Software Redesign of a Multi-Purpose Test Setup for Silicon Dioxide Studies

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***Abstract*—The high-luminosity upgrade of the Large Hadron Collider (LHC) necessitates a comprehensive understanding of radiation damage in silicon sensors for the CMS High Granularity Calorimeter (HGCAL). This project addresses the need for a robust and maintainable software framework to automate the characterization of the Silicon Dioxide. The pre-existing software, ported from a previous project, was a tightly coupled and unstable system suffering from legacy code, significant duplication, and inconsistent design. This work details the redesign of the measurement software, focusing on creating a modular, configuration-driven, and stable architecture, while maintaining support for legacy measurement classes. The new system, orchestrated by a central runner, utilizes a YAML-based configuration to dynamically initialize devices and define measurement parameters. The refactored codebase is significantly smaller, more maintainable, and provides a reliable foundation for current and future silicon sensor studies.**

***Index Terms*—Silicon Sensors, Radiation Damage, IV/CV Measurements, Software Engineering, Test Automation, HGCAL, CMS.**

I. Introduction

The High-Luminosity upgrade of the Large Hadron Collider (HL-LHC), scheduled to begin operation in 2026, will increase the instantaneous luminosity by an order of magnitude, presenting significant challenges for the existing detectors. To cope with the resulting high radiation levels and particle densities, the Compact Muon Solenoid (CMS) experiment will replace its endcap calorimeters with the High Granularity Calorimeter (HGCAL). This new detector will utilize hexagonal silicon pad sensors in its high-radiation zones, chosen for their intrinsic radiation hardness and fine segmentation, which are essential for particle-flow reconstruction algorithms. These p-type silicon sensors, with active thicknesses of 120, 200, and 300 μm, are expected to withstand neutron equivalent fluences of up to 10^{16} n_{eq}/cm^2 [1].

To ensure the performance and reliability of the HGCAL, it is crucial to systematically characterize the effects of radiation on these sensors. This is achieved by subjecting sensor prototypes to controlled doses of ionizing radiation and characterizing their electrical properties through Current-Voltage (IV) and Capacitance-Voltage (CV) measurements. Recent work has focused on developing novel methods to assess surface radiation damage, such as measuring the threshold voltage for inter-electrode isolation ($V_{th,iso}$) to compare different silicon dioxide variants [2]. This highlights the dynamic requirements of the research and the need for a software framework that can easily accommodate new, complex measurement techniques.

The software was based on a Python framework for the ARRAY wafer probing system [3], [4]. While the hardware setup was effective, the complexity of this repurposed system control software has shown to be a bottleneck for current and future research. This work was initiated to redesign the software, moving towards a more modern, reliable, and flexible framework to support ongoing and future silicon dioxide sensor studies.

II. Analysis

The initial analysis of the existing system and user workflows was conducted to define the requirements for the new software architecture.

A. Hardware Setup and Measurement Types

The setup characterizes various test structures printed on the unused edges of the silicon wafers, primarily Diodes, Strips, and Gate-Controlled Diodes with MOS capacitors (GCD-MOS) as shown in figure 1.

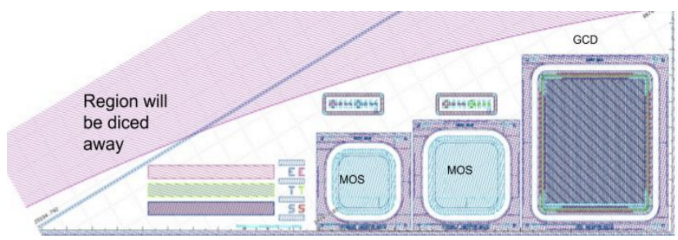

Fig. 1. Example halfmoon of a silicon wafer, containing a GCD-MOS

Each type of sample requires a specific hardware setup, with specific measurement device requirements. A Keithley 2001 multimeter is dedicated to reading a PT1000 sensor on the PCB for continuous temperature monitoring across all measurement types. The setup as used in the irradiation lab is shown in figure 2. Note that this setup does not include all possible devices, since during this session only the GCD-MOS structures were studied.

1) GCD-MOS Measurements: This test structure contains three different devices, two MOS capacitors and a Gate-Controlled Diode, as shown in figure 1 The MOS capacitors (MOShalf, MOS2000) are characterized by applying a reverse bias voltage sweep with a Keithley 2410 sourcemeter while measuring the capacitance with an LCR meter. The Gate-Controlled Diode is characterized by applying a voltage sweep

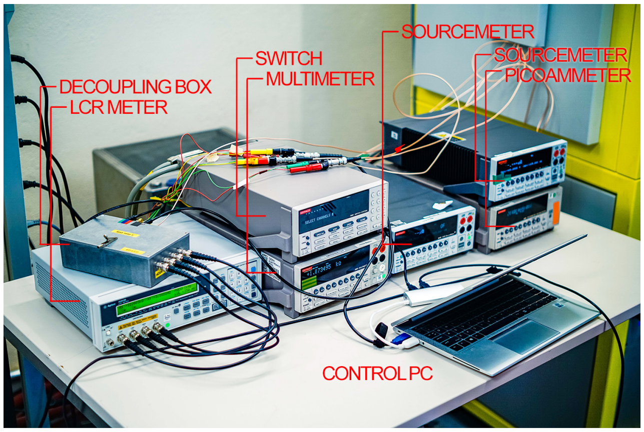

Fig. 2. Device setup in the irradiation lab, next to Obelix

to the gate with one sourcemeter, while a second sourcemeter applies a constant bias to the front of the diode. The resulting low-level leakage current is measured with a Keithley 6487 picoammeter. There is an option to apply a constant front bias, during irradiation, to the MOS2000 structure. An example of a typical acquisition can be seen in figure 3.

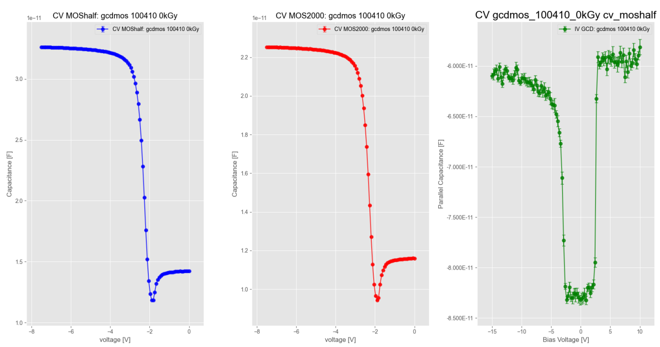

Fig. 3. IV and CV curves of a GCD-MOS structure at 0kGy during the system integration test.

2) Diode Measurements: The diode structures are used to study the surface properties of the silicon, using IV and CV measurements. From these measurements the $V_{th,iso}$ value is extracted [2]. In the CV measurements the back plane is reverse biased and the capacitance is read out from the diode pad for three different guard ring configurations: grounded, shorted and floating, as shown in figure 4. The voltage value where the capacitance starts to sharply increase in the guard ring floating configuration, corresponds to the $V_{th,iso}$. In the IV measurements the diodes back plane is reverse biased and the current is read out from the pad and guard ring separately. The voltage value where the two curves meet corresponds to the $V_{th,iso}$. This can be clearly seen in figure 5.

3) Strip Measurements: The strip test structures are used to investigate inter-strip isolation properties. This involves CV scans at various LCR meter frequencies. Additionally, inter-strip resistance is measured by applying a reverse bias to the backplane, sweeping a small voltage on one strip, and

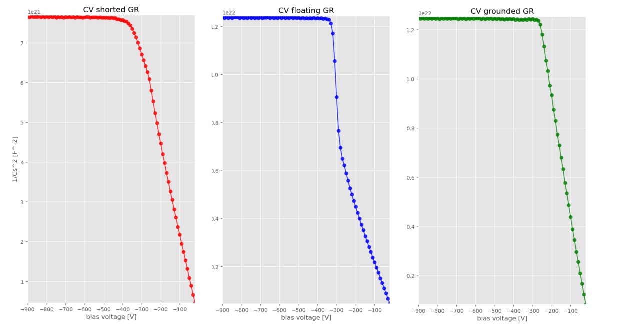

Fig. 4. CV scan of a diode at 1kGy, showing the guard ring shorted, floating and grounded to the pad.

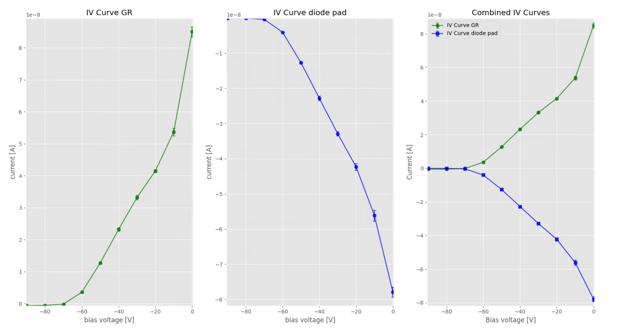

Fig. 5. IV scan of a non irradiated diode, showing the pad and guard ring, plus the combined slopes.

measuring the induced current on an adjacent strip. This produces an R-V curve showing resistance as a function of backplane bias. Note that the empty graph in figure 6 is due to only executing measurements for 2 LCR frequencies.

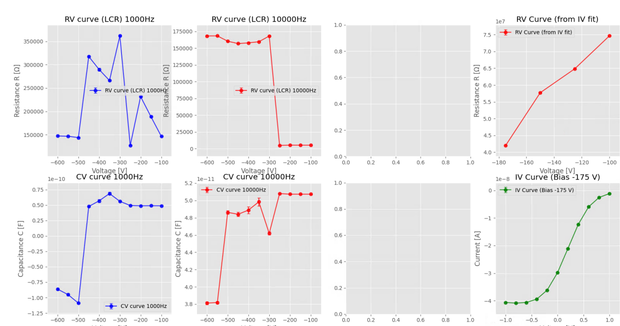

Fig. 6. Strip measurements with irradiated samples

B. Codebase Investigation

The existing codebase was plagued by issues stemming from an incomplete migration from Python 2 to Python 3, extensive code duplication, and hardcoded parameters that made it inflexible and prone to errors. The lack of a clear architecture meant that changes in one part of the code could have unforeseen consequences elsewhere, making development risky and debugging difficult. A good example of this is the direct importing of individual measurement classes, instead of using a module. This could cause measurements that are not part of the current testset to raise exceptions, even though they are not required to run.

C. Requirements and Design Considerations

Discussions with the primary users revealed a clear set of requirements. A GUI was deemed unsuitable due to the highly dynamic nature of the codebase; new measurement techniques could necessitate parameter changes not reflected in a static GUI. Instead, a command-line interface (CLI) driven by a comprehensive configuration file was preferred for its flexibility and suitability for batch processing. Key considerations included:

- **Maintainability:** The new codebase must be easy to understand, modify, and extend.
- **Flexibility:** The software should support different combinations of hardware and sample types without code modification.
- **Reliability:** The system must be stable, with robust error handling to protect hardware and ensure data integrity.
- **Reproducibility:** The core measurement logic must remain consistent with previous versions to ensure historical data comparability.

The ”ideal scenario” is a system where a user could define an entire measurement campaign in a single configuration file and launch it with one command.

D. Legacy Hardware Integration

A practical requirement was the integration of an older Agilent 4263B LCR meter, which communicated via a legacy GPIB protocol. A new compatibility layer was developed, which incidentally allowed for a much higher trigger rate. This revealed a separate issue with the Keysight E4980 driver, where an ill-configured acquisition function sent GPIB commands in an order that left the instrument in an unready state after each trigger, slowing it down.

III. Proposed Architecture Redesign

Based on the analysis, a new software architecture was designed with a focus on modularity, centralization, and extensibility.

A. A Centralized, Modular Design

The new architecture, shown in figure 7 is centred around a single entry point, ‘runner.py‘, which orchestrates the entire experiment. This runner parses a YAML configuration file that defines all experimental parameters, from hardware addresses to measurement sequences. This design decouples the high-level control flow from the measurement and device-specific logic.

The structure is designed to anticipate future modifications by making it easy to add new measurement and device classes. External systems are integrated strategically: the Obelix x-ray machine control remains a separate subroutine for safety, while the chiller control was integrated as a parallel thread for non-blocking temperature management. To maintain legacy support, the temperature management program can still be run as a standalone script.

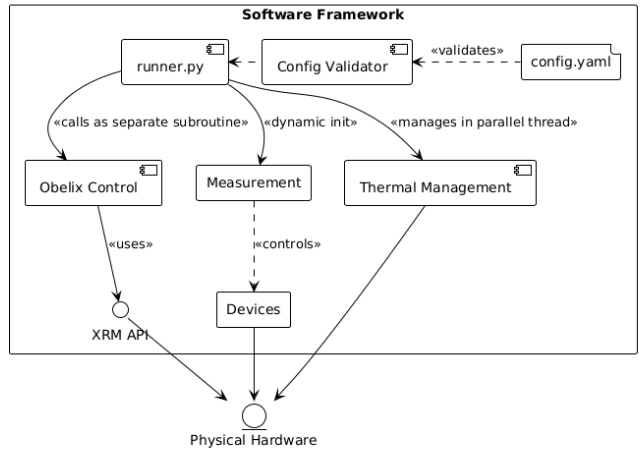

Fig. 7. Diagram of the new system architecture, showing the central runner, configuration file, and dynamic loading of measurement and device modules.

B. Development Strategy

A plan of action was established to guide the transition from the old codebase to the new one. A key principle was to ensure the repeatability of historical measurements at every stage of development, verified by back-to-back testing. GitHub Issues was used to track bugs, feature requests, and known problems, ensuring visibility for future developers.

IV. Implementation and Results

The proposed architecture was successfully implemented. The process involved rewriting the control logic while preserving the core instrument commands to ensure measurement consistency. In short, this meant that the code responsible for the global control was completely rewritten, while the measurement and device classes kept their original structure. For example, the device classes still utilized the functions as they were adopted from the ARRAY codebase, alongside additions that were needed to integrate them in the new architecture. The measurement classes had their parameters moved to be initialized in the measurement base class, but retained the three step ”initialize, execute, finalize” structure. The most significant changes happened in the measurement base class, which was now responsible for setting up the environment defined in the config files, specific for the requested measurement type. An example of such a configuration can be found in appendix B.

Unforeseen challenges were addressed, most notably a last-minute change to the Obelix API [5], which was successfully integrated just before the scheduled test campaign. Numerous quality-of-life features were implemented:

- Calculation of partial dose if an irradiation is stopped prematurely.

- A check for existing logs to prevent accidental re-irradiation of a sample.
- Generation of full-size plots with error bars and aggregated logs per run.
- Dynamic chiller setpoint updates via a thread-safe queue.
- Tuneable parameters for the CV plateau detection algorithm.

By removing redundant code and unused legacy files, the total codebase was reduced from 31,788 to 9,141 lines [4].

A. Irradiation Test Campaign

A last minute change in the lab schedule meant we only had access to Obelix for two days instead of 2 weeks. It was decided that using the GCD-MOS structures would be optimal, since these required the widest range of devices. For the other structures, a secondary validation session needs to happen in the future.

The redesigned software was validated during a multi-day system integration test with the Obelix x-ray machine. The system successfully automated the entire campaign, acquiring high-quality IV and CV data as a function of dose. The initial full irradiation session indicated an issue with the adaptive plateau detection logic. Figure 8 shows that the system was too sensitive, terminating the measurement prematurely. This was quickly resolved by adjusting its parameters via the configuration file, highlighting the flexibility of the new design.

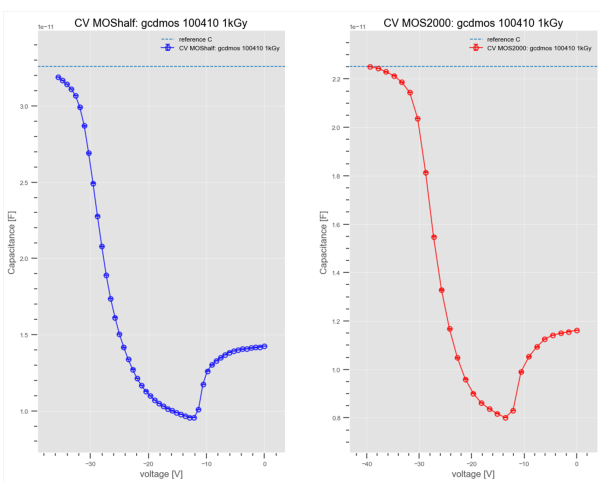

Fig. 8. Premature plateau detection and measurement termination

B. LCR Meter Performance

To ensure that the faster acquisition speed of the improved LCR meter driver did not negatively affect measurement quality, a comparison was made against historical data, and the other LCR meter. The results show that the measurement error is minimal and comparable across the full frequency range, validating the new implementation. With the new, faster implementation, running samples at room temperature occasionally resulted in inverted CV measurement data points, as shown in figure 9. This necessitated an ‘inter-trigger_delay‘ parameter to prevent these measurement artifacts. Testing shows that the delay effectively removed the measurement inversion, and at a sample size of 10 with 0.1ms inter-trigger delay, the new implementation is still 3 seconds faster per data point as compared to the previous implementation with the more modern LCR meter.

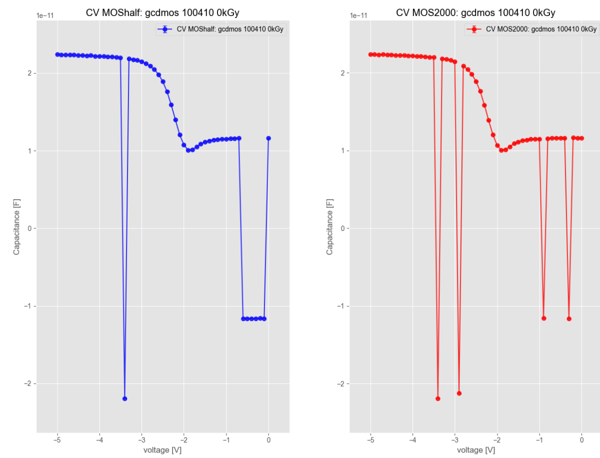

Fig. 9. Example of an inverted CV curve artifact observed at room temperature with 0ms inter-trigger delay.

V. Future Work

While the core objectives of the project have been achieved, several tasks remain:

- **Documentation:** The highest priority is to create comprehensive documentation, including a user wiki with examples, explaining the architecture and the impact of all configuration parameters.
- **Verification:** Due to limited lab access, the redesigned Diode and Strip measurement setups have not yet been fully validated in an irradiation campaign.
- **Schema Updates:** The configuration validation schemas need to be updated to include the latest parameters and features.
- **Minor Fixes:** A few minor bugs and quality-of-life improvements remain, which are tracked on GitHub.

VI. Conclusion

This project has successfully transformed an unstable, legacy codebase into a more modern and maintainable software framework for silicon dioxide characterization. The modular, configuration-driven architecture will not only streamline current research but also facilitate future extensions and adaptations.

Acknowledgments

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APPENDIX

APPENDIX A: IRRADIATION SETUP

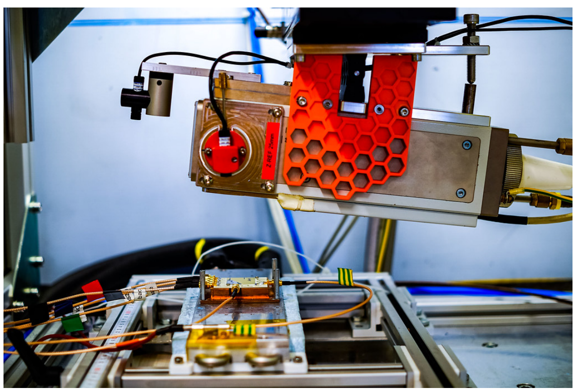

Fig. 10. A GCDMOS sample in the Obelix irradiation machine

APPENDIX B: EXAMPLE CONFIGURATION

```
measurement_type: 'gcdmos'
sample:
  type: 'gcdmos'
  id: '200484'
  preexisting_dose: 0

devices:
  sourcemeter_1:
    model: 'ke2410'
    address: 8
    lim_cur: 1.0e-3

  sourcemeter_2:
    model: 'ke2410'
    address: 25
    lim_cur: 1.0e-3

  switch:
    model: 'ke7001'
    address: 7
    connections:
      MOShalf: 1
      MOS2000: 3
      picoammeter: 9

  lcrmeter:
    model: 'agilent_4263b'
    address: 17

  picoammeter:
    model: 'ke6487'
    address: 15
    lim_cur: 100.0e-9

  multimeter:
    model: 'ke2001'
    address: 16
    sensor_r0: 1000

measurements:
  testset: [moshalf, mos2000, gcd]
  dynamic_voltage_range:
    enabled: true
    voltage_array_size: 100
    range_multiplier: 1.1

  CV:
    range:
      v_start: 0.
      v_end: -300
      step_size: -10
    sample_size: 10
    lcr_amplitude: 0.250
    lcr_frequency: 10000
    delay: 7
    trig_delay: 0.1
    plateau_window: 10
    plateau_extention: 1.15

  IV:
    range:
      v_start: 10
      v_end: -10
      step_size: -1
    sample_size: 10
    gcd_diode_bias: 5.0
    delay: 2.0

irradiation:
  shutter_id: 3
  doselist: [0, 1, 2, 3, 4, 5, 10, 20, 40, 70, 100]
  initial_measurement: true
  dose_rate: 16
  voltage: 40
  current: 50
  biasing: false

temperature_management:
  chiller:
    enabled: true
    model: 'chiller_cc_505'
    port: 'COM8'
    default_temperature: 20
    update_frequency: 2
  logging:
    directory: 'temperature_management/
    termperature_logs'
    log_interval_sec: 20
  plotting:
    update_interval_sec: 2
```

Listing 1. Example configuration file used for the GCD-MOS irradiation.