A Self-compensated Preamplifier Survived up to 1 Mrad of Total Ionizing Dose based on GBWP Compensation

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1. Introduction

For the last forty years, various radiation-hardened-by-design (RHBD) techniques have been developed to meet the design requirements of irradiating environment in nuclear and space field. Improvements on the readout circuit for radiation sensors in performance degradation have been adopted in current nuclear plant systems; however, next generation sensors in reactor core and/or preparation for severe events in existing reactors require advanced circuit structures that can provide relatively long viability in harsh conditions. In addition, an enhanced readout circuit for radiation can reduce any signal interference and electrical noise caused by long coaxial cable due to location of readout circuit near the sensor.

Previous research for total ionizing dose (TID) effects has been systemically conducted, although it has predominantly focused on analysis and reduction for radiation effects. These research has been investigated for degradation of single transistor performance such as threshold voltage shift, leakage current increase, trans-conductance reduction, and electrical noise increase caused by radiation [1-5]. Furthermore, radiation influence for unit circuits, bandgap reference circuit, and BiCMOS amplifier, were analyzed respectively, in terms of output DC voltage balance and Spurious-Free Dynamic Range (SFDR) [6-9]. With reference to these results, directly compensated method rather than reduction for radiation effects are highly required for more technological advancement.

Preamplifiers are essential components used to bridge two different signal-processing worlds between physical data from sensors and digital expression for human recognition. One of preamplifier structures, a charge-sensitive amplifier (CSA) is widely used in front-end readout circuit for sensor due to the excellent converting linearity [10]. However, these advantages can disappear due to amplitude, fall time decrease, and electrical noise increase caused by induced radiation.

For this reason, this paper provides novel circuit structure of self-compensated CSA for TID effects by using measurement on amplitude degradation of replicated CSA and gain bandwidth product (GBWP) compensation using a Miller capacitor. This direct compensated method can deliver reliable signals for long period of time in harsh radiation environment beyond existing reduction technology for TID effects.

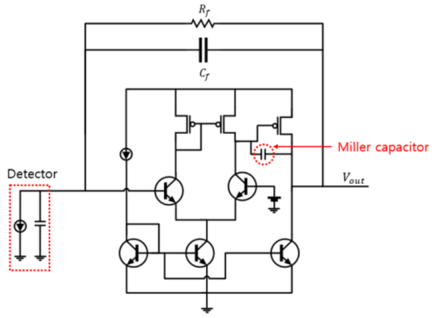

Fig. 1. Schematic of a charge-sensitive amplifier consisted of BiCMOS with feedback resistor, feedback capacitor and Miller capacitor.

2. Performance degradation of an OP-Amp based on BiCMOS

A p-type MOSFET device has radiation-hardening characteristics because major carriers are not electrons but holes. Moreover, an npn BJT, unlike n-type MOSFET, only undergo an indirect influence of base current reduction for TID effects thanks to transistor structure [6-7]. Along with modest radiation effects, physical properties such as lower 1/f noise and higher trans-conductance than a n-type MOSFET lead to configuration of BiCMOS OP-Amp combining npn BJT with p-type MOSFET as shown in Fig. 1 [9]. Therefore, in this paper, CSA consisted of BiCMOS were investigated about TID effects in terms of gain degradation and electrical noise.

2. 1. Gain degradation of BJT

The base currents for the npn BJTs are composed of recombination current (I_{B1}) and injection current (I_{B2}) caused by carrier transfer between base and emitter terminals [11]. First, Recombination current is expressed by

$$I_{B1} = \frac{Q_B}{\tau_b} \tag{1}$$

where Q_B is the total quantity of electrical charges of minority carrier inside the base region. The small minority carrier life-time (τ_b) means that most of the carriers have been recombined.

Second, the injection current provoked by holes injection from base into emitter is given by

$$I_{B2} = \frac{qAD_p}{L_p} P_E(0) = \frac{qAD_p}{L_p} \frac{n_i^2}{N_D} exp \frac{V_{BE}}{V_T} \quad (2)$$

where L_p is the diffusion length of minority carrier inside emitter region, D_p is the diffusion coefficient of hole, q is the magnitude of charge, A is the sectional area, and $P_E(0)$ is the concentration of the minority carrier injected into the emitter from the junction of base region. The total base current can be obtained by summations ($I_B = I_{B1} + I_{B2}$).Then, current gain (β_F) is expressed by [11]

$$\beta_F = \frac{I_C}{I_B} = \frac{1}{\frac{W_B^2}{2\tau_b D_n} + \frac{D_p W_B N_A}{D_n L_p N_D}} \quad (3)$$

where W_B is the width of the base region, D_n is the diffusion coefficient of electron and the N_A/N_D is the relative doping ratio of the base region and the emitter region. Previous studies have indicated that a dominant factor of the gain degradation in case of npn BJTs from equation (3) is reduction of carrier life-time (τ_b) due to electron inside base region recombined with trapped holes provoked by radiation inside isolation oxide between emitter and base terminals [6].

2. 2. Noise analysis based on BJT

Conventional BJTs have three noise sources; the thermal noise of minority carrier spreading resistance from base to emitter region, the shot noise associated with the junction potential barrier of base and corrector current, and the 1/f noise of the base current [12]. Similar to gain degradation mechanism of BJT, a predominant noise source by induced radiation is 1/f noise sources rather than thermal noise and shot noise due to generation of the additional traps [13]

3. Self-compensated CSA for radiation hardness

The CSAs composed of BiCMOS have a key characteristic of GBWP reduction due to base current increase caused by induced radiation [14]. This phenomenon leads to gain degradation at high frequency and delayed fall time. Conversely, a maintained GBWP gets rid of radiation effects for output signals of CSA. In this circuit, GBWP expressed by

$$\text{GBWP} = \frac{g_m}{C_c} \quad (4)$$

where g_m is the trans-conductance of differential input stage and C_c is the Miller capacitor as shown in Fig. 1. From equation (4), Miller capacitor is inversely proportional to GBWP. For this reason, a steady decrease in GBWP can be compensated with controlled Miller capacitance and circuit configuration of which was suggested in this paper.

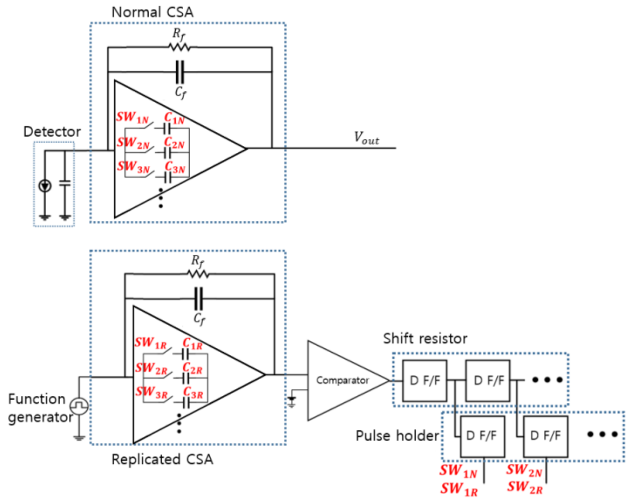

Fig. 2. A novel CSA configuration for GBWP compensation by using measurement on amplitude degradation of replicated CSA and GBWP compensation with increased or decreased Miller capacitor.

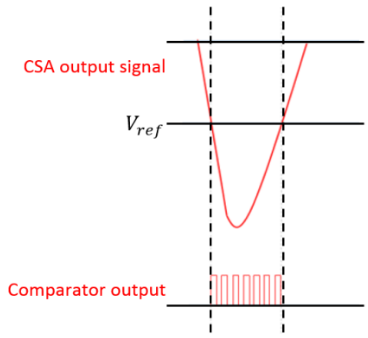

Fig. 3. A measurement method of attenuated CSA output signal caused by TID effect with comparator and reference voltage (V_{ref}).

To realize a radiation hardening CSA with GBWP compensation, circuit components include a replicated CSA, comparator, shift resistor, pulse holder, and group of Miller capacitors with switches as shown in Fig. 2. This proposed circuit starts operation from an output signal of a replicated CSA generated by an incoming constant signal at function generator. According to TID effects, the output signals will be attenuated and delivered to a comparator to measure degree of attenuation as shown in Fig. 3. Produced pulses from a comparator are used to adjust Miller capacitance with a shift resistor and pulse holder. Increase or decrease of Miller capacitor can be simply carried out with transistor switches ($SW_{1N}, SW_{2N}, SW_{3N}$, $SW_{1R}, SW_{2R}, SW_{3R}$) and capacitors ($C_{1N}, C_{2N}, C_{3N}, C_{1R}, C_{2R}, C_{3R}$) as shown in Fig. 2. In summary, an attenuated output signal of replicated CSA by TID effects will produce a fewer pulses than before from a comparator. As a result of this, Miller capacitance will be decreased and GBWP will be kept from equation (4). As shown in Fig. 4, self-compensated CSA for radiation effects was designed and fabricated.

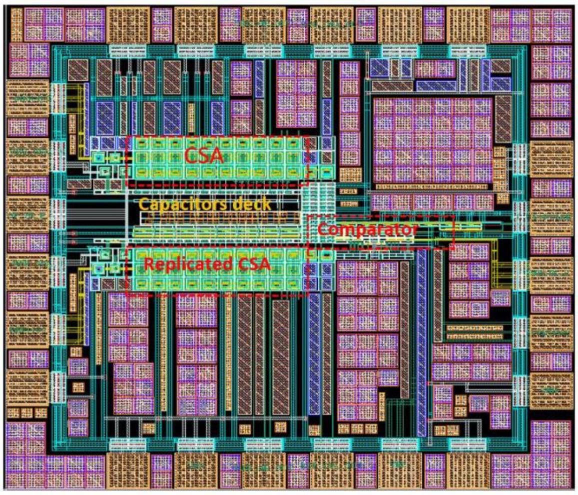

Fig. 4. Self-compensated CSA for radiation effects was designed and fabricated. It composed CSA, replicated CSA, capacitors deck, and comparator.

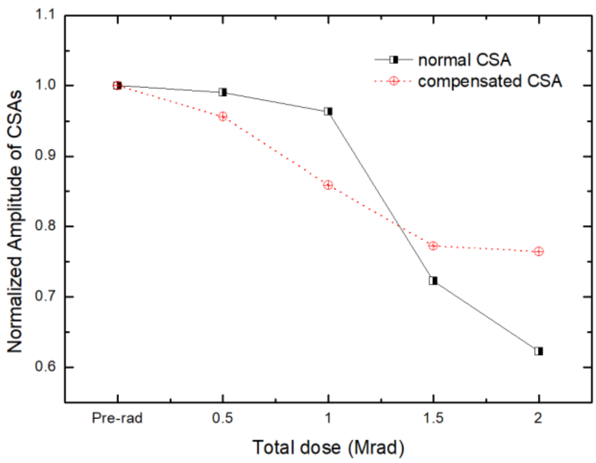

Fig. 5. During the irradiation test with Cobalt-60 γ-ray exposure up to 2 Mrad, output signals of self-compensated CSA were measured.

4. Experimental Setup

The γ–ray irradiation tests were performed with Cobalt-60 of high level activity: 490 kCi at KAERI. We exposed the CSAs to up to 2 Mrad with dose rate of 0.5 Mrad/hour. The test boards and equipment for the measurements were placed away from the irradiation room with 10 m BNC coaxial cables.

The input current pulse from a function generator was set to 200 nA and 1 μsec to supply all of the CSAs. For the entire experiments, output signals of CSAs were measured in real time using high-end oscilloscope at 20 GHz sampling rate.

5. Experiment Results

Fig. 5 shows the 66 percent decrease in amplitude of a normal CSA composed of BiCMOS with Cobalt-60 γ-ray exposure up to 6.4 Mrad. These phenomenon can be explained with equation (1) and (3), since generated traps as a result of radiation inside oxide layer can lead to base current (I_B) increase by reducing minority life time. For this reason, incident radiation can bring gain degradation and fall time increase which are represented by GBWP.

To recover attenuation in GBWP, self-compensated CSA were introduced in this paper. This proposed circuit, from equation (4), can be operated by increase or decrease of Miller capacitance. As shown in Fig. 6, output signals of a CSA have variation of 3.7 percent with Cobalt-60 γ-ray exposure up to 1 Mrad.

4. Conclusions

In this paper, the proposed self-compensated CSA for robustness to radiation are presented. Furthermore, this circuit provides advantages in amplitude and fall time variation. To reduce the variation, smaller capacitance value and greater number of Miller capacitor can be achieved. The revised circuit was fabricated and tested. This work was supported in part by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science and ICT (2016M2A8A1952801).

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