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THERMOELECTRIC AND MICROBATTERY HYBRID SYSTEM WITH ITS POWER MANAGEMENT

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ABSTRACT

Integration of a power source with a MEMS to obtain an autonomous or remote system is a very challenging task. Such a device is currently being developed. It consists in hybriding an energy storage system (thin film solid state battery) with a scavenging energy system (thermogenerator) in a very small volume. It requires also power management to both control charge of the battery by the thermogenerator and discharge of the battery by the load, i.e. a sensor for instance.

1. INTRODUCTION

Important technological innovations emerged during the past decade in the field of MEMS. Current development programs dedicated to MEMS are mainly focused on the technology necessary to fabricate and implement MEMS. Nevertheless, solutions for their energy supply and the associated power management have to be found. Indeed, available MEMS require "hardwire" connection for either power or communication. Integration of power source with the MEMS to obtain an autonomous or remote system appears to be a challenging task of major interest in the MEMS field.

In order to sustain long-term operation with a device that is as small as possible, a micropower supply should include both energy conversion and energy storage. A hybrid system comprising a thermoelectric generator, a thin film solid state battery and its associated power management is presented.

New progress in microbattery development such as integration directly on an integrated circuit and final electrochemical characteristics of this energy source are discussed. Second part of the paper is dedicated to the hybridation of such a microbattery with a thermogenerator. Behavior of these two systems connected together with a specific power management is presented.

2. REQUIREMENTS FOR AN AUTONOMOUS POWER DEVICE

Capability to be integrated in a small volume (< 1 cm^3) with the other components (sensor, RF module…) necessary to the behaviour of the whole system is one of the main requirements for an autonomous power device (see figure 1).
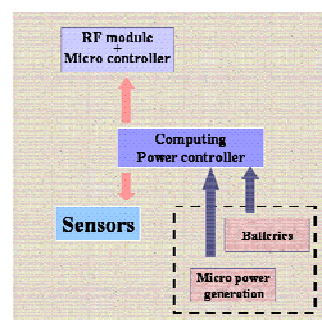

Figure 1: Autonomous sensor architecture

The other main requirement deals with the energy profile furnished by the system. Two characteristics are important to be achieved: first the maximum power necessary (most of time linked with the wireless communication) and secondly the life time.

Considering all these constraints, the only viable solution implies to have both a energy scavenging and a energy storage systems. The energy scavenging system allows having an unlimited source of energy and the energy storage system permits to power the load even if the surrounding energy is not available for a while. It can also be designed to furnish peak power.

Main contributors to the energy consumption are mainly the wireless communication module and the DC-DC converters that will have to be used in the power

management in order to adapt the voltages furnished by the energy scavenging system (that can change depending on the outside conditions) and required by the thin film solid state battery and the load.

Depending on the communication mode that will be used, power of a few hundred of milliwatts can be satisfactory (see figure 2). Energy required for the IC will also be in the order of 100-200 µW.
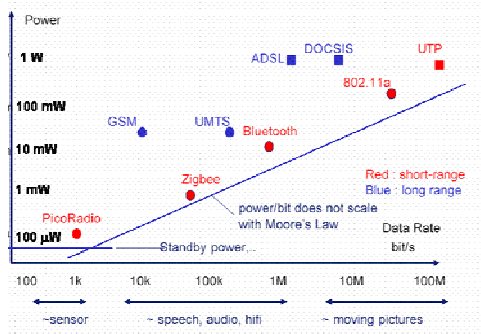

Figure 2: Energy consumption for wireless communication

Power consumption of the system can be significantly reduced by optimizing the communication profile and the IC behavior (standby duration, powering of the dc-dc converters only when scavenged energy is high enough…).

From all these considerations, it appears that the micro-power device should be able to provide power in the range of 100 µW/1 mW.

In this paper, we chose to use a thin film thermogenerator as scavenging energy source and a thin film solid state battery as energy storage system. These two power devices can be realized by thin film deposition methods and are perfectly adapted to integration with MEMS.

3. THIN FILM SOLID STATE BATTERY DEVELOPMENT

The thin film solid state battery is realized by Physical Vapor Deposistion techniques (PVD) such as sputtering and thermal evaporation (see figure 3) [1]:

- First metallic coating achieved by DC magnetron sputtering acts as electrical collectors
- Second layer based on TiO_xS_y is deposited by RF magnetron sputtering of a titanium target in a H_2S reactive environment to serve as positive electrode;

- Lithiated glass coating achieved by RF sputtering overlaps previous layer and constitutes the solid electrolyte
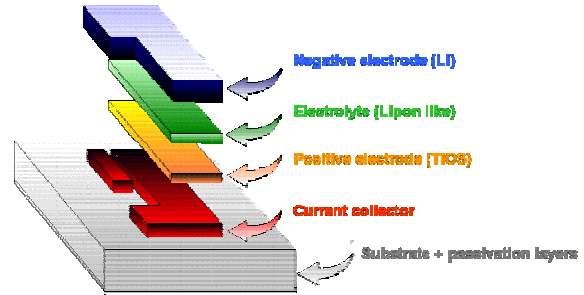- Finally, a lithium layer deposited by thermal evaporation serves as negative electrode

Figure 3: Microbattery architecture

The superposition of the different active layers allows an active electrochemical cell about 10 µm thick.

All the layers of the microbattery are obtained at low temperature (i.e. below 200°C). Such a characteristic is very important since it permits to deposit the battery directly on an Integrated Circuit or on a polymer substrate such as Kapton for instance.

Such a power source operates between 3 and 1V. It offers an energy density of about 100 µAh/cm² and can deliver up to 3 mA/cm² (see figures 4 and 5). Moreover, this kind of system exhibits high cyclability (thousands of cycles without capacity loss) and is very electrochemically stable (no self discharge).
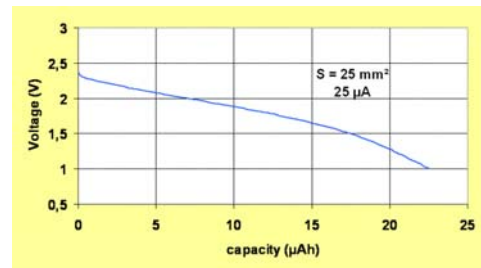

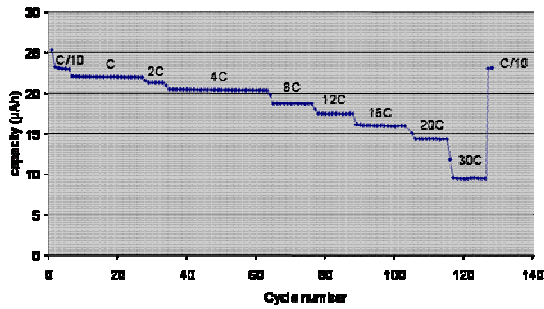Figure 4: Discharge curve of a TiOS/Lipon/Li microbattery (10 µA/cm² rate)

Figure 5: Evolution of capacity of TiOS/Lipon/Li
microbattery with charge and discharge rate

Since lithium is very sensitive to moisture, the battery has to be protected under ambient air by very efficient barrier. A specific thin film barrier has been developed. It consists in a multi-layer system with an overall thickness lower than 6 μm. All the process is realized at low temperature (< 60°C) to avoid any degradation of the lithium layer. The different layers form an alternation of polymer (obtained by PECVD techniques, based on SiO_xC_y layers) and metallic layers (obtained by PVD techniques). Specific attention is paid to obtain a low stressed multi-layer system.

Such an encapsulation was characterized from a barrier point of a view by a specific test consisting in depositing metallic lithium on a wafer followed by the realization of the encapsulation and then submitting the whole system to severe humidity conditions (85°C, 85% humidity rate). The system is then periodically weighted in order to detect any oxidation of the lithium. Lithium encapsulated with our multilayer system presents no mass increase after more than 60 hours in these conditions (see figure 6).
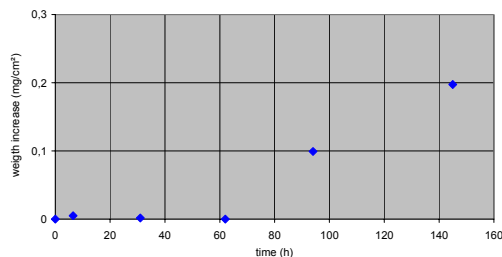

Figure 6: Mass increase of lithium test cells in
85°C/85%HR conditions

TiOS/Lipon/Li microbattery with its specific thin film encapsulation is thus obtained by a process perfectly compatible with a deposition on an IC (low temperature, thin film deposition techniques). Realization of such a power storage device on an IC was performed (see figure

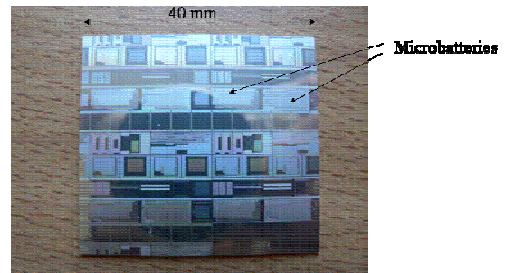7) and leads to a satisfactory behavior of the microbattery and the associated IC.

Figure 7: Microbattery deposited directly on an integrated circuit with its power management

4. THIN FILM THERMOGENERATOR

The thin film thermogenerator is obtained, as the thin film solid state battery, by sputtering techniques. The precise process is described elsewhere [2]. It consists in an alternation of bismuth and antimony lines electrically connected in series. The surface of one component is 1 cm². Around 50 systems can then be realized on one 4" glass substrate (see figure 8). Bi and Sb were chosen as reference materials in order to evaluate the potential of this kind of architecture.
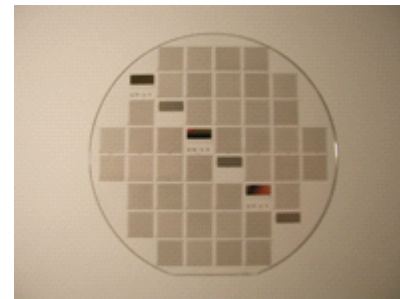
Figure 8: Bi-Sb device realized by microelectronic technologies (PVD deposition, photolithography)

Thermoelectric results obtained with the first prototype give an output power of decades of 0.2 μW/cm² for a thermal gradient of 40°C. As these values were obtained with Bi-Sb system, it is valuable to consider that power in the range of 100 μW/cm² for a $\Delta T = 5$°C will be reached in the next generation device with higher efficient materials such as Si-SiGe.

5. POWER MANAGEMENT

To manage the power provided by the thermogenerator to be stored in the microbattery, a specific ASIC is designed

with a specific care to reduce power consumption and so to save as much power as possible for the application. The ASIC allows different functions: monitoring of discharge and control of charge of the microbattery, interface between energy scavenging and microbattery, interface between power device and load, control of the scavenged energy.
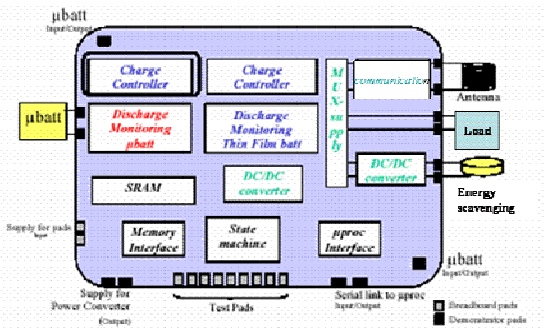

Figure 9: Functional architecture of the power management die

Different blocks of the ASIC have already been realized and characterized from an electric consumption point of view.

5.1. The Microbattery discharge controller

This part of the asic supervises the voltage of the microbattery and gives the state (charged or discharged). The circuit is designed on the CMOS F8 ST-Microelectronics process: it is a 0.18 micron technology with non volatile memory and high voltage transistors. It allows the voltage range used for the microbattery, i.e. 1.6 to 2.8V in the application.

The microbattery is considered as discharged when the voltage becomes lower than a threshold of 1.6V ± 100mV. This voltage is compared with a reference voltage, independent of the temperature and voltage supply.

This design can be cut in three blocks: the circuit of comparison, the circuit generating the signal of activation and the level setting circuit which maintains the exit of the comparator. Only the two last described circuits run permanently and then must be conceived so as to consume the least possible.

In order to limit consumption, the circuit of comparison is activated only a small fraction of time. This block is made of an oscillator of 1 Hz built from a reference of current of 200 pA. Then this clock is filtered to generate a pulse at desired frequency. The reference of current is produced from architecture of H.J. Oguey and D. Aebischer [3],

which has no resistance. Always to have less consumption, a Schmitt trigger rectifies edges on the output of the oscillator [4].

The table 1 gives some simulation results relate to block consumption.

block	Reference current	Oscillator	Gene. signal ACT	Compara-tor	Level setting	Complete Block
spec	200pA	1Hz	Pulse : 1s/hour	1,6V ± 30mV		
Cons..	1nA	0,49nA	0,42nA	active (1s/1h): 16nA standby : 0,14 nA	0,1 nA	~20nA ~4 nA

Table 1: consumption for the monitoring of microbattery discharge

Tests performed on the circuit after realization give good compliance with simulation. The oscillator has a frequency of 740 mHz with an average consumption of 400 pA.

5.2. The Microbattery charge controller

This part of the asic provides constant current in order to charge the microbattery. The current of charge is fixed to be 10 µA/cm² of microbattery. The charge starts only in the presence of a power supply higher than 2.9 V and if the voltage of the microbattery is less than 2.4V. The criterion to stop the charge is a threshold of 2.8V.

The charge controller of the microbattery includes three principal blocks: a block of comparison checking the state of the microbattery, a state machine ordering the start of the charge, and the charger itself.

During the charge of the microbattery, the circuit provides a charging current of about 26.9 µA to the battery and consumes 35.4 µA: an output (Icharge/Iconso) of 78% is thus reached. The blocks which consume permanently are designed so as to consume a total current smallest as possible (maximum a few tens of pA).

5.3. Other components of the power management

Blocks dedicated to control of the energy scavenged and interface between microbattery and thermogenerator are still under development. They will be fabricated when a next version of thermogenerator is completed.

The passive component requested for the realization of DC-DC converters for instance will be inserted in the

final system as discrete elements. Typical DC-DC converter exhibit a electrical consumption of a few tens of μW. Specific attention will be put on the use of low consumption systems.

The electric consumption that have been either modeled or measured confirm the first evaluation of the power to be furnished by the power device.

6. SYSTEM ARCHITECTURE

Final objective of this work is to integrate all the different components on a same substrate. The area dedicated to each component will be adjusted to the applications requirement: available thermal gradient and consequently energy that be scavenged, peak power requested by the load.

In order to minimize the surface of substrate, microbattery will be deposited on the integrated circuit. Passive components and thermogenerator will be on other parts of the substrate.

One of the main characteristics requested for the substrate is to have a high thermal conductivity in order to favorite a high thermal gradient. While typical PCB substrates have thermal conductivity below 10 W/m/K, ceramic substrates (such as alumina or SiC) have thermal conductivity ranging from 20 to 90 W/m/K. Such substrate will thus be preferred.

7. CONCLUSION

This paper presents the status of work undertaken at CEA in order to realize a demonstrator integrated thin film energy scavenging and storage components with their associated power management.

Thus, innovative technological bricks have been designed, produced, and tested:
- a microbattery direcly built on chip
- a thin film thermogenerator that can provide the energy necessary to the recharge of the microbattery
- an ASIC to manage the power management of the microbattery.

A second generation of thin film thermogenerator is on progress. Its characterization in terms of thermoelectric power will allow designing final blocks of the ASIC and completion of the final system.

8. REFERENCES

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