

DOSFET-L02: AN ADVANCED ONLINE DOSIMETRY SYSTEM FOR RADFET SENSORS

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Abstract

Radiation-sensing field-effect transistors (RADFETs) are integrating dosimeters that have found wide application in space and particle accelerator environments. We present a new system, the DOSFET-L02, for the readout of up to four RADFET sensors. The system features enhanced readout stability, support for long sensor cables, an adjustable exposure bias voltage of up to 30 V, and integrated temperature measurement. Recent measurements demonstrate the performance of the system with RADFETs at bias voltages of 9 V, 25 V, and under zero bias.

INTRODUCTION

Radiation-sensing field-effect transistors (RADFETs) are integrating dosimeters that have found wide application in space and particle accelerator environments. Over the past decade, the accelerator community has used these miniature sensors in several facilities for the monitoring of ionizing radiation doses from the mGy to the kGy range [1–5].

One of the recent installations is in operation at the fourth-generation light source FERMI@Elettra [6]. More than 70 RADFETs monitor radiation doses in various positions along the linac, especially in the sensitive permanent magnet undulators. This dosimetry system has been in continuous operation since the end of 2010. It employs a custom readout unit, the DOSFET-L01, which takes measurements from up to four sensors and communicates them to the control system over Ethernet. The system and its performance are described in detail in [7].

From the experience gathered with the DOSFET-L01, we have identified a few desirable improvements for the next version of the system:

- Higher and adjustable sensitivity
- Temperature measurement
- Better handling of long cables
- Remote firmware update capability

In this paper we present a new version of our readout system, the DOSFET-L02, which addresses these points. After a short overview of the system design we discuss its performance on the basis of data taken with the first prototype boards.

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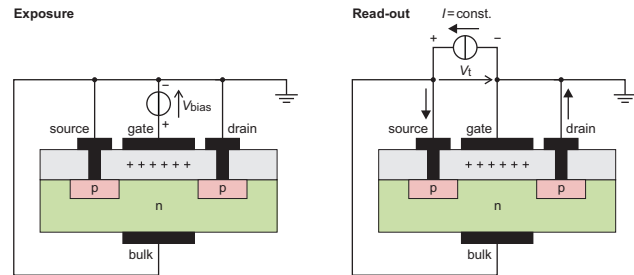


Figure 1: Schematic representation of a RADFET in exposure and readout configuration.

DOSIMETER PRINCIPLE

A RADFET is basically a p-channel MOSFET with an unusually thick layer of silicon dioxide below the gate electrode (Fig. 1). Ionizing radiation causes the removal of electrons, leaving behind a stationary positive space charge in the oxide layer. The build-up of this space charge can be substantially enhanced by applying a positive bias voltage to the gate electrode, but it also takes place when all electrodes are short-circuited (under *zero bias*).

The more dose is deposited on the dosimeter, the higher is the amount of positive charge stored in the oxide layer. The presence of this positive electric potential makes it harder to put the MOSFET into its conductive state – in other words, a stronger negative potential has to be applied to the gate electrode in order to create a conductive inversion layer in the bulk silicon below the oxide. The readout system (or *reader*) uses this effect by forcing a well-defined constant current through the transistor: The higher the threshold voltage (V_t) needed to obtain this current, the higher the dose absorbed by the RADFET.

SYSTEM DESIGN

Like its predecessor, the DOSFET-L02 is a 19-inch rack mount unit with a height of 1 RU (4.4 cm). Up to four external RADFET sensors can be connected using inexpensive USB 3 cables. We use the commercial RFT-300-CC10 RADFET from REM Oxford Ltd.¹ which contains two transistors that are read out separately. A custom *RADFET mount* board connects the sensor to the cable and serves as a convenient mounting support (Fig. 2). It also carries a digital thermometer with an absolute accuracy better than

¹REM Oxford Ltd., 64a Acre End St., Eynsham, Oxford OX29 4PD, United Kingdom

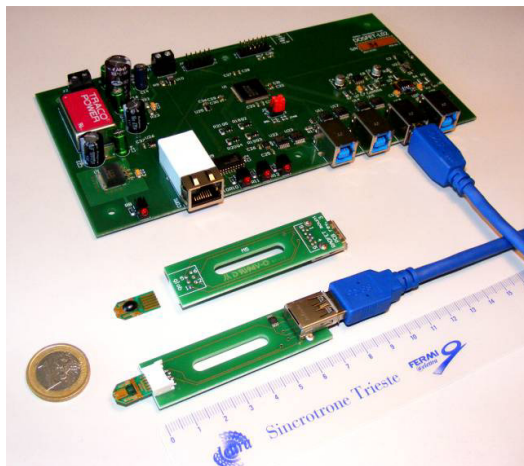


Figure 2: Photo of a DOSFET-L02 prototype board with two RADFET mount boards and sensors.

± 0.5 °C (rms) that has been chosen for its good properties under exposure to ionizing radiation.

Figure 3 shows a strongly simplified schematic of one of the four channels of the DOSFET-L02. While the reader is in stand-by (while no readout is in progress), it applies an adjustable bias voltage between 0 and 30 V to the gate electrodes (G_1/G_2) of the connected RADFETs; all other electrodes remain grounded.

The four-wire measurement technique is used for readout. A constant current of 490 μ A is forced through one of the transistors via the common bulk/source (B/S) terminal and the respective drain terminal (D_1 or D_2). The threshold voltage V_t is tapped on the RADFET mount board with independent, practically current-free sense lines. This eliminates the resistances of cables and connectors from the measurement. The value of V_t is digitized through a high precision instrumentation amplifier and 24-bit ADC.

The DOSFET-L02 is controlled via Ethernet using a simple ASCII-based protocol. In the prototyping stage, we have been taking data with a directly connected PC and a custom data acquisition tool. As we proceed to the installation of the new devices in FERMI, the existing Tango server will be upgraded to allow full integration into the control system of the facility.

The firmware of the DOSFET-L02 can be updated via the Ethernet port without the need to physically access the device. This can be a major advantage at facilities where most of the electronics is installed in an accelerator tunnel. A jumper allows to disable the remote update feature if desired.

PRELIMINARY CHARACTERIZATION

All measurements presented here have been performed with prototype boards of the DOSFET-L02. The final version will incorporate several modifications that should improve the performance of the electronics.

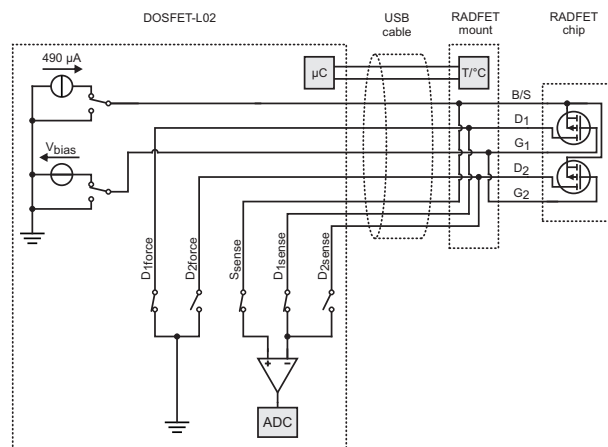


Figure 3: Schematic of one readout channel of the DOSFET-L02.

Table 1: List of Sensors and Irradiation Parameters

| Sensor | Dose rate (Gy/h) | Bias (V) |
|--------|------------------|----------|
| 002 | 5.00 | 25 |
| 003 | 4.88 | 25 |
| 009 | 5.00 | 9 |
| 012 | 4.88 | 9 |
| 018 | 5.00 | 0 |

Noise and Useable Voltage Range

The voltage noise of the readout with the internal ADC was examined with RADFETs of various irradiation states, i.e. at different values of V_t . The measurement noise is typically on the order of 60 μ V (rms) and does not exceed 100 μ V (rms) in the worst case. At this level, the measurement is practically always limited by thermal or post-irradiation drifts of the RADFET. The electronics can track the threshold voltage linearly up to 26.4 V. An extended range of up to 26.7 V can be used with negligible error.

Irradiation Tests

We irradiated a number of RFT-300-CC10 RADFET sensors with gamma radiation from a Caesium-137 source at PSI². Three sensors were aligned to the source point of the radiation so that they received a dose rate of 5.00 Gy/h, two others at a slightly larger distance were exposed at 4.88 Gy/h. Two of the sensors were biased with 25 V, two with 9 V, and one was kept at zero bias. Table 1 shows a summary of the irradiation parameters.

The sensors were irradiated in three intervals of 1, 4.5, and 37 hours, with short breaks in between. During these breaks, significant fading (downward drift) of the voltage

²Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

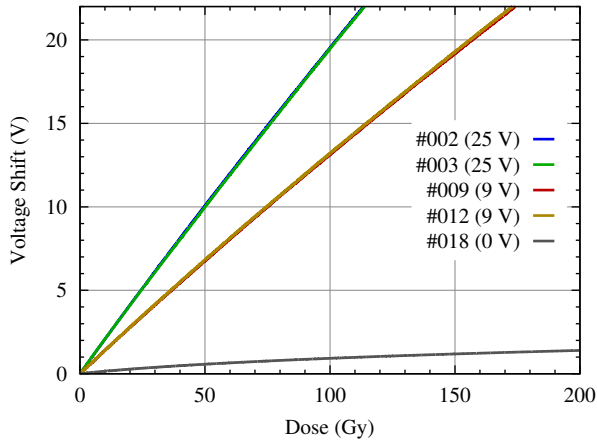


Figure 4: Measured calibration curves for bias voltages of 0, 9, and 25 V.

was visible for the RADFET exposed under zero bias. This is in line with the observations reported in [7]. The biased sensors showed only a small upward drift of the voltage, which is an expected effect from the detrapping of electrons from “slow interface states” in the transistor [8].

MOSFET dosimeters are usually calibrated in dose vs. voltage *shift* ΔV . This voltage shift is defined as the difference between the current threshold voltage and the threshold voltage of the unirradiated transistor, $\Delta V = V_t - V_{t0}$. Figure 4 shows an overview of the responses obtained from the irradiated sensors. While reserving a detailed discussion for a separate paper, we may state that RADFET response at positive bias voltages is much higher and more linear than at zero bias. The remaining nonlinearity can be roughly described by a power law with an exponent close to unity. The following fit functions approximate our data at 9 V and 25 V:

$$V_{\text{bias}} = 25 \text{ V} : \quad \Delta V = 0.2326 \text{ V} \cdot (D/\text{Gy})^{0.9624}$$

$$V_{\text{bias}} = 9 \text{ V} : \quad \Delta V = 0.1683 \text{ V} \cdot (D/\text{Gy})^{0.9462}$$

The inverse functions may be used to convert measured voltage shifts to doses:

$$V_{\text{bias}} = 25 \text{ V} : \quad D = 4.552 \text{ Gy} \cdot (\Delta V/\text{V})^{1.0390}$$

$$V_{\text{bias}} = 9 \text{ V} : \quad D = 6.578 \text{ Gy} \cdot (\Delta V/\text{V})^{1.0569}$$

The behavior of RADFETs at zero bias cannot be described by a simple power law. It is necessary to take the fading of charge from the oxide into account in order to obtain a useable calibration function. For our RFT-300-CC10 sensors, such a function has been proposed in [7].

Temperature Effects

The DOSFET-L02’s fixed readout current of 490 μA has been chosen because it reduces the temperature coefficient

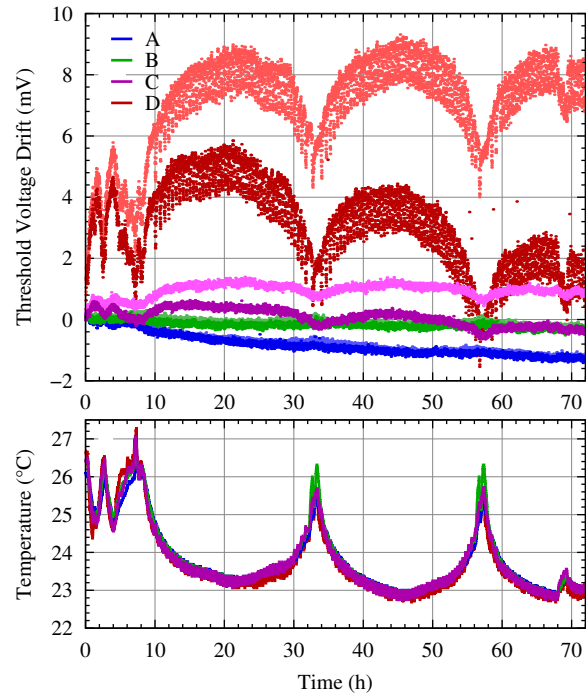


Figure 5: Temperature effects on the threshold voltage of RADFETs that have absorbed different radiation doses. A(blue)–Unirradiated sensor with 5 m cable. B(green)–Unirradiated sensor with 100 m cable; C(purple)–41 Gy at zero bias; D(red)–1000 Gy at zero bias; Light and dark traces of the same color indicate transistors on the same chip.

of V_t to a minimum for unirradiated sensors. However, temperature effects gradually become more important as the RADFET absorbs more dose. We have performed a few preliminary measurements using the digital thermometers of a DOSFET-L02 prototype with four connected sensors:

- Sensor A: Unirradiated with 5 m of cable.
- Sensor B: Unirradiated with 100 m of cable.
- Sensor C was irradiated to a dose of 40.9 Gy under zero bias about two years ago (5 m cable).
- Sensor D was irradiated to a dose of 1 kGy under zero bias about two years ago (5 m cable).

Figure 5 shows the drift of the threshold voltages over three days. To make comparison of the small effects easier, the V_t curves have been shifted to start at zero at the beginning of the measurement. The temperature has day–night excursions of more than 3 °C, overlaid by a ripple of about 0.5 °C from a remote air conditioning unit.

As expected, the unirradiated sensors show almost no temperature dependence. Even the reading from RADFET B on the far end of a 100 m long cable spool is practically stable, which we interpret as a positive effect of the four-wire measurement technique. The moderately irradiated

sensor C shows a temperature-correlated drift on the order of 1 mV. A somewhat bigger effect of more than 4 mV peak-to-peak is visible on kilogray-dose sensor D. However, with respect to the full threshold voltage shift of several volts, the relative drift remains below the percent level.

Apart from temperature effects, other uncorrelated drifts are clearly present in the data. A temperature correction of the measured threshold voltages is therefore not straightforward and we will defer a discussion until a study under more controlled conditions can be done.

CONCLUSION

With the DOSFET-L02, we have developed an advanced measurement system for RADFET dosimeters that allows us to overcome several limitations of previous devices.

Application of a positive bias to the sensors vastly increases their responsivity at the expense of limiting the measurable dose range. The fine-grained adjustability of the bias voltage implemented in the new system therefore allows us to adapt it to the particular requirements of various measurement environments. Based on the data presented in this paper, we estimate that a sensitivity on the order of 10 mGy can be reached.

Temperature effects become more important as the RADFETs get irradiated to higher doses. Although their relative impact is quite small, thermal drifts can easily be mistaken for the absorption of radiation dose. A temperature reading from the immediate vicinity of the sensor, as implemented on the new *RADFET mount* boards, is therefore a welcome information. An automatic correction of the threshold voltage readings for temperature seems possible but requires further study.

Finally, the DOSFET-L02 is much better suited for dose monitoring in remote locations than its predecessor. The capability of updating the device firmware via Ethernet limits the need for local maintenance access, and the measurement performance is not impaired by the use of sensor cables up to a length of at least 100 m.

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