Radiation Hardened Op-amp Design for 1 Mrad TID

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1. Introduction

There is increasing demand for radiation hardening electronic circuits that can survive in radiation environments, such as nuclear facilities, space, medical equipment and severe-accident. The vulnerability of electronic circuits in radiation environments is one of the main causes in the development of nuclear electronic devices. Therefore, various studies have conducted to develop radiation hardening electronic devices [1]. This paper especially discuss an operational amplifier (op-amp) among these electronic circuits.

Op-amps have been widely used in electronic circuit such as pre-amplifier, integrator and so on. In addition, they are a key component of analog processing systems and an essential part of many signal systems. Recently as the demand increases for integrated circuits, analog circuit designs become more important.

For these reasons, we propose a new radiation hardening two-stage op-amp with two ideas, and compare the conventional two-stage op-amp with the proposed two-stage op-amp by simulations.

2. Conventional Two-stage Op-amp

Figure. 1 shows a schematic of the designed two-stage op-amp. The first stage of the two-stage op-amp consists of a differential pair that converts the input voltage to current. The second stage is a common source amplifier that conducts a negative feedback with an output from the drain of M_4 connected to compensating capacitor (C_c). C_c can widen bandwidth and improve the stability. M_6 is responsible for reference current and forms a current mirror with M_7 and M_8. The current of the M_7 operate as the biasing of the differential amplifier and the M_8 is current source of second stage.

The first stage gain (A_1) of two-stage op-amp is

$$A_1 = -G_{m1} \cdot R_{o1} = -g_{m1,2} \cdot R_{o1} \qquad (1)$$

The second stage gain (A_2) of two-stage op-amp is

$$A_2 = -G_{m2} \cdot R_{o2} = -g_{m5} \cdot R_{o2} \qquad (2)$$

Final gain of the op-amp is multiplication of (1) and (2)

$$\begin{aligned} A = A_1 A_2 &= g_{m1,2} \cdot R_{o1} \cdot g_{m5} \cdot R_{o2} \\ &= g_{m1,2} \cdot g_{m5} \cdot (r_{o2}//r_{o4}) \cdot (r_{o5}//r_{o8}) \qquad (3) \end{aligned}$$

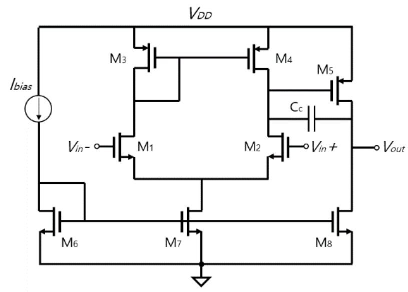

Figure. 1. Conventional two-stage op-amp

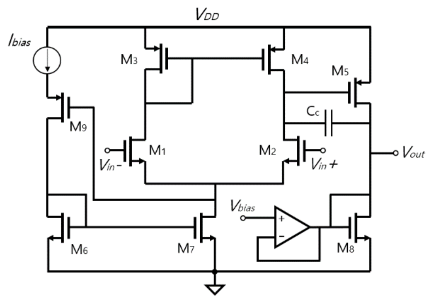

Figure. 2. Proposed two-stage op-amp

When the MOSFET is in radiation environments, there are many effects on the MOSFET such as increasing the sub-threshold leakage current, shifting the threshold voltage and changing the saturation current because of electron-hole pairs generated in SiO_2 interface by incident radiation. Fortunately, total ionizing dose (TID) hardly affect the PMOS, because the major carriers of PMOS are holes that they are not easily trapped in the silicon interface to be caused V_{th} shift. Since NMOS is opposite, TID has an effect on NMOS that V_{th} is shifted and leakage current is increased [2]. Therefore, we make a proposed op-amp for compensating the leakage current to NMOS.

3. Proposed Two-stage Op-amp

In the proposed two-stage op-amp, we add two ideas to NMOS. First, we add the compensation circuit to PMOS (M_9). When I_d of NMOS (M_7) decreases because of TID, the lowered I_d flow the gate of M_9. Then, I_d of M_9 increases and the increased I_d flows the gate of M_7 again. It would compensate for the lowered I_d of M_7. Second, we add an additional op-amp to the gate of M_7 and connect the gate and drain of M_8. It would prevent a current drop like a diode.

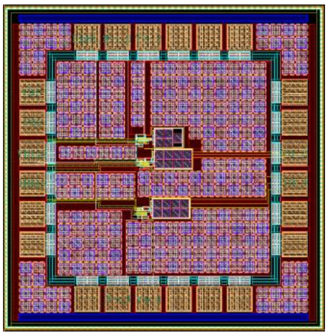

Figure. 3. Layout included conventional and proposed op-amps

As shown in Figure. 3, the layout consists of and proposed op-amps using eleven pads. The total chip size is 942.8 μm width and 956.6 μm length.

4. Simulation Results

In order to compare the op-amps in two different environments, pre-radiation and radiation by simulations. The designed op-amp fabricated in 180 nm process operates at the supply voltage of 1.8 V. V_{bias} of the proposed op-amp is 0.8 V. I_{bias} of conventional and proposed op-amps are 54 μA and 84 μA, respectively.

4.1 In Pre-Radiation Specification

The conventional op-amp exhibits a gain of 51 dB with a 52° phase margin in pre-radiation environments. After corner simulation, gain value drops to 46 dB when 'fast/fast', and it increases to 52 dB when 'slow/slow'.

The proposed op-amp exhibits a gain of 40 dB with a 60° phase margin in pre-radiation environments. After corner simulation, gain value drops to 36.2 dB when 'fast/fast', and it increases to 40.3 dB when 'slow/slow'.

4.2 In Radiation Specification

We connect an additional current source modeled by radiation impact events to M_2 to simulate irradiation test. We connect only one current source to maximize the experimental results, but it will be actually less impact. After looking at the papers about leakage current, we can derive this equation in common [2], [3].

$$I_{leakage\ current} \cong A\left(\frac{W}{L}\right)\log TID + B \quad (4)$$

where A is about 10^{-8} and B is about 10^{-9} as the initial leakage current. The $\left(\frac{W}{L}\right)$ of M_2 is $\left(\frac{30}{0.18}\right)$. The equation (4) shows that the leakage current flow tens of μA at 1 Mrad. So we assume that the leakage current source induced by radiation effects is 15 μA.

Next, we compare the conventional op-amp with the proposed op-amp by simulation. Table. I shows each simulation result. The conventional op-amp comes out

Table. I. Simulation results of two-stage op-amp

	Before irradiation		1 Mrad irradiation	
	Conventional op-amp	Proposed op-amp	Conventional op-amp	Proposed op-amp
Gain (dB)	51	40	28 (45 %)	36 (10 %)
Phase Margin (deg)	52	60	61	62
Gain Band Width (MHz)	76	97	41	83
3dB Band Width (MHz)	0.19	1.05	1.4	1.7

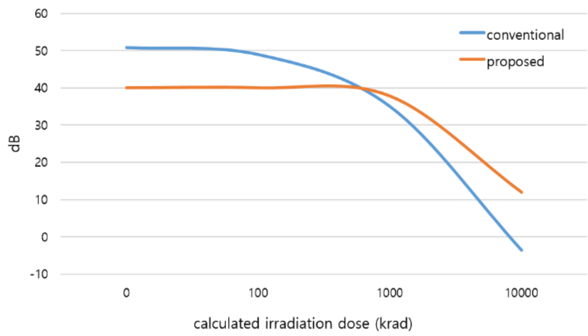

Figure. 4. Gain versus calculated irradiation dose of conventional and proposed op-amps

the 28 dB gain with the 61° phase margin after irradiation. By contrast, the proposed op-amp comes out the 36 dB gain with the 62° phase margin after irradiation. Compared to before irradiation, the gain of conventional op-amp drops 45% from 51 dB to 28 dB and the gain of proposed op-amp drops 10% from 40 dB to 36 dB. Figure. 4 shows the gain value versus the calculated irradiation dose of the conventional op-amp and the proposed op-amp. This shows that the proposed op-amp is highly stable in the radiation environments.

5. Conclusion

We design the radiation hardened two-stage op-amp that compensate the leakage current using an internal op-amp when the current drop in radiation environments. The simulation results show that gain drop of conventional and proposed op-amps are 45% and 10% for 1 Mrad, respectively. It verifies that the proposed op-amp compensates for leakage current better than conventional op-amp, like the theoretical predictions.

After the chip is completed, we will perform irradiation tests. The irradiation tests will actually show that the proposed op-amp can withstand high radiation better than the conventional op-amp in radiation environments.

Acknowledgements

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