PEACPocket : a technological demonstrator for future multimedia smart card

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Abstract

This presented work has been conducted in a framework of a project with the objective to associate power microsources into smart cards in order to create novel functionalities. To demonstrate the feasibility of such a new powered microsystem, a demonstrator named PEA Card is under development.
It is powered by two rechargeable batteries:

- A microbattery on chip for security applications.
- A Thin Film Power Battery inside the card packaging to recharge the microbattery and to supply user interfaces.

An ASIC, used as substrate for the microbattery, manages the energy of the two power sources. It is designed to have a very low consumption. A processor and a display, powered by the embedded Power Battery, allow the user to access data without external source of energy. An RFID antenna permits a contactless charge of the two batteries.

1. Introduction

The multi-applicative smart card appears to be the next generation of cards, which could revolutionize not only electronic commerce, but also smart communication, access control, biometrics… Today such a product is not available on the market. It is the reason why the research Centre of CEA-Grenoble, in cooperation with its industrial partners ST Microelectronics and HEF R&D have launched the "PEAC Pocket" project end 2002.

The main goal of this project is to develop and embed new technological blocks for future smart cards:

- Two power microsources compatible with the packaging process of the card.
- An integrated circuit (ASIC) dedicated to the power management.
- A user interface (processor, display and buttons) which drives scenario to demonstrate the correct operation of the two previous developments.

The main purpose of this paper is to present the architecture of this PEA Card and to describe the conception of the power sources and the ASIC.

2. Architecture of the PEA Card

We could list different applications for smart cards like people identification with the e-passport, banking with the e-purse and transport with the e-ticket. Those applications have to be safe and the future smart card must have new embedded functionalities to reach higher level of security. We can imagine an active sensor powered by a micro-source which detects intrusions on the card and activates a counter-measure function (for instance erase critical information) and a Real Time Clock which can stamp transactions to ensure data integrity. The PEA Card brings together technical innovations to show the feasibility of such a smart card. This demonstrator includes two batteries, a battery management chip (ASIC), a processor, a low consumption display, two buttons, an RFID antenna and a smart card module, (see figure 1 and [8]).

- Two batteries are embedded to have two functionalities. On one hand, microbattery above the die allows security applications. This microsource supplies RAM memory containing critical information, which could be erased in case of attack or intrusion. The permanent supply of this RAM shows the ability of the microbattery to support security applications. On the other hand, Thin Film Power Battery with higher capacity and sustaining fast charge is dedicated to power microsystems in the card like user interfaces (display …) and to ensure the recharge of the microbattery.

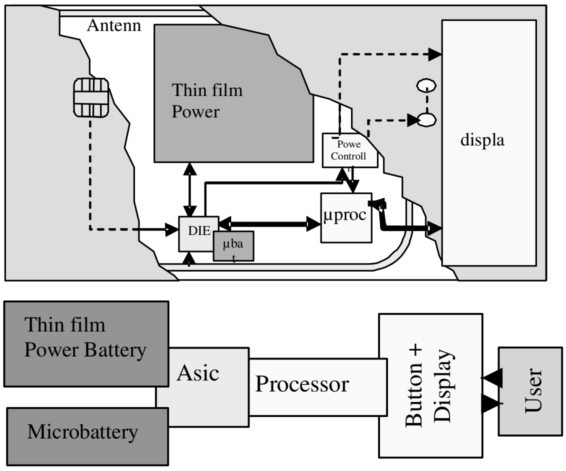

Figure 1: Global architecture of the PEA Card.

- One of the functions of the 'Battery management' die is to manage the energy of the two sources embedded in the card. The die controls the charge and discharge of the two batteries. The consumption of this part must be very low regarding to applications (RAM retention). This die is a substrate for the microbattery. The compatibility between the die and battery processes is critical. Many tests have been done and the best manufacturing process was found.

- A processor is implanted to drive the display and control interface with user. The PEA Card embeds a flexible and low power display. This display compensates the lack of information we notice today in contactless use, and permits to check and display information without contactless reader.

- The RFID Antenna and the smart card module allow the charge of the Thin Film Power Battery. The antenna allows contactless charge and data transmission.

3. Microbattery on chip

The microbattery is realised by PVD techniques such as sputtering and thermal evaporation, (see figure 2), [1]

- first metallic coating achieved by DC magnetron sputtering acts as electrical collectors
- second layer based on TiS_xO_y is deposited by DC to serve as positive electrode.
- glass coating achieved by RF sputtering overlaps previous layers and constitute the solid electrolyte
- Finally, a lithium coating deposited by thermal evaporation serves as negative electrode.

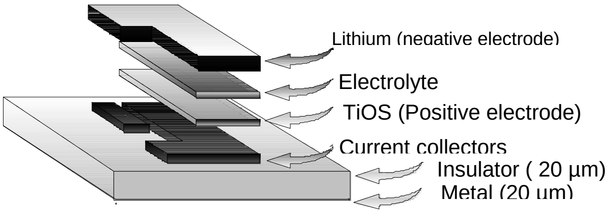

Figure 2: *Microbattery architecture*

The superposition of these layers allows an active electrochemical cell about 10 to 15 µm thick. Since lithium is very sensitive to moisture, the cell has to be protected against ambient air by very efficient barrier.

Such a power source operates between 1.6 V and 2.8 V. It offers an energy density of about 100 µAh/cm^2, high cyclability with more than 1000 cycles without capacity loss and is very electrochemically stable (no self discharge).

3.1. Size reduction and deposition on ASIC wafer

To deposit the microbattery directly on chip, developments have been performed to scale up the battery to fit the chip size (less than 25 mm^2) and to ensure physical adherence with the chip without disturbing the ASIC components.

3.1.1. Size reduction

Rechargeable microbattery already developed by HEF R&D has a surface from 2 to 4 cm^2. To study the consequences on the electrical performances of the microbattery when reduced, new stainless masking system were designed and machined.

Thus microbatteries with different sizes (typically 25 mm^2, 100 mm^2 and 200 mm^2) were deposited onto Si wafer and tested at low rate, (see figure 3). The results show that, in this size range, the embedded energy of the microbattery is directly linked to its active surface for the same surface.

The microbattery has a capacity of 45µAh/cm² per micron of positive electrode. Consequently, the entire surface available on chip has to be used to have a maximal energy.

3.1.2. Chemical compatibility with Si substrate

In order to evaluate the potential chemical interactions between microbattery and functional ASIC used as a substrate, some microbatteries of 200 mm^2 were deposited on a processed wafer supplied by ST Microelectronics. Observations of cross section by SEM show no chemical diffusion at short time between the materials constitutive of the ASIC and the micro battery, (see figure 4).

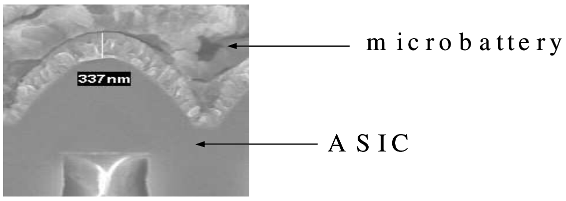

Figure 4: Observation of the cross section

3.1.3. Masking system

Intensive investigations have been performed to develop masking system for permitting the deposition of microbattery on Si wafer. Indeed, each mask must have a good flatness and a thermal behaviour similar to this of Si during the deposit process, in order to have a good contact with the Si wafer substrate.

It is the reason why different solutions of metallic materials have been evaluated and tested. Presently, a masking system is available: its design, its constitutive material and its manufacturing process have been defined and microbatteries were thus manufactured on ASIC, (see figure 5).

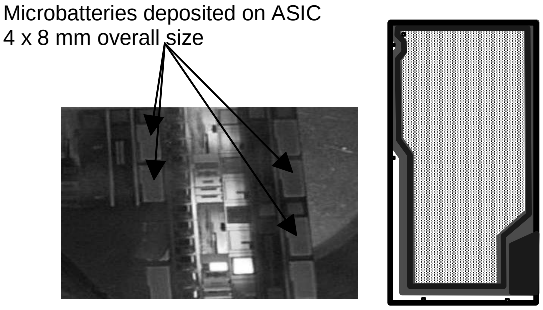

Figure 5: Microbatteries deposited on ASIC

The first results seem to be very promising. The relative location of each layer seems to be correct, and the microbatteries deliver an open circuit voltage. However, electrochemical expertises have to be pursued in order to check their electrical behaviour and to study the effects of the ASIC topology on their performances.

3.2. Packaging of the module "microbattery on chip"

Since lithium is very sensitive to moisture, microbattery has to be protected by an encapsulation barrier constituted of metal or polymer. Its total thickness has to be less than 50 µm in order to meet with the constraints of integration into card. And its machining process has to be suitable with handling of Si wafer.

Thus, two ways of encapsulation are studied: one based on lamination of thermobonding film associated to thin metallic foil, the other one is inspired from microelectronics techniques like Physical Vapor Deposition techniques.

3.2.1. *Encapsulation by lamination*

Taking into account the specifications of the smart cards, the thickness of the packaging layer has to be reduced at least to 50µm. Several promising bonding films are under evaluation.

However, in order to open the thermo bonding film range compatible with lithium, a pre-encapsulation made of a PECVD film obtained with organic precursor was deposited on the battery. A 0.1µm thick $Si_xC_yO_z$ film allows a first protection of the lithium layer, [1]. Lithium oxidation is followed by weight increasing method. The weight-increasing rate is measured at $2x10^{-3}$ mg/cm^2.mn (it corresponds to an oxidation of 0.02µm of Li per minute).

The thermo bonding film thickness should be as small as possible in order to limit the edge entry of moisture. Lamination process allows reducing the total encapsulation film thickness to less than 50 µm.

3.2.2. *Encapsulation by PVD*

The second solution has the advantage to use techniques compatible with microelectronic and smart card embedding processes. The use of a single inorganic thin films (for example alumina, silica, silicon nitride) obtained by Physical Vapor Deposition at low temperatures have been first examined. First experiments have shown that due to the high roughness of the lithium of the microbattery, a first step of planarisation is necessary. This will be done by a first coating of polymer at low temperature.

4. Thin Film Power Battery

The second rechargeable battery, integrated into the card packaging, is a flexible Thin Film Power Battery (TFPB) dedicated to ensure microbattery charge and to supply temporarily user interface functions (keyboard, display…). It will have to be fast charged: a complete charge of the battery is planned in less than 3 minutes. Its nominal voltage has to be higher than 2V and its capacity of about 10 mAh. To be integrated into the PEA Card, its thickness must be inferior to 400 µm whereas its maximal surface is about 6.5 cm^2, because of the small free place into the card.

So a strong effort of development is made on the implementation of its components (electrodes and electrolyte) and on their assembling into new battery architecture.

4.1. Lithium-ion technology

The Thin Film Power Battery is based on the lithium-ion technology, which today offers the higher energy densities, with higher nominal voltage (typically 3.6V), capable to be charged in maximum 1 hour (classically 5 hours), [2]

These rechargeable batteries are composed of electrodes made by coating of slurries on metallic foils. The slurries are constituted of powered active material mixed with electronic conductive additives and a polymer binder, the whole mixture being dissolved into an organic solvent. After drying, the electrodes are calendered to reduce their thickness and then to increase the volumetric energy.

The electrolyte based on anhydrous organic solvent containing Li salts is impregnated into polymer membrane, which ensures the physical separation and the electronic isolation between the two electrodes. Figure 6a shows the electrochemical system of Thin Film Battery composed with two square electrodes separated by an electrolytic membrane. The system is then packaged in a hermetic metallic pouch, in order to be protected against moisture, (see figure 6b).

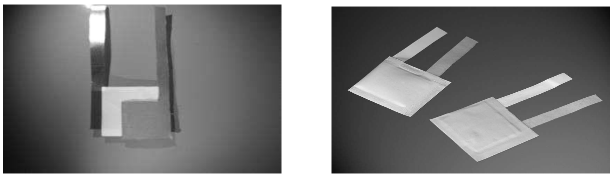
(a) (b)

Figure 6: Thin Film Battery and its components

4.2. Active materials for electrode

Active materials for classical Li-ion batteries are today lithium cobalt oxide and graphite. The positive electrode based on lithium cobalt oxide is a very good material for high power but graphite negative electrode limits the recharge times. Indeed, if the charge rate is too high, there is an elevated risk of lithium dendrites formation that shortens the cycle life of the battery or may even lead to internal short-circuit, [3].

It is the reason why CEA has developed a new high power negative electrode based on lithium titanate Spinel $Li_4Ti_5O_{12}$, capable to sustain faster charge rates, [4]. For instance, at 20C rate (i.e. charging time of 3 minutes), the charged capacity of this materials represents 41% of its specific capacity on thin electrodes with surfacic active mass content of about 0.5 mAh/cm^2, (see figure 7).

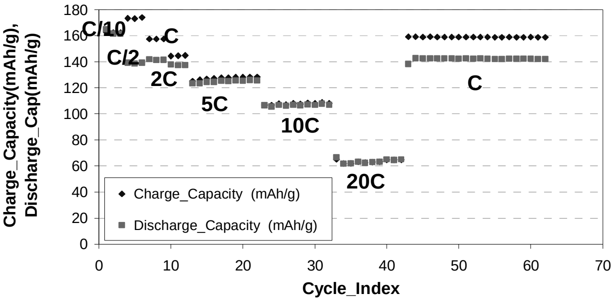

Figure 7: Capacity of CEA $Li_4Ti_5O_{12}$ vs charge rate

The Thin Film Power Battery thus is based on a commercial lithium cobalt oxide for the positive electrode associated with CEA lithium titanate negative electrode and its nominal voltage is about 2.3V.

4.3. Electrode formulation

Electrical performances of the Thin Power Battery strongly depend on the electrochemical behavior of each electrode, which also depends on the nature and the contents of each compound. Moreover, the surfacic active mass content of the electrodes have to be increased up to 1 to 1.5 mAh/cm^2, in order to fulfill the volumetric energy density required for the final demonstrator.

So, studies were conducted in order to optimize the formulation of each electrode and to reach their better power behaviour with a surfacic active mass of 1.5 mAh/cm^2. Different polymer binders and several conductive additives with different morphologies and specific surfaces were tested.

The methodology of the design of experiments was applied in order to limit the number of trials. The responses selected for the exploitation of the experiments were based on the quality of the coated layer (adherence on the metallic foil) and the power performances (capacity at fast rate 10C and loss of capacity), see figure 8.

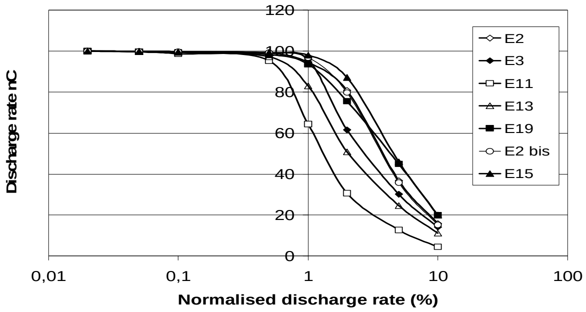

Figure 8 : Normalised capacity versus discharge rate for different $LiCoO_2$ electrode formulations E_i ($1.5 mAh/cm^2$).

Thus, tendencies were enlightened like the effects of binder content and the influence of the particle morphologies for the conductive additives. For each electrode, an optimized formulation was defined and first prototypes were assembled using the electrode formulations and classical commercial electrolyte with Celgard© separator.

4.4. Electrolyte formulation

Electrolyte and separator membrane ensure the Li^+ ions transport from positive electrode to the negative electrode during the recharge step, and inversely during the discharge. At fast charge rate, specific characteristics for the electrolyte are aimed; it concerns its viscosity, its ionic conductivity, its chemical stability towards the electrode materials and its window of electrochemical stability [5]. The physico-chemical properties of the membrane are also very influential like the porosity, the pore morphology, the separator thickness …

So, investigations have been undertaken to optimise the formulation of the electrolyte component to make it usable in power applications. Thus, new electrolytes have been designed from commercial solvents with different salt contents. They are tested for comparison with commercial separators and a lab polymer membrane developed by CEA for power applications. The experiments are conducted in button cells with optimised $LiCoO_2$ and $Li_4Ti_5O_2$ electrodes and presently their behaviours in ageing at C charge/ C discharge rates are examined.

The results are promising: some electrolyte/separator combinations seem to exhibit high cycling stability. In particularly, the CEA membrane associated with modified commercial electrolyte shows a very stable behaviour, with a loss of capacity inferior to - 0,0118% / cycle, i.e. the cycling life of such a battery is easily over 1500 cycles at C rate. See figure 9.

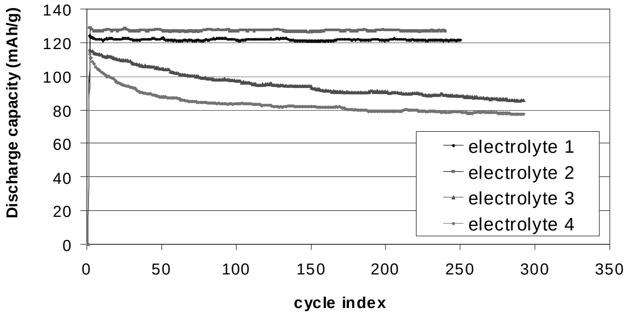

Figure 9 : Endurance tests with different electrolytes ($LiCoO_2$ $1.59 mAh/cm^2$ / CEA membrane / $Li_4Ti_5O_{12}$ $1.75 mAh/cm^2$)

4.5. Assembling and packaging

In order to reach the specification of the Thin Film Power Battery to be integrated into the PEA Card, its volumetric density has to be increased while keeping its performances in power. Thus, final thickness of electrodes after calendaring, thickness of packaging, geometry of each component and their arrangement, connexions with the other components of the card have to be optimised. Thus, for instance, studies were launched to optimise the calendering parameters like temperature, pressure … Other investigations about final size and format are in progress too.

5. Design of the ASIC

To manage the power stored into the microbattery and the Thin Film Power Battery, 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. Thus, the ASIC allows 4 functions:

- Monitoring of discharge and control of charge for the microbattery.
- Monitoring of discharge and control of charge for the Thin Film Power Battery.
- An interface with external power supply (inductive coupling or other external power)
- Applicative functions: retention of data in RAM and interface with processor to transmit charge/discharge status of batteries.

In addition, a state machine and an interface with the microcontroller assure the data communications to the user. See figure 10.

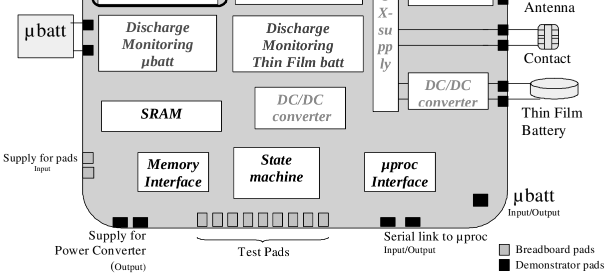

Figure 10: functional architecture of the Leti die

5.1 The Microbattery discharge controller.

This part of the asic supervises the tension of the microbattery and gives the state (charged or discharged) to the supervisor (then to the user via the display).

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. The design of the ASIC has ultra low power constraints.

The 'discharge monitoring microbattery' block is the most critical part of the design because it is only supplied by the microbattery. Then it must be designed with very low power constraints and a wide voltage range (1.6V to 2.8V which are the extreme voltage of the microbattery in the application).

The microbattery is 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 (see figure 11): the circuit of comparison, the circuit generating the signal of activation (ACT) 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 one second every hour. The application (RAM retention) needs 50nA. The discharge of the microbattery is very slow and a monitoring per hour is enough. This block is made of an oscillator of 1Hz built from a reference of current of 200pA. Then this clock is filtered to generate a pulse every hour.

The reference of current is produced from an architecture of H. J. Oguey and D. Aebischer [6], which has no resistance. Always to have less consumption, a Schmitt trigger rectifies edges on the output of the oscillator [7].

For security reason, the activation signal is generated in situ. In this way, hackers have less possibility to attack the chip.

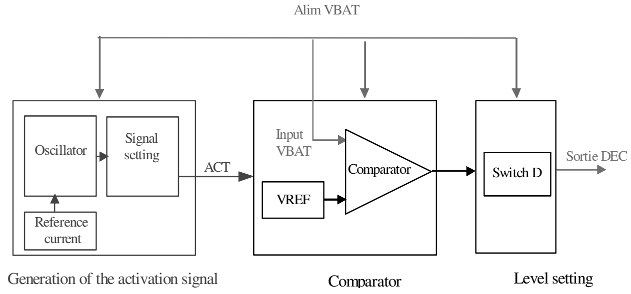

Figure 11: The microbattery discharge monitoring block.

The Table 1 gives some simulation results related 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.

The discharge controller die was received in Sept. 2004. The test of the circuit gave good compliance with simulation. The oscillator has a frequency of 740mHz with an average consumption of 400pA. The frequency is lower than expected but is not a problem for our application.

5.2. The Microbattery charge controller.

This part of the asic provides constant current in order to charge the microbattery. When the voltage of the microbattery is less than the threshold, the 'discharge monitoring microbattery' block sets a signal to inform the smart card supervisor: the supervisor could decide either to active the charge of the microbattery if a source is present either to active the secure function before the complete discharge of the battery.

The microbattery could be charged either by inductive coupling in case of contactless smart card, either by the Thin Film Power Battery embedded in the body of the card, or by contact via the module of the smart card.

The principal difficulty in the choice of the architecture of this circuit comes from the number of the power connected to the circuit. They are three, previously described.

The microbattery must be charged with a current of about 25µA. The charge starts only in the presence of a power supply higher than 2.9V 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 (see figure 12): a block of comparison checking the state of the microbattery, a state machine ordering the start of the charge, and the charger itself.

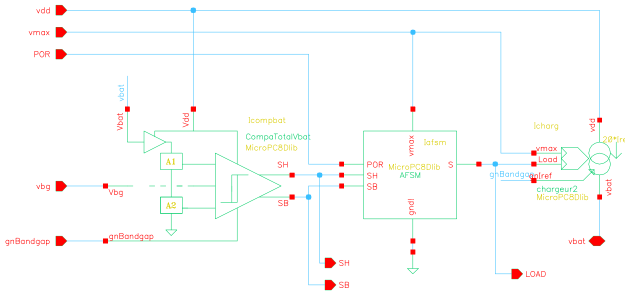

Figure 12: Scheme of the microbattery charge controller

The overall consumption of the circuit depends on the operating mode. In the presence of an external power vddc, and during the charge of the microbattery, the circuit provides a charging current of about 26.9µA to the battery and consumes 34.5 µA: an output (Icharge/Iconso) of 78 % is thus reached. Without external power, all the current necessary to the operation of the circuit comes from the microbattery. The blocks which consume permanently are designed so as to consume a total current smallest as possible (maximum a few tens of pA), see Table 2.

	Typ.	Variation in temperature		Worst case
		0°C	60°C	
Charge current (µA)	26.9	24.6	29.6	22.7 to 31.9
Consumption on microbattery (pA)	11.4	1.7	89.2	7.8 to 17..3

Table 2: charge current and consumption on microbattery when no charge is carried out

The charge controller die was received in Jan. 2004. The component is completely functional and the charge current is 28µA.

6. Conclusions

This paper presents the status of works undertaken in the PEAC Pocket project in order to achieve a demonstrator (the PEA Card) integrating two embedded power sources.

The objective of the project is to demonstrate novel functionalities, which will be integrated into the new generations of smart object. Thus, innovative technological bricks have been designed, produced and tested.

These new components are:

- A microbattery built directly on chip for security applications;
- A fast rechargeable Thin Film Power Battery with higher capacity for user interfaces and microbattery recharge
- A specific ASIC to manage the energy of the two rechargeable batteries (charge and discharge controls) with a strong constraint of very low power consumption.

A user interface (display, buttons…), a driver processor, an antenna and a module for charge, these new components will be integrated into the PEA Card. Up to now, each component is individually developed. Their preliminary characterisations (power consumption, power performances, overall size…) supply the technological information necessary to define the PEA Card design.

The final ASIC, including charge and discharge blocks (described in this paper), RAM and state machine (for application) is on progress and will be produced at the beginning of year 2006. A complete demonstrator, with all elements embedded in a card is forecasted on summer 2006.

Acknowledgements

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References

[1] M. Martin, F. faverjon: ‘A multilayer semi-industrial vacuum deposition equipment for producing ultrathin batteries’, Thin Solid Films, Vol. 398-399, November 2001, Pages 572-574.

[2] J. Danroc, F. Sanchette, S. Martinet, E. Damery, H. Rouault and R. Salot, J. Phys. I France 12 (2002) Pr 2-121-129.

[3] K. Nakahara, R. Nakajima, T. Matsushima and H. Majima: 'Preparation of particulate $Li_4Ti_5O_{12}$ having excellent characteristics as an electrode active material for power storage cells', Journal of Power Sources, Volume 117, Issues 1-2, 15 May 2003, Pages 131-136.

[4] S. Jouanneau, C. Bourbon, F. Le Cras, H. Lignier, patent n° E.N. 04 09 207, "Composé pulvérulent d'oxyde mixte de titane et de lithium dense, procédé de fabrication d'un tel composé et électrode comprenant un tel composé", (2004)

[5] K. Xu,: 'Nonaqueous Liquid Electrolytes for Lithium-Based Rechargeable Batteries', Chem. Rev., 2004; vol 104(10); pp 4303-4418.

[6] H. J. Oguey et D. Aebischer : 'CMOS current reference without resistance', IEEE Journal of Solid-state Circuits, vol. 32, NO. 7, july 1997, pp. 1132-1135.

[7] S.F. Al-Sarawi : 'Low power Schmitt trigger circuits', Electronics letters, vol. 38, No. 18, 29 august 2002, pp 1009-1010.

[8] http://www.avesodisplays.com/sol/smart_cards.html