Design of a Radiation Hardened Bandgap Reference Circuit for Cold Junction Compensation under High Radiation Environments

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1. Introduction

Today, a thermocouple thermometer is widely used in various industry [1]. It has the advantage of the low cost, wide measurement range, stability, fast response and so on. Therefore, it has been also utilized in nuclear power plants (NPPs) to measure temperature for the NPPs safety [2].

The critical principle of the thermocouple is Seebeck effect. If one side is connected to the hot junction, and the other is connected to the cold junction as known as a reference junction, a voltage difference is generated by the different temperature between two different metals [3]. The temperature can be measured by using Eq. 1 when the reference junction temperature is constant.

$$ V_T = S \cdot (T_H - T_C) $$ (1)

The traditional method is to use the 0°C water-bath. However, it is not commonly used in these days because the water bath is relatively bulky to use in practical sites. Another approach is to utilize hardware compensation such as a CMOS integrated circuit. In this paper, the reference junction compensation is implemented by using a bandgap reference (BGR) circuit.

These circuits require accurate voltage and stability. However, the output voltage of a BGR slightly changes when variations due to temperature, supply voltage, and process are occurred.

Moreover, in high dose radiation environment, the BGR circuit is affected by another variation due to incident radiation. When radiations penetrate into oxide region of MOSFET, it generates electron-hole pairs. Some carriers are promptly recombined but other carriers can be trapped in the SiO_2-Si interface [4]. This effect occurs the threshold voltage variation at CMOS devices, resulting in change of the output reference voltage of the BGR circuit [5]. Therefore, it is necessary to minimize the influence of radiation.

This paper shows the concept of the BGR circuit to prevent radiation effects. First, we will explain the concept of radiation hardened by design (RHBD) topology. Second, we are going to show the result of the irradiation test result of bandgap reference circuit. Finally, the conclusion and future work are shown.
putting the temperature sensor can be measured and calculated the target temperature using Eq. (2).

\[ V_{\text{input}} = V_{\text{REF}} + V_T = S \cdot T_H \]

(2)

2.2 Concept of Proposed Design

Two conventional BGR circuits have the same temperature coefficient (TC) but different output references as shown in Fig. 2 and Fig. 3. The proposed circuit is designed with a subtractor and two identical BGR circuits. Then, the final reference voltage can be calculated by the difference between the two conventional reference voltages. Therefore, the final reference voltage is defined like Eq. (3).

\[ V_{\text{REF}} = V_{\text{REF2}} - V_{\text{REF1}} \]

(3)

Generally, a reference voltage of a traditional BGR changes depending on the supply voltage. In Fig. 3, PM1, PM2, NM1 and NM2 are the current reference circuit providing constant current to the whole system. As supply voltage decreased, current decreased either because of the channel-length modulation effect.

Fig. 4 shows the schematic of the proposed design by using the voltage subtracting radiation hardened bandgap reference. The two identical BGR circuits with different supply voltages are effected by radiation uniformly, then the each reference voltage, \( V_{\text{ref1}} \) and \( V_{\text{ref2}} \) are increased due to increased leakage current in single transistors induced by incident radiation. The final output, \( V_{\text{REF}} \) as a temperature indicator, is eventually obtained by the subtraction of each reference voltage of the two identical BGRs.

3. Irradiation test and temperature simulation result

The irradiation test was conducted using the Cobalt-60 source of high level activity 490 kCi as shown Fig. 5. The BGR chips were exposed during the 20 hours and the total radiation dose is calculated to 22.9 kGy.

Fig. 6 shows the irradiation test result on BGR circuits. It shows that the conventional BGR has about the radiation error of -16.74 mV, while the proposed BGR has 9.57 mV.

Moreover, we had conducted the irradiation test to 4 MGy about BGR circuits using the identical radiation source. However, the test equipment malfunctions due to high level radiation dose. So we could not obtain the test data, but initial value of BGRs and the data after irradiation experiment could be used to compare conventional BGR and proposed BGR. After the 4 MGy irradiation test is conducted, the amount of reference voltage variation is about 55 mV of conventional BGR, while the proposed BGR has 24 mV.
TABLE I: Comparison with conventional BGR and proposed BGR

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<tr>
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<th>Conventional BGR</th>
<th>Proposed BGR</th>
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<tbody>
<tr>
<td>Supply voltage (V)</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Voltage reference @ 25°C (mV)</td>
<td>717</td>
<td>180</td>
</tr>
<tr>
<td>Error (due to temperature)</td>
<td>0.95%</td>
<td>0.87%</td>
</tr>
<tr>
<td>Temperature coefficient (PPM/°C)</td>
<td>62</td>
<td>56.2</td>
</tr>
<tr>
<td>$\Delta V_{REF}$ (due to radiation @ 22.9 kGy)</td>
<td>-16.74 mV (2.33%)</td>
<td>9.57 mV (5.31%)</td>
</tr>
<tr>
<td>$\Delta V_{REF}$ (due to radiation @ 4 MGy)</td>
<td>55 mV (7.67%)</td>
<td>24 mV (13%)</td>
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Fig. 7 reports the change of the reference voltage over a temperature range of -30 to 125°C. By the simulation, the conventional BGR has the temperature error of 0.95 % and TC of 62 ppm/°C, while the proposed BGR has 0.87 % and 56.2 ppm/°C. Table I shows the comparison with the conventional BGR and the proposed BGR. The irradiation test and temperature simulation results show that the proposed BGR has more stable for radiation effects and temperature variation than the conventional BGRs.

4. Conclusions

The radiation hardened bandgap reference circuit is designed in this paper. The key idea is that the circuit can mitigate the radiation variation by subtracting reference voltages of two identical BGRs, resulting in supplying constant output voltages. The whole circuit was designed in a 180 nm standard CMOS process. As for irradiation test, the proposed design achieves about the radiation error of 9.57 mV (5.31 %) and 24 mV (13 %) at the total dose 22.9 kGy and 4 MGy, respectively, and the temperature coefficient of 56.2 ppb/°C in the range of -30 to 125°C, while the conventional bandgap circuit has 16.74 mV (2.33 %), 55 mV (7.67 %) and 62 ppm/°C. Therefore, the proposed design BGR is about 57.2 % more stable for radiation dose.

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