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Low-Current Sensing Circuit and Topology for Portable Gamma Radiation Sensor

M. S. Ailavajhala
Boise State University

M. R. Latif
Boise State University

M. Mitkova
Boise State University

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M. S. Ailavajhala, M. R. Latif, M. Mitkova
Department of Electrical and Computer Engineering
Boise State University
Boise, ID

***Abstract*— A sensing circuit is presented for a portable/handheld semiconductor based radiation sensor, which senses low current changes without the inclusion of transistor noise issues. This circuit design block was implemented using supporting circuit architectures to enable sensing between 33pA to 1nA using low voltages. Additionally, a unique circuit topology is presented by which the effect of radiation damage to the silicon substrate and any devices on the substrate is reduced.**

Keywords*— *Low-current, Radiation sensing circuitry, Circuit topology.

I. INTRODUCTION

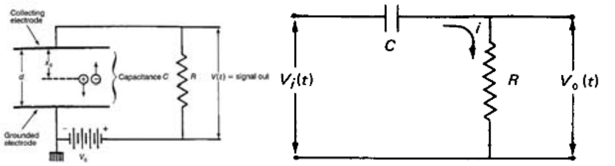
Investigating new semiconductor materials capable of effectively sensing radiation is a prevalent need today. One of the main requirements for determining whether a material is suitable for radiation sensing is that it must have a high resistivity >10MΩ [1]. Assuming a 1V bias is applied to this material with 10MΩ resistivity, 100nA current is created. New radiation sensors require at least 10MΩ resistance [1], but current sensing circuitry using MOSFETs have an internal noise level near the 1-10nA range. The number of radiation sensing materials is limited because the resistance of a potential material must lie between this 1-2 orders of magnitude range, while this range being increased will allow greater freedom for developing new materials for radiation sensing.

II. CIRCUIT DESIGN

A. Traditional Design

Due to the circuit limitations, current radiation sensors increase the applied voltage to try to sense higher currents to circumvent this issue [2]. This is not an ideal solution to create portable radiation sensors. The issue that can occur by increasing the applied voltage to the sensors is the possibility of this large voltage being coupled with other devices on the same silicon substrate. This coupling effect can change the device operation and to prevent this issue, very good insulators are required. Increasing the applied voltage will significantly strain the insulators and increases the probability of oxide degradation. Some examples of large voltage sensing circuits are shown in Figure 1(a,b).

The radiation sensor design that is used for this application has the ability to become embedded and other details regarding this sensor details are mentioned elsewhere [3, 4]. The radiation sensor cannot be used as a discrete device in the circuit design, but rather it is required to be modeled as a circuit element to be able to simulate in cohesion with the sensing circuit. The ultimate goal is to detect the change in current in the radiation sensor whose pre radiation currents are within the tens of picoamps. From device measurements, it was observed that the radiation sensor can be modeled as a variable resistor, but for the purposes of the simulations, the device has been modeled as a current source. This is a valid substitution since the current through the sensor is directly proportional to the resistance of the device.



(a) (b)

Figure 1: a) Large voltage external sensing differentiating circuit b) Simplified external circuit [5]

There are many circuit configurations that have been used to sense low currents (nA range), but all of these configurations require the low sense current to pass through a MOSFET. When a very low current passes through a MOSFET whose internal noise is greater than the original signal, the original signal is hidden within the noise and it is therefore difficult to determine whether the measured output is the amplification of the noise or the original signal. For such reasons, the conventional currents to voltage converters fail to meet this requirement, which is conceivable in this circuit design. The advantage of this circuit design is the complete avoidance of the device current to pass through any MOSFET.

B. Proposed Design

The methodology used for these simulations is based on charge transfer, which is performed by charging a capacitor with a constant current source and then sensing the voltage across the capacitor. For a circuit with such topology two main considerations need to be taken, time and capacitor size. It is necessary to work at very low frequencies in such low current circuits. In the applications of radiation sensing, microsecond or nanosecond sensing capability is not required, but the sensing ability should be within a reasonable time scale. The range in milliseconds would be suitable for such purposes; hence, the selected sensing period was 20ms. Thermal noise is the primary source of noise in low frequency circuit, which is

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approximately 25mV. The lower limit for the theoretical calculations was performed with 100mV to try to avoid this issue.

Another important consideration in this design is the size of the capacitor. The smaller the capacitor size, the faster it will achieve 100mV limit with the least amount of time and for the smallest current. On the other hand, this limits the highest sensing current ability, since the highest voltage in a circuit cannot exceed the voltage applied to the entire system. These simulations were performed using a 1 micron design with a VDD of 1V so the highest voltage cannot exceed 1 volt. Based on these limitations and using a 10pF capacitor and 20 ms period with 50% duty cycle, the sensing current ranges from 1nA to 100pA. This cannot sense current levels near 10-30pA, therefore there are two options, either increasing the clock period or decreasing the capacitor size. Varying the clock is not advisable in case other elements are dependent on this clock, while decreasing the capacitor size is a fabrication challenge. Using capacitors in parallel is convenient, but to enable specific capacitors without having the current from the device traverse a MOSFET makes this topology extremely difficult to accomplish. Advantage of this circuit design is that it offers not only one capacitor, rather it offers two different capacitors, by enabling a single switch. The described circuit is shown in Figure 2.

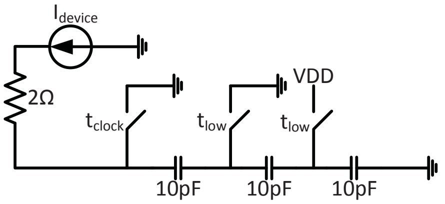


Figure 2: Circuit concept design

1) *Design Specifications*

The radiation sensor is represented by the current source to offer a conceptual view of the current range that is capable of being sensed and the 2 Ω resistor represents the contact resistance as well as other miscellaneous resistance that are naturally present in fabricated devices. Capacitance values that are achievable using this topology are 10 pF and 3.33 pF where the former is capable of sensing comparably higher currents and the latter for sensing low currents. The lower capacitance value is achievable by opening the t_{low} switch, creating 3 capacitors in series and for sensing higher currents, the switch is closed creating a 10pF capacitor. The charging of the capacitors occurs by periodically opening the t_{clock} switch that allows the current to go the capacitors and discharging the capacitors occurs by closing the t_{clock} switch directing the current to go directly to ground. The charging time selected for this circuit was 10 msec and 10 msec of discharging time, which allows 50 measurements to be made per second. Averaging these 50 points, ensures that faulty readings and any other anomalies are completely avoided due to the natural redundancy of this sensing methodology. The calculated current sensing range is from 33pA to 1nA, which is a significant span that will increase the current sensing range by 2 extra orders of magnitude.

C. *Circuit Level Implementation*

This design was also verified using simulations, where all the switches were replaced with MOSFETs and the entire circuit is split into 4 blocks. The first block is a voltage reference [6] and other external conversions required for accurate functionality of the entire circuit, which is followed by the sensing circuit represented in Fig. 4.

After the current is converted into a voltage, this voltage cannot be immediately converted into the user specific method because any noise on the output circuitry used to relay the change in voltage could become coupled to the capacitors causing faulty readings. For such reasons, a voltage buffer is required that will have a wide range to duplicate the voltage values achieved at the output of the current to voltage converter circuit. The advantage of using a buffer is that the output of the current to voltage conversion circuit goes to a high impedance node, which does not accept any current but only senses the voltage at that node. A rudimentary buffer was created to simulate the functionality of the circuit, while more sophisticated rail-to-rail buffers could also be applicable for this purpose. Two types of buffers are used in the buffer stage, which has either the capability to sense very low voltages (close to 0V) or high voltage range (close to VDD). Combining the two outputs will offer some of the benefits and provide a larger voltage range than using only one of these buffers but at the smallest and largest voltages, the weaker buffer will dominate and overwhelm the effect of the other buffer circuit. To resolve this issue, two pass gates were creates which when provided sufficient voltage, will pass the input voltage to the output. The layout of these pass gates will allow the buffer with the low voltage sensing ability to be passed when t_s is open and once t_s is closed the output of the other buffer will be passed to the output while blocking the output of the low voltage buffer to prevent any interference.

The switch corresponding to the t_{low} will be closed once the voltage reaches a user specific value. This enables the high current sensing circuit regime. Switch designated by t_s will be triggered on if and only if t_{low} is closed and a specific threshold current has been achieved. The circuit diagrams for these various blocks are shown in Figure 3 (a-c), 4 and 5.

Note that the radiation sensing circuit block does not have any VDD affecting any active capacitors. This block is completely independent of any reference voltage, and the radiation-sensing device is the only source of power for the capacitors. The VDD in that circuit is merely to ensure that all nodes are driven to specific voltages to reduce the effect of any radiation-induced changes. This node is described in more detail in the fabrication of the rad hard device. All the devices were simulated using a 1-micron process, and this circuit is adaptable towards smaller devices less than 1 micron. The clock used for this simulation was a square pulse with a 20ms period and 1 ns rise and fall time. The results of the simulations are shown in Figure 6 (a-f), where the red graph refers to the circuit output while the blue graph refers to the output voltage of the device sensing circuit block.

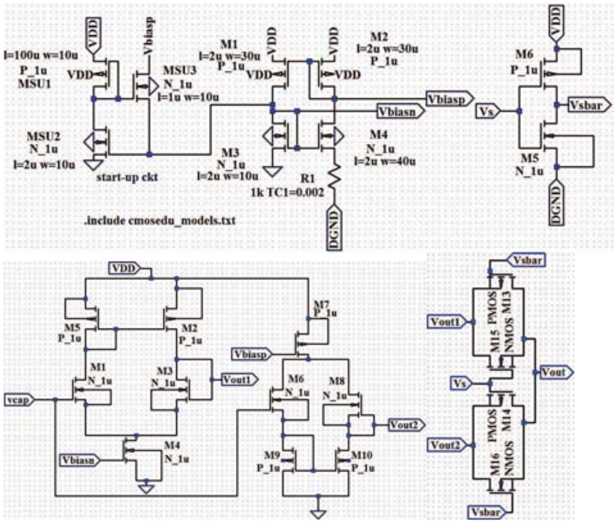


Figure 3: a) Voltage reference Circuit block b) Buffer Circuit Block c) Output Pass gates Circuit Block

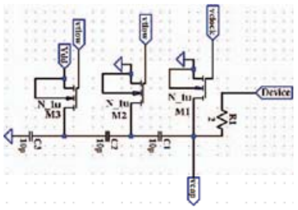


Figure 4: Radiation Sensing Circuit block

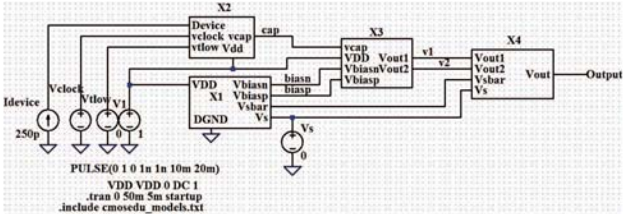
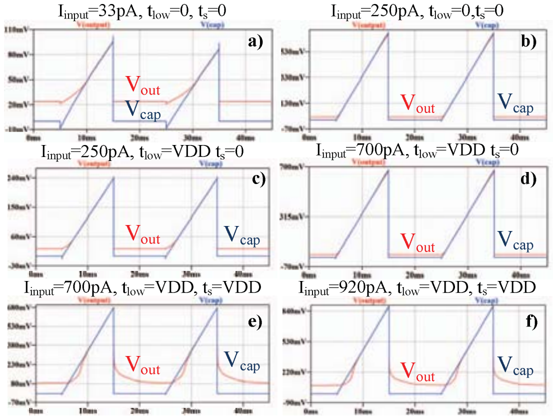


Figure 5: Top view of all circuit blocks and their corresponding connections


I_{input}=33pA, t_{low}=0, t_s=0

I_{input}=250pA, t_{low}=0,t_s=0

I_{input}=250pA, t_{low}=VDD t_s=0

I_{input}=700pA, t_{low}=VDD t_s=0

I_{input}=700pA, t_{low}=VDD, t_s=VDD

I_{input}=920pA, t_{low}=VDD, t_s=VDD

Figure 6: Simulation results for (a) I_{input}=33pA (b) I_{input}=250pA (c) I_{input}=250pA (d)I_{input}=700pA (e) I_{input}=700pA (f) I_{input}=920pA

D. Circuit Topology

The second part of the circuit design was to make this entire circuit radiation hard, which is aided by the unique circuit design. When radiation using photons, interacts with a material, it generates an electron with significantly high energy, which can penetrate deep into any material substrate and cause damage to various electronics. This issue is a very important issue that affects the performance of all circuits in the presence of radiation and for this reason, there have been significant amount of research to investigate this issue [7-11]. The interaction of this high-energy electron with a single device causes a sharp increase in voltage/current, which can burn out devices or cause inaccurate reading, which has to be avoided at all costs. It is important to either capture or slow down these electrons to reduce the damage. This can be achieved using large capacitors and this topology is made with a purpose since these capacitors can hide all the devices on the substrate and prevent any radiation induced electrons to penetrate and alter the devices that are created on the silicon substrate. These capacitors could be created using the low-k dielectric material, currently used to insulate the various metal lines on top of the devices.

The material used between metal lines usually has a very low ε_r to try to limit the capacitance between two adjacent lines. In this design, the low ε_r material has a dual role: to capture any radiation-induced charges and form the capacitor, which is used for sensing, making this material very beneficial. The capacitor thickness increases the probability to capture all incident radiation, thus a thicker capacitor will protect the underlying devices. In case these electrons have the ability to penetrate to the substrate, the capacitors will be energized to have a constant electric field to slow down these electrons. Electrons have a negative charge so application of an electric field can change the path of these electrons because the applied electric field can slow down these electrons. An electron is attracted to higher voltage and thus the topology is created keeping this in mind. Figure 7 reveals the cross section details the layout of these devices.

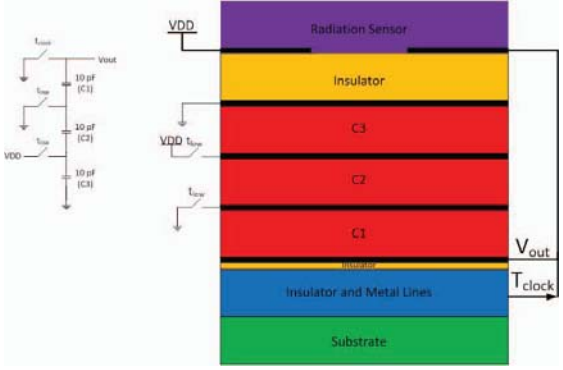


Figure 7: Cross section of Final fabricated device

When a high-energy electron is generated at low radiation doses (t_{low} is open), the electron passes through the insulator layer underneath the radiation sensor and enters the C3 capacitor, is in close proximity of the ground node, which is a source of electric fields and can disturb the path of the

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electron. By the time this electron reaches C1, its original velocity would have been diminished or could have been stopped within the capacitor stack depending on the electron energy. The disturbances created by this one electron at low doses are offset by averaging 50 measurements within a second. At high radiation doses on the other hand, the electron will experience not only one electric field, but it will experience 3 electric fields because of the VDD applied to the metal contact between capacitors C2 and C3. This will significantly alter the electron energy and it will aid in preventing the electron from entering C1.

Verification of this topology was performed using Casino simulator, which uses a Monte Carlo method to determine the trajectory, penetration depth and interactions with material [12]. Certain assumptions were taken into consideration, resembling the environment these radiation sensors experience during γ-ray exposure. When gamma rays interact with material, an electron of high energy is generated, whereas in the simulation, the original electrons are specified with certain energy and angled at a specific direction. To accommodate this discrepancy, the thickness of the radiation sensor was increased by 1 order of magnitude (1 μm) to ensure the incident electron beam interacts with the sensor prior to entering the capacitors at different angles. The energy of the electrons was chosen to be large enough that without the capacitor barrier, the devices on the Si substrate will be substantially damaged. The simulations were performed without metal lines, electric field and standard densities of SiO$_2$ for the insulator, which were specified within the simulation [12]. The capacitor thicknesses were calculated using a dielectric constant of 2.5 [13] with a cross section area of 900μm, which is larger than the 500μm device dimensions and adjusted for other discrepancies resulting in a capacitor thickness of 1.7μm. After the simulation, note that the only very weak electrons have penetrated through the capacitors, confirming that this topology can reduce the radiation induced effects on the silicon substrate.

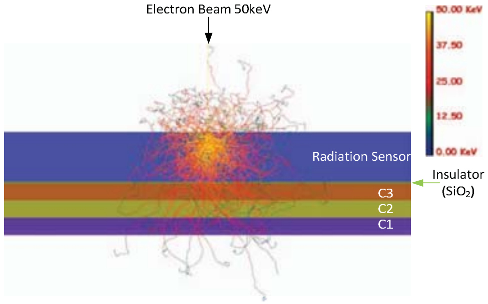

Figure 8: Electron beam simulations validating the circuit topology

III. CONCLUSION

In this work, a radiation sensing circuit is presented, which is applicable for sensing low currents without traversing through any MOSFETs. A novel circuit topology is also presented which reduces the effect of radiation induced high energy electrons. This topology is also verified by the application of a Monte Carlo simulator. The benefit of this design is the capability to create a portable radiation sensing device using low voltages.

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REFERENCES

[1] A. Owens, *Compound Semiconductor Radiation Detectors*: Taylor & Francis, 2012.

[2] W. H. Tait, *Radiation detection*. London; Boston: Butterworths, 1980.

[3] M. Ailavajhala, M. Mitkova, and D. P. Butt, "Simulation and process flow of radiation sensors based on chalcogenide glasses for in situ measurement capability," *physica status solidi (c),* vol. 9, pp. 2415-2419, 2012.

[4] M. Mitkova, P. Chen, M. Ailavajhala, D. Butt, D. Tenne, H. Barnaby, and I. Esqueda, "Gamma ray induced structural effects in bare and Ag doped Ge–S thin films for sensor application," *Journal of Non-Crystalline Solids,* 2013.

[5] N. Tsoulfanidis, *Measurement and detection of radiation*: Taylor & Francis Group, 1995.

[6] R. J. Baker, *CMOS: circuit design, layout, and simulation* vol. 18: Wiley-IEEE Press, 2011.

[7] Y. Boulghassoul, P. Adell, J. Rowe, L. Massengill, R. Schrimpf, and A. Sternberg, "System-level design hardening based on worst-case ASET simulations," *Nuclear Science, IEEE Transactions on,* vol. 51, pp. 2787-2793, 2004.

[8] S. Buchner, D. Wilson, K. Kang, D. Gill, J. Mazer, W. Raburn, A. Campbell, and A. Knudson, "Laser simulation of single event upsets," *Nuclear Science, IEEE Transactions on,* vol. 34, pp. 1227-1233, 1987.

[9] P. Dodd, F. Sexton, G. Hash, M. Shaneyfelt, B. Draper, A. Farino, and R. Flores, "Impact of technology trends on SEU in CMOS SRAMs," *Nuclear Science, IEEE Transactions on,* vol. 43, pp. 2797-2804, 1996.

[10] R. L. Pease, A. Sternberg, L. Massengill, R. Schrimpf, S. Buchner, M. Savage, J. Titus, and T. Turflinger, "Critical charge for single-event transients (SETs) in bipolar linear circuits," *Nuclear Science, IEEE Transactions on,* vol. 48, pp. 1966-1972, 2001.

[11] M. Savage, T. Turflinger, J. Titus, H. Barsun, A. Sternberg, Y. Boulghassoul, and L. Massengill, "Variations in SET pulse shapes in the LM124A and LM111," in *Radiation Effects Data Workshop, 2002 IEEE*, 2002, pp. 75-81.

[12] P. Hovington, D. Drouin, and R. Gauvin, "CASINO: A new Monte Carlo code in C language for electron beam interaction—part I: Description of the program," *Scanning,* vol. 19, pp. 1-14, 1997.

[13] M. Baklanov and K. Mogilnikov, "Non-destructive characterisation of porous low-k dielectric films," *Microelectronic Engineering,* vol. 64, pp. 335-349, 2002.