Basics of Passive PMOS Radiation Sensing for Low Earth Orbit

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Abstract

Low Earth Orbit (LEO) is where the majority of the new generation of satellites, called cubesats, orbit. The region is defined as any orbit less than 2000 kilometers above sea level. The radiation environment in LEO is harsh for electronics, with energetic particles ranging from electrons, to protons, to heavy ion nuclei, interacting with semiconducting devices. This paper seeks to explain a passive method of quantifying the Total Ionizing Dose (TID) experienced by a space mission in LEO by utilizing PMOS MOSFET devices.

I. Introduction

The purpose of this paper is to explain the methods by which MOSFET technology can be used to measure TID experienced by a space mission. The paper shall cover a basic background of PMOS technology needed for the reader to understand the interactions between semiconducting devices and the LEO radiation environment. We then proceed to detail said interactions, with an emphasis on device parameters to be monitored in order to obtain a measurement of the TID experienced by the space mission.

The need to monitor TID, defined here as the total energy (usually from proton or electron strikes) injected into the insulting layer of a FET semiconducting device, arises from the fact that radiation can have adverse effects on the electronics of a space mission. Semiconducting devices can have device parameters altered to the point where integrated circuits can fail, resulting in the failure of the mission. Therefore, if the TID is monitored the likelihood of failure of various components can be determined provided a knowledge of their radiation "hardness".

II. Basics of PMOS Technology

MOSFET's (Metal Oxide Semiconducting Field Effect Transistors) are a transistor technology that typically consists of three terminals:

- The gate, where a voltage can be applied to control the flow of electrons through the source or drain.
- The drain.
- The source.

All MOSFET devices have a fourth terminal, called the body or bulk, but it is typically omitted in practice and is regularly shorted to either the source or drain of the device. The key point of MOSFET technology is that the voltage applied to the gate modulates the channel between the source and the drain, allowing for a current to flow between the terminals. The gate current is close to zero due to the high impedance oxide layer between the gate and the drain-source channel. This fact explains the ubiquity of CMOS (complementary metal oxide semiconductor) in digital integrated circuits as the high impedance gate terminal leads to significantly lower power draw when compared to bipolar junction devices, or various other semiconducting devices. At high frequencies there does exist shunt capacitance between the various terminals, but these are excluded in this use case due to the low frequency gate current.

There are two types of MOSFET devices, PMOS and NMOS. We discuss only PMOS devices here as they are the device to be applied as a radiation sensor for reasons detailed in Section III. A PMOS device has its drain-source channel negatively doped, with a positive dopant applied to the source and the drain terminals. Applying a negative voltage to the gate (relative to the source) will create a channel for the flow of charge. If the drain voltage is lower than the source voltage, we achieve a current from source to drain. If the drain is at only a slightly lower potential than the source ($V_{ds} < V_{gs} - V_T$) the drain current (i_d) behaves linearly with respect to the source drain potential difference (V_{sd}). It should also be noted due to the high impedance gate oxide ($i_g = 0$) and Kirchhoff's Current Law that the drain current is equal to the source current and is governed by the equation:

$$i_d = \frac{1}{2}\mu_p \frac{W}{L}((V_{sg} - V_t)V_{sd} - \frac{V_{sd}^2}{2}) \qquad (1)$$

μ_p and $\frac{W}{L}$ are device parameters denoting hole mobility and width to length ratio respectively. Once the source-drain voltage difference of the device exceeds a certain point ($V_{sd} > V_{gs} - V_T$) the IV response becomes saturated, resulting in very little change in drain current with respect to increasing source drain voltage. A typical PMOS IV response can be seen in Figure 1. Note that the slope of the current in the saturation region is non-zero in a real life application due to channel length modulation. This is ignored in this application as we operate in the linear region of operation. [3]

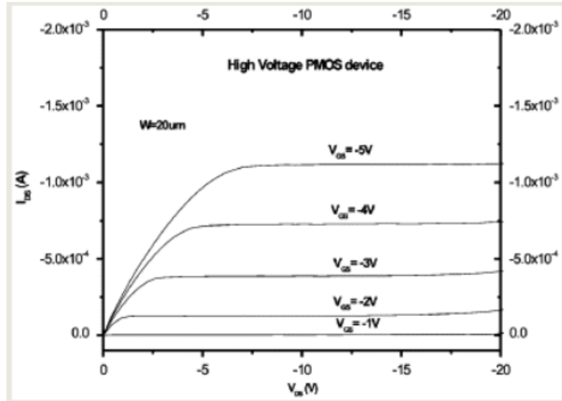

Figure 1: *Normal PMOS IV Response*

III. PMOS Application to Radiation Sensing

Radiation detection circuitry is easily implemented in PMOS technology due to the nature of the interaction between the semiconducting region of the device (the source-drain channel) and the environment. Recall the drain-source channel is negatively doped in a PMOS device. Ionizing radiation striking the device with enough energy deposits more holes, or positive carriers in this region, leading to a more positive doping. This effect is primarily due to gamma and X-rays removing electrons from Silicon atoms [1]. This more positive doping leads to the fact that in order to maintain a constant current the device must alter other parameters due to the shift in threshold voltage. It can be seen from (1) that in order to maintain a constant current with respect to a changing threshold voltage the source voltage (V_s) must vary with respect to threshold voltage. Suppose some radiation effect has interacted with the device and

$$V_{t1} = V_{t0} + \Delta V_t \qquad (2)$$

We hold drain current constant and ground the gate and drain terminals. This implies that:

$$V_{s1} = V_{s0} + \Delta V_s \qquad (3)$$

and thus the drain current becomes

$$i_d = C(((V_{s1}) - V_{t1})(V_{s1}) - \frac{V_{s1}^2}{2}) \qquad (4)$$

This leads to the conclusion that, when a constant source current is applied to the source drain channel and the device is being irradiated the source voltage must vary as a function of the total device irradiation. This allows the user to sample source voltage over time and relate that voltage to the radiation environment.

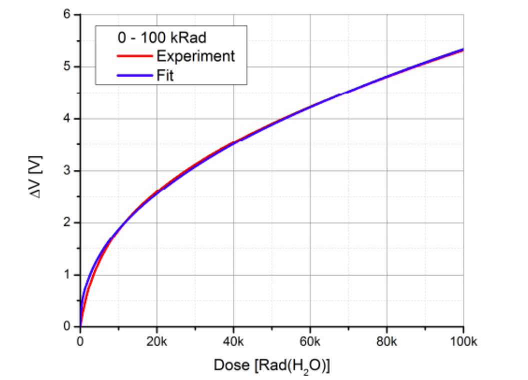

Figure 2: *Radiation Response Curve*

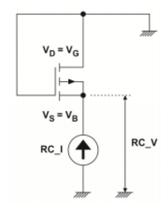

Figure 3: *Varadis Readout Circuit*

The next logical question is how to obtain the radiation response curve as typical radiation testing methods of semiconducting device can be prohibitively expensive, especially for university CubeSat missions. Thankfully various vendors, such as Varadis [2], sell PMOS devices specifically meant to monitor a radiation environment for biomedical, aerospace, or defense applications. The company has published a response curve shown in figure 2.

This data can then applied to the space mission and readout circuitry can be implemented in order to send radiation data down as telemetry. In combination with this data, various spacecraft components life cycles can be monitored in a constant and quantifiable radiation environment, allowing the mission to produce valuable science data on its electronics.

IV. Implemented Circuitry

The circuit can be implemented in various ways. The suggested implementation from Varadis can be seen in figure 3.

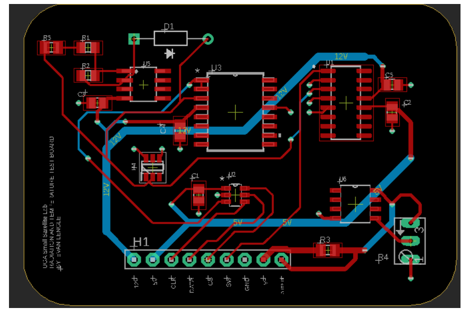

Figure 4: *Routed PCB*

We choose to allow for switching between "readout" and "sense" modes of the transistor. In readout mode a 10-micro-amp current is forced into the source of the device. This current comes from a LM-334 current source IC. A DG412DY-ND analog switch is utilized to switch between readout (current forced into the source) and sense (all terminals grounded) modes. The voltage is fed into an operational amplifier (OP470) configured as a buffer to provide appropriate load current to the selected analog to digital converter (AD7476). The AD7476 ADC samples the source voltage at a rate determined by the master computer on the spacecraft, and contains internal circuitry as to operate as an SPI (Serial Peripheral Interface) slave. The slave select signal can be generated by a timer IC set to the desired sampling frequency or by the master computer. For simplicity we allow the master computer to generate the signal, though in situations where pin count is constrained utilization of a separate IC to generate this signal is allowable. Proper decoupling capacitors and resistors are required to set the 10-micro-amp current, and to regulate the power supplied to the circuit. All capacitors and resistors used are 0805 SMT for ease of hand assembly.

Testing the circuit can be a challenge when it is integrated into the spacecraft, so a separate PCB was fabricated by OSHPark and assembled in house to test functionality. Figure 3 shows the routed EAGLE file and Figure 4 shows the assembled board in house.

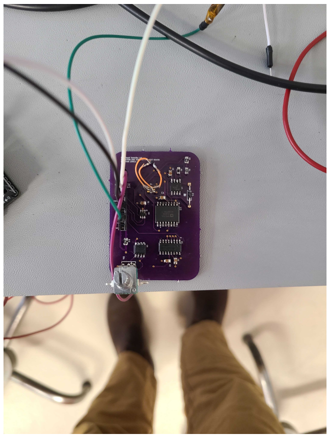

Figure 5: *Assembled PCB*

V. Results and Conclusion

Initially a current was forced into the source of the circuit and a voltage reading was take by simply probing across ground and the MOSFET source terminal. This voltage was observed to be approximately 1.7 volts, which can be taken as the unirratiated voltage. Any increase in this voltage in orbit can be assumed to be due to radiation effects. An Arduino UNO was used to read the output of the AD7476 ADC over SPI, and a nominal reading of 1400 was monitored from the SPI output. The ADC has 12-bit precision and a voltage reference of 5 volts, so this confirms the ADC is functional. When the analog switch is flipped the ADC reading goes to 0, as is to be expected when there is no current forced in the PMOS source terminal.

It can be concluded that this system will function as intended in LEO, and will allow CubeSats to monitor their radiation environment for a low cost of approximately $200 . This can be used to determine component radiation failure states (such as magnitude of increased power draw) for future missions, so redundancy or error margin can be planned for in initial mission planning stages.

References

[1] Momčilo M. Pejović and Milić M. Pejović (May 17th 2017). Application of pMOS Dosimeters in Radiotherapy, Radiotherapy, Cem Onal, IntechOpen, DOI: 10.5772/67456. Available from: https://www.intechopen.com/books/radiotherapy/application-of-pmos-dosimeters-in-radiotherapy

[2] https://www.varadis.com/products/VT01

[3] Microelectronic Circuits (Adel S. Sedra, Kenneth C. Smith), Oxford University Press, 2004.

[4] Martines, Luz Maria S., "Analysis of LEO Radiation Environment and its Effects on Spacecraft's Critical Electronic Devices" (2011). Dissertations and Theses. 102.