LabOSat: Low cost measurement platform designed for hazardous environments

M. Barella¹,³, G. A. Sanca⁴, F. Gómez Marlasca², G. Rodriguez¹, D. Martelliti¹, L. Abanto⁴, P. Levy²,³, F. Golmar¹,³,⁴

¹Centro de Micro y Nano Tecnología del Bicentenario, INTI, San Martín, Bs. As., Argentina
²Centro Atómico Constituyentes, CNEA, San Martín, Bs. As., Argentina
³Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Bs. As., Argentina
⁴Escuela de Ciencia y Tecnología, UNSAM, San Martín, Bs. As., Argentina
mbarella@inti.gov.ar

Abstract—In this work the characteristics and performance of LabOSat platform to carry out experiments over electronic devices in aggressive environments are described. Configurable, portable, low weight and low cost are the main features. First measurements made in our laboratory are presented before testing in space.

Index Terms—Measurement instrument, portable platform, space mission, non-linear devices, resistive switching.

I. INTRODUCTION

LabOSat is a universal platform to perform experiments in harsh environments such as outer space, low pressure - low temperature conditions or high levels of radiation. LabOSat-01, the first version of the platform, is designed to harbour devices to be tested electrically under this kind of conditions. Inside LabOSat-01, there is a module, called MeMOSat, which forces with voltage or current customized sweeps ReRAM non-volatile memory devices and can be easily adapted to any two-terminal device. Moreover, this module, can run endurance tests to study how extreme conditions degrade the memory cells. Its predecessor, MeMOSat-1, is up and running inside “Tita”, a BugSat manufactured by the argentinian company Satellogic [1] which is presently in a LEO (Low Earth Orbit) at approximately 500km.

Nowadays, two boards LabOSat-01 are being integrated on the new satellites that the company is developing and there is a third board executing the programmed experiments at our labs as control sample. Figure 1 shows the board with an inset of a ReRAM device.

In the following sections, a general description of system’s hardware and software is given. Then, the capabilities of the board are explained followed by the description of the devices measured in this work. Finally, the characterization of current source and the implementation of LabOSat in the laboratory are presented. This work is the first step to validate LabOSat as an instrument platform for performing electronic measurements in hazardous environments.

II. SYSTEM OVERVIEW

A. Hardware description

The building blocks of LabOSat are depicted in Figure 2. The core of the board is a mixed signal microcontroller MSP430F1612 (Texas Instruments) which controls all the peripherals circuits (blocks) designated to specific tasks. This microcontroller is frequently used in Low Earth Orbit missions to drive CubeSats and was tested by NASA [2]. It uses 12-bit DACs outputs to precisely control the voltage or the current that will stimulate on-board devices. The 12-bit ADCs inputs are used to measure the response of the DUTs and other parameters that are periodically checked to guarantee the correct behaviour of the board. Finally, there are several addressing pins located at the GPIO ports that are dedicated to switch between blocks or modes of operation. The following are the most relevant blocks of LabOSat-01:

To measure temperature we use a LM74 thermometer (Texas Instruments) which communicates through SPI and is configured to measure temperatures over 0°C up to 125°C. Nevertheless, all commercial components of LabOSat are designed to operate in temperature ranges from -40°C to 85°C.

The dosimeters block, COTS pMOS transistors characterized as radiation sensor, is designed to measure total ionizing radiation. This module is crucial for space applications or measurements inside a particle accelerator for example.

The MeMOS block is dedicated to experiments over memory devices, particularly, devices based on Resistive Switching phenomena [3] which are expected to work well under big dose of radiation. Other devices could be embedded such as non-volatile memories like flash memories.

There is another experiment running inside LabOSat de-
signed to study the performance of transistors. This block is named xFET and basically can test any transistor device, commercial or custom made.

The goal of the last two blocks is to electrically test devices degradation under hostile conditions. Stimuli to test devices can be delivered sourcing voltage or current and controlled with high precision using DAC outputs. When sourcing voltage, current limitation is possible. As said before, measurements are made using the ADC inputs and each of them is preceded by a buffer and an amplifier in order to gain or attenuate the signal giving wide range measurements and avoiding out-of-range ADC readings. The MeMO block allows operation over 28 devices and the xFET block over 6.

The current source circuit was inspired by the current loop used in the CIAA project [4] and was implemented with minor modifications to fulfill the requirements of ReRAM devices. This current block allows LabOSat to perform new experiments in MeMO module in contrast to its predecessor MeMOSat-1. When sourcing current, LabOSat can deliver up to 23mA with a maximum power of 230mW over DUT.

PCB is made of four layers where the outer ones are ground planes and the inner layers hold the tracks routed with Manhattan strategy to reduce crosstalk and parasitic capacities. LabOSat also has an external port to perform MeMO or xFET remote experiments in a reduced-size board. The board weights 36g and it’s dimensions are 100 × 100 × 15mm which makes LabOSat a light-weight and portable platform.

**Fig. 2: Block diagram of LabOSat-01.**

**Execute Standard Test:** The stdTest instruction or Standard Test routine comprises several steps where supply voltage of the board (V\textsubscript{battery}), temperature (T), dosimetry (dosimeters’ voltage) and response of ReRAM devices and transistors is measured. Figure 3 shows the pseudo-code of the Standard Test routine. This instruction can only be executed once a day.

```
stdTest request
if a day has passed then
execute Standard Test
else
do not execute Standard Test
end if
```

```
stdTest execution
read dosimetry, \textsubscript{V\text{battery}} and T
for each ReRAM in bank 1 do
measure IV or endurance test
end for
read \textsubscript{V\text{battery}} and T
for each ReRAM in bank 2 do
measure IV or endurance test
end for
for each xFET do
measure modulation and output characteristic curve
end for
read \textsubscript{V\text{battery}} and T
```

**Fig. 3: Pseudo-code of Standard Test request and execution.**

**How measurements are reported:** The sendReport instruction requests the last report generated by LabOSat. It could be the report of a Standard Test or other instruction (not explained here). The length of the report is informed within the first bytes making the communication more robust by the implementation of a timeout.

**C. Interface and Communication**

All data is saved on microcontroller’s flash memory after execution. To download, communication through SPI with sendReport command must be done. The length of the report depends on the kind of instruction sent and it is reported within the first bytes of data, inside the header of the report. The header also contains an identification number of the board, the report number, the CRC-16 of the report itself, a time stamp that indicates when the last instruction was executed and a status byte which indicates errors and logs. The calculation of report’s CRC-16 is executed to check if memory or communication was corrupted by a bit flip as a result of ionizing radiation for example.

The decodification of the report is made with a Python script which facilitates the reading of the flash data and allows to see easily if the behaviour of each device differs from last execution.

The LabOSat-01 is programmed to produce reports of less than 3 kB because of satellite’s telemetry bandwidth availability. On Earth, as we want to reproduce same operation...
conditions (except the harsh environment) the report is downloaded with an emulated satellite made with an Arduino Nano using the built-in SPI to USB module and a script written in Python. The emulation program, i.e. communication and decodification, is called pySat.

III. DEVICES UNDER TEST

A. Single-bit ReRAMs

The on-board DUTs are tri-layer structures composed of two metallic electrodes divided by an oxide thin film fabricated at our laboratories. The studies are focused on non stoichiometric titanium oxide (TiO$_{2-x}$) and manganite La$_{1/3}$Ca$_{2/3}$MnO$_3$. On this devices, the Resistive Switching works, taking advantage of oxygen vacancies inside the oxide cell. When an electric field is applied it produces the formation of mixed filamentary structures formed by these vacancies and metal atoms from the electrodes. This structure reduces the resistance of the dielectric oxide cell working as a parallel resistance of lower value. In some cases, depending on the applied field, the filamentary structure could short circuit the electrodes and leave the device in a very Low Resistance State (LRS).

The switching between different non-volatile resistance values or “states” is exhibited when this filamentary structure is disarmed (or even fused) and formed again. This is accomplished by applying voltage or current pulses of opposite polarity (bipolar Resistive Switching).

Measurement principle: The way we test degradation on devices is performing IV curves and endurance tests. The first allow us to study the dynamic response of the cell, precisely how SET (write) and RESET (erase) process evolve from first IV curve. The latter let us to understand how degradation modifies the device’s performance as a memory unit working in a static way.

The devices can be controlled imposing a voltage or injecting current through it. In the first case, as can be seen from Figure 4a, the device is in series with a shunt resistance and the value of $V_2$ is measured to infer the voltage drop over the device. On the other hand, when current control is preferred, the device is subjected to the circuit showed in Figure 4b and $V_1$ gives information of the voltage drop over it. Either the case, the stimulus of the source will depend on the kind of experiment to be performed and the voltage or current value imposed by the source is set with the DAC output of the microcontroller. Each mode is configured with multiplexers and/or switches that are addressed with GPIO ports. As sources only apply positive voltage (current) two switches give the control of the polarity of the devices.

1) Voltage mode: the math to obtain the voltage drop and the current through the device when the voltage source is selected is shown in the following equations. The source sweep ($V^{+}$), parasitic resistances ($R_3$ and $R_4$) and shunt are known and $V_2$ is measured so Kirchhoff’s law returns:

\[ I_{\text{mem}} = \frac{V_2}{R_{\text{shunt}}} \]  
\[ V_{\text{mem}} = \Delta V = V^{+} - V_2 - I_{\text{mem}}(R_3 + R_4) \]  

b) Current mode: when current control is selected, the source sweep ($I^{+}$) and parasitic resistances ($R_1$ and $R_2$) are known and $V_1$ is measured instead. In this case, Kirchhoff’s law returns:

\[ I_{\text{mem}} = I^{+} \]  
\[ V_{\text{mem}} = \Delta V = V_1 - I_{\text{mem}}(R_1 + R_2) \]  

If polarity is inverted, either current or voltage mode, current flowing through memory can be considered negative taking into account the device Bottom and Top Electrodes. In consequence, voltage drop will be negative too.

Parasitic resistances arise from on-resistance of multiplexers and switches. Actually, LabOSat uses DG406 and ADG5413, respectively. Both of them have been characterized on Earth as a function of supply voltage at room temperature but, in order to obtain more accurate data, measured temperature and supply voltage can be used to extrapolate the tabulated data (datasheets available from Analog Devices and Maxim, respectively). As a result, this will improve the estimation of voltage drops and currents.

As said in Section I, the devices can be subjected to two different kind of experiments: endurance test and IV test, static and dynamic response test, respectively.

The Endurance Test concerns application of successive pulses of opposite polarity in order to achieve a fixed number of commutations. For example, if the device is in High Resistance State (HRS) and one commutation is desired to occur, the test will run applying SET pulses until the transition to the LOW state takes place. In case of two commutations, after reaching the LRS, RESET pulses will be applied until high state is recovered.

The amplitude, duty cycle and period time can be configured and if the writing pulse (either SET or RESET) is done in voltage mode also the shunt resistance must be configured. Between each writing pulse a reading pulse is applied to measure if the state of the device has changed. Additionally, the algorithm behind the test requires two preset levels (states or resistance values) to define a window of operation. Is desired that each pulse commutate the device between levels.
outside this window but, if is not the case, the number of tries, i.e. the number of pulses of SET or RESET pulses, can be augmented.

By the same token, the IV Test can be configured to stimulate the sample with a current sweep or a voltage sweep. The sweep is interpreted as a sequence of triangular stimuli, cast by the number of points (steps) and incremental positive and negative amplitude. As a result, the triangular sweep, starts from zero up to the maximum positive amplitude, then to maximum negative amplitude and back to zero. The maximum amplitude is defined by the number of steps multiplied by the incremental amplitude. Polarity of sweep can be set to start negative or positive. Henceforth, a starting positive voltage stimuli would be 0 → \( V_{\text{pos}} \) → 0 → -\( V_{\text{neg}} \) → 0.

The sweep can be configured to read the resistance state between sweep steps. Also if voltage control is selected the value of the shunt resistance must be set. When the current sweep is selected the shunt parameter is ignored.

In addition, as this platform is designed to work under aggressive environments, storage of measurements is limited due to restriction in download bandwidth. Because of this, the number of steps per record is another parameter to set when IV test configuration comes into play. This parameter is related with the number of steps to be applied because it determines how many steps would be recorded.

Coupled with this configuration LabOSat software allows to select how many ADC readings are going to be done in each measurement. Possible values are one, two or four readings. After acquisition, the readings are averaged and reported as a single value.

B. Transistors

The fabrication of these multi-finger transistors use non-CMOS compatible materials and were fabricated within a cleanroom facility.

Measurement principle: Experiments on transistors are configurable to perform voltage sweeps on drain with fixed gate voltage and the opposite, sweeps on gate with fixed voltage over \( V_{\text{NFT}} \). Figure 6. Source voltage, \( V_S \), is set to 1V but can be simply configured via hardware to any desired value. Measurements are taken from \( V_D \) node and converted to drain current using the known value of \( R_D \) and the applied \( V_{\text{NFT}} \):

\[
I_D = \frac{V_{\text{NFT}} - V_D}{R_D}
\]

(5)

This let the user plot two distinctive curves of the transistor: the output characteristic curve (\( I_D \) vs. \( V_D \)) and the transfer curve (\( I_D \) vs. \( V_G \)).

Encapsulation

As devices are custom-made within cleanroom facilities an encapsulation step is needed before integration to LabOSat. First, fabricated samples are diced to small dies to fit in a commercial SOIC-16 where they will be wire bonded. Second, an epoxy over the bonded devices is placed to protect them from physical damage. After the curing of epoxy the encapsulated devices are submitted to vacuum test up to 10^-3mbar and harmonic and random shaking test from 10Hz to 1kHz with 6.8g (RMS) maximum amplitude.

Between every fabrication step, from deposition over silicon wafer to epoxy protection on SOIC, an electric test is performed to see if the device is still working as expected. A picture of a device after the whole fabrication process is shown in Figure 1 (inset).

C. Dosimeters

LabOSat-01 has two commercial pMOS transistors that were characterized before integration to boards. These devices work as dosimeters, in the sense that incident radiation dose can be inferred from periodic measurements of the threshold voltage. As \( V_{\text{th}} \) is affected by the Total Ionizing Dose (TID), its shift can be used to estimate the dose absorbed by the board. This parameter is measured indirectly by biasing the source of the pMOS with a known current and voltage (\( I_S \) and \( V_S \)) while the drain is grounded. Then, reading the gate voltage allows to observe variations in \( V_{\text{GS}} \) which will be traduced to \( V_{\text{th}} \) variations [5, 6].
IV. RESULTS

Linearity of the platform

One of the improvements of LabOSat-01 with respect to MeOSat-1 is the possibility of forcing current through the ReRAM devices. Characterizing this block is critical to understand how measurements are made. The linearity of the current block was checked forcing current sweeps of half DAC range to a 1kΩ resistor while sampling ADC inputs and the DAC output with a Keithley SCS-4200. Also, LabOSat was asked to report the results in order to compare both acquisitions.

The response of the current source and acquisition stages was found to be linear in the range 0 - 2.5V. The data measured by LabOSat is in agreement with the curves acquired with the SCS-4200. The characterization of this block can be seen in Figure 7. The linearity of the system is guaranteed along the ADC input range. Additionally, this graph shows the capability of LabOSat when recording data. If an ADC is out of range, the channel is saturated. Then, LabOSat discards the measurements taken by that channel and changes to the next not-saturated channel to continue to sample the signal without saturation avoiding losing changes of the device response.

This measurement allowed to find DAC offset voltage, DAC gain error and the ADC gain error for the microcontroller. These values were found to be lower than the maximum reported by the manufacturer and are being used for software correction in data processing.

Working with DUTs

As shown at the inset of Figure 8 the memory cell exhibits the typical behaviour of a Resistive Switching Device. The non-smooth electrical hysteresis indicates that commutation is achieved [7], [8].

During the SET process, as the device is being controlled by current, the transition from HRS to LRS is power regulated meaning that \( P = I^2R \) will be diminished if the remnant resistance gets lower.

The 12-bit DAC of the microcontroller and the ability of LabOSat-01 to precisely control current and voltage over the same device allow us to observe the dynamic behaviour of a typical commutation. Within set process 349 pulses are applied and 447 for reset process. The number of steps per record for set process is set to 5 and 7 for reset, this gives a record of 63 data points for set and 69 for reset. With this in mind the curve acquired with the platform has 132 points. This number was chosen to equitably distribute data storage along 18 devices, 13 ReRAM devices and 5 xFETs.

![Dynamical response obtained with different instruments over the same TiO2-x-based ReRAM device. Inset: IV curves of the device after two consecutive Standard Tests.](image)

**Fig. 8:** Dynamical response obtained with different instruments over the same TiO2-x-based ReRAM device. Inset: IV curves of the device after two consecutive Standard Tests.

Comparative Analysis

To illustrate the performance of LabOSat-01 as a measurement and characterization instrument, same I-V curves were performed on a Keithley SCS-4200 over the same device. These experiments were performed using KITE software with two routines to perform a current controlled SET sweep followed by a voltage controlled RESET sweep. Two SMUs were used to stress the sample. The programmed stimuli involved 142 steps for set and 302 for reset. The software allowed us to record the responses in all steps of the sweeps. Comparison can be seen in Figure 8.

Same behaviour is observed in dynamic response with either instrument. The shift between curves raises from fact that when devices are coupled into LabOSat-01 for testing, parameters of the IV test must be tuned to obtain the desired response as said in Section III-A. In contrast, measurements done with SMUs can be considered to be performed without any loads.

Experiments over transistors are shown in Figure 9 and 10. The plots concern several sweeps of \( V_{AFET} \) for different fixed gate voltages and sweeps on gate for different fixed \( V_{AFET} \) voltages. In the modulation curves, Figure 9, besides LabOSat forces the sweeps on \( V_{AFET} \) with same voltage values, \( V_{DS} \) are not repeated between curves. As described in Section III, \( V_{AFET} \) is imposed and \( V_G \) is directly measured so, actually, \( V_{DS} \) is deduced from measured data as \( V_G - V_S \). This effect is consequence of the presence of \( R_D \) which allows LabOSat to calculate current through drain in a simple and effective...
way. In more sophisticated instruments, as the Keithley SCS-4200 used in this work, there is no effect due to loads because the measurement principle is different from the one employed by the platform. However, this effect does not disturb the observation of the transistor behaviour.

![Graph showing the relationship between I_D and V_GS](image)

Fig. 9: xFET drain current vs. drain-to-source voltage measured with LabOSat-01 and Keithley SCS-4200 for several values of V_GS indicated next to solid curves. The line depicts the effect of the load over the drain for same V_FET.

Transfer curves of transistors, Figure 10, need to be analyzed taking into account that R_D keeps V_FET ≠ V_D. When V_GS ∼ 0, V_FET ∼ V_D but increasing gate polarization leads to a bigger current flow through drain and so V_FET > V_D for V_GS > 0. This difference depends on the value of the load over the drain. At first sight, a small value seems to be the correct choice but the ADC’s resolution sets a minimum value in order to clearly resolve drain currents. On the other hand, a large value would give a good dynamic range to work with drain currents but would produce high voltage drops. In this case, LabOSat was designed to work with a medium load (500Ω) to obtain ratios V_D/V_FET > 0.85 (15% variation from V_FET). The shaded area in the plot indicates the points that differ in more than 10%, out of this area curves acquired with LabOSat and SCS-4200 overlap within the error bars.

V. CONCLUSIONS

First measurements with LabOSat-01 returned excellent results and exhibited to be in great agreement with the ones performed with more sophisticated and expensive equipment. They also showed that LabOSat is capable of forcing negative and positive currents (or voltage) on two-terminal devices. The ability to perform dynamic and static experiments and the flexibility it has when recording data make LabOSat a great instrument to study ReRAM devices.

In summary, LabOSat is a portable, configurable and low cost platform to perform voltage and current sweeps plus endurance test over electronic devices in harsh environment.

ACKNOWLEDGMENT

The authors would like to thank to R. Ferreira, E. Paz, W. R. Acevedo and D. Rubi who participated in the fabrication of ReRAM devices; P. Stoliar, L. Hueso, E. Lopez and L. Patrone who were involved in fabrication of xFET devices; M. G. Inza and J. Lipovetsky who facilitated the dosimeters. The authors acknowledge financial support from ANPCyT PICT 2013-0788 ”MeMOSat” and UNSAM-ECyT FP-001.

REFERENCES