoretically and experimentally described and validated. Finally, the whole chip is tested working with all circuits collecting energy form more than one source at the same time.

On the other hand, Chapter 3 is focused on the development of a BioChip with the integrated instrumentation to work with three electrodes amperometric Biosensors. First of all, it is introduced the conception of three electrodes Biosensors and how they work. Voltammetry, EIS and amperometric techniques are also introduced to the reader.

The potentiostat architecture is clearly explained and experimentally tested using a real substance. The obtained results with the full-custom approach are compared with the ones obtained using a commercial potentiostat. In that way, the correct operation of the designed instrumentation is fully validated.

Furthermore, this chapter explains the conception of a Lock-In amplifier circuit used to detect the real and imaginary parts of the complex impedance coming from the Biosensor. This circuit is theoretically explained and some simulated results are shown. It is also introduced on this chapter the conception of Biotelemetry or how to transmit information from the subcutaneous device to the external reader. Then, the implemented protocol in this work is detailed.

Chapter 4 finally describes the design and conception of the Self-Powered CMOS Front-End architecture for Biomedical Subcutaneous Devices. All circuits are presented in detail as well as the powering through an Inductive link. The power and communication antenna as well as the connections between the MHCP IC, the BioChip IC and the sensor are also explained.

The results obtained with the final capsule prototype with a size less than 4.5 cm × 2.5 cm are shown and commented in detail. It is analyzed the problems regarding the misalignment between the internal and external antennas. Finally, the prototype has been validated as a detector. To conclude with the book, Chapter 5 presents the conclusions and possible future options that may arise from this work.

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