Development of charge sensitive amplifiers based on various circuit board substrates and evaluation of radiation hardness characteristics

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Ultra-low noise charge sensitive amplifiers (CSAs) based on various types of circuit board substrates, such as FR4, Teflon, and ceramics (Al2O3) with two different designs, PA1 and PA2, were developed. They were tested to see the noise effect from the dielectric loss of the substrate capacitance before and after irradiation. If the electronic noise from the CSAs is to be minimized and the energy resolution enhanced, the shaping time has to be optimized for the detector, and a small feedback capacitance of the CSA is favorable for a better SNR. Teflon- and ceramic-based PA1 design CSAs showed better noise performance than the FR4-based one, but the Teflon-based PA1 design showed better sensitivity than ceramic based one at a low detector capacitance (<10 pF). In the PA2 design, the equivalent noise and the sensitivity were 0.52 keV FWHM for a silicon detector and 7.2 mV/fC, respectively, with 2 μs peaking time and 0.1 pF detector capacitance. After 10, 100, 10^3, 10^4, and 10^5 Gy irradiation the ENC and sensitivity characteristics of the developed CSAs based on three different substrate materials are also discussed.

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1. Introduction

The two main roles of the charge sensitive amplifiers (CSAs) for radiation detector systems are to extract signals induced by the incident radiation and to amplify them to obtain a better signal-to-noise ratio (SNR), which reduced contribution of input noise [1]. One can obtain induced charge signals from radiation detectors by applying voltage bias to the detector. In this regard, CSAs are considered to be the most common way to obtain measurable signals from a radiation detector. Room-temperature semiconductor radiation detectors, in particular, require high-voltage bias to be applied, but produce a small signal from the electrodes; therefore, a low-noise preamplifier is required to read out the small signal. Since contribution of the preamplifier electronic noise can be fairly significant in the measurement of the energy deposition of the incident radiation in a semiconductor detector [2], the intrinsic noise of the preamplifier must be reduced for low-energy measurements below a few keV. The noise can be primarily suppressed at the input stage of the charge sensitive amplifier (CSA) by choosing a low noise junction field effect transistor (JFET) and by optimizing feedback capacitance and resistance values of the preamplifier [3–7].

In addition, there is increasing demand for radiation-tolerant nuclear electronics which can survive in a high-field radiation environment, for such applications in space missions, high-dose irradiation facilities, and severe-accident scenarios [5–7]. Vulnerability of electronic circuits to a radiation field has been one of major concerns in the development of nuclear electronics, and numbers of algorithmic and instrumental studies have been performed to develop radiation hardened electronics for radiation detectors [4]. In this study, we aimed to develop a low-noise preamplifier for high-resolution gamma spectrometry with room-temperature semiconductor material, which can also survive in a high radiation field environment. We designed two types of preamplifiers, PA1 and PA2, on 3 kinds of circuit substrates made of different material. The performance of CSAs with each design and substrate was compared with a commercially available preamplifier module (eV-5093, eV-Products) which is known to show good sensitivity (3.6 mV/fC when the input detector capacitance is 1 pF) and low noise characteristics, in terms of equivalent input noise charge (ENC: ~58 electrons) for the 1–100 pF source capacitance of room-temperature semiconductor detectors. Radiation hardness of the developed CSAs was also investigated with irradiation experiments. Change in ENC value and sensitivity of each preamplifier after irradiation was compared, and robustness of each preamplifier configuration was evaluated.

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2. Design and test procedure

The overall design of CSA in this study includes a JFET in each module. To mitigate the input current noise from the fluctuation of leakage current at the gate and the shot noise from the fluctuation of the drain current of the JFET, as well as (1/f) noise, a JFET with very low gate leakage current and drain current with small input capacitance was chosen for both preamplifier designs. The schematic of circuit connection for PA1 and PA2 CSAs are shown in Fig. 1. They are composed of several stages, including a current source, analog amplifiers, buffers and feedback components. PA2 design is different from PA1 in the analog amplifier and the buffer in an attempt to increase the sensitivity while preserving low noise characteristics. An additional input through the 1 pF capacitor, Ccal, has also been placed for the calibration purpose. And the values of feedback resister (Rf: thick film chip resistor for high voltage, VISHAY Intertechnology, INC.) and feedback capacitor (Cf: thin-film ceramic capacitor, AVX Co.) of all CSAs, are 1 GΩ and 0.1 pF.

In order to confirm the correct operation and to compare the performance of two designed preamplifiers, graphs of the output signals according to the change of Cf value for PA1 and PA2 are obtained as shown in Fig. 2 using OrCAD Pspice simulator (Cadence Design Systems, Inc.). The input current was used by the value of induced current when 662 keV energy was incident on the Si-PIN detector (1 cm x 1 cm x 0.5 mm) used in experiment condition. The sensitivities of PA1 and PA2 were 7.5 mV/fC and 5.3 mV/fC, respectively and both amplifiers show the good linearity of gain against the value of used feedback capacitance (Cf). In addition, the charge collection efficiency (CCE) as a function of feedback capacitance, showing that the charge on the input reflects the pulse output height, can be obtained as shown in Fig. 3 using Eq. (1), and PA2 shows more stable performance due to its higher sensitivity.

\[
\text{CCE} = \left( \frac{\Delta V_{out}}{Q_{in}} \right) \times 100 \%
\]

where \(\Delta V_{out}\) is the output amplitude of CSA and \(Q_{in}\) is the input charge.

Fig. 4a shows the physical construction of the developed

![Fig. 1. Schematic connection diagrams of the developed CSAs: (a) PA1; (b) PA2.](image1)

![Fig. 2. Pspice simulation output graphs of the developed CSAs: (a) PA1; (b) PA2. Note. The time delay of signals was 100 ns and enforced.](image2)
preamplifiers, and Fig. 4b shows the testing board for CSAs. The preamplifiers were fabricated on printed circuit boards (PCBs) made of FR4, which is a composite material composed of woven fiberglass cloth with flame resistant with an epoxy resin binder, Teflon, or a ceramic material (aluminum oxide, Al₂O₃). The approximate size of the developed CSAs was slightly less than 1 sq.-inch. All components were placed on the front side of each PCB (Fig. 4a). We tested a total of 6 kinds of CSA with both design (PA1 and PA2) placed on PCBs made three types substrate material which have the same IC components for all, to investigate the effects on noise through the dielectric loss of the substrate capacitance.

The performance of CSA can be evaluated in terms of ENC, sensitivity (gain), power consumption, and radiation hardness. Since radiation detectors typically produce induced charge signals, the detector system’s noise level can be conveniently expressed in terms of equivalent noise charge, which is equal to the detector signal that yields a signal-to-noise ratio of 1. ENC can be assessed on the basis of the following three standards, i.e., the IEEE standard 301–1988 [9], CEI/IEC 61151 [10] and GB/T 4079–94 [11]. Among many methods guideline in those standards, the AC (alternating-current) voltmeter method, in general, has been used most frequently; however, it is not only complex and costly owing to the needs for amplifying small analog signal processing but also vulnerable to interference of the surroundings such as radiation, which makes the noise measurement inconvenient and causes the derangement. Therefore, we adopted the MCA (multi-channel analyzer) method to obtain the ENC noise of the CSA, by measuring V₅N (mV) and V₅M (mV); here, V₅N and V₅M are the noise voltage outputs from the shaping amplifier (572A, ORTEC) which has CR-RC⁴ and 0.5 μs of peak time for the Si-PIN detector with and without using the CSA, respectively. The noise voltage outputs can be measured from the peak value of the signal shown in the oscilloscope and can be also obtained with MCA. Fig. 5 shows a block diagram of the measurement system for the ENC as well as the energy spectrum using MCA.

The ENC and an equivalent value expressed in terms of energy (ΔE) are calculated from output voltage amplitude of CSA (VCSA), test input capacitance (CT = CD + CCAL), one electron charge (q = 1.6 × 10⁻¹⁹ C), peak value of observed signal by oscilloscope (Vp), and test input voltage (VT) in the following manner:

\[ \text{ENC} = \frac{V_{CSA} \cdot C_T \cdot V_T \cdot 2.35 \cdot W}{V_p \cdot q} \quad \text{[number of electrons]}, \]

\[ V_{CSA} = \sqrt{(V_N)^2 - (V_M)^2} \quad \text{[mV]}, \]

\[ \Delta E = W \cdot \text{ENC} \quad \text{[eV]}, \]

where W is the W-value (ionization energy, i.e., Si = 3.6 eV, CdZnTe = 4.5 eV), which depends on the detector material. VT (mV) and CT (F) are the pulse height of the test pulse and the capacitance for the charge injection, respectively.

To evaluate the noise of the CSA with the circuit assembly, V₁ (mV) and VCSA (mV) were measured with an oscilloscope and a true

![Fig. 3. Graph of the Pspice simulation for charge collection efficiency of PA1 and PA2 versus feedback capacitance.](image)

![Fig. 4. Photographs of: (a) CSAs placed on 3 different kinds of substrate material and (b) the evaluation board for testing characteristics of CSAs.](image)

![Fig. 5. A block diagram of the CSA’s noise measurement system using multichannel analyzer (MCA). Note. CD, Cc, and CCAL are detector capacitance, AC-coupling capacitance, and test capacitance for calibration, respectively.](image)
root-mean-square (RMS) voltmeter, respectively, with changes in the capacitance of the variable capacitor (C_D), representing the detector capacitance. Since the value of C_T is already known, ENC can be easily calculated from Eqs. (2)–(4). W was set to 3.6 eV. The value of 2.35 in Eq. (1) is a constant, which is used to convert the RMS width to the full width at half maximum (FWHM) [12].

The signal delay, noise, and power consumption of CSA all depend on the dielectric constant of the separating insulator [12]. Therefore, capacitive coupling of signal and cross talk between the interconnection will cause signal delay and increase the noise. The relative dielectric constant (ε′), a dissipation factor (D_f) at 1 GHz, called a loss tangent (tanδ), and D_f values per unit thickness (D_f/mm) of each material used in this study are shown in Table 1.

In general, the amplitude of signal losses largely depends on the following three factors, all of which are functions of frequency: (1) conductor loss, (2) dielectric loss, and (3) radiation loss. Conductor loss depends on the frequency, and dielectric and radiation losses depend on the square root of the frequency [13,14]. When the noise is measured for a system producing fast rising time signals under 2 ns (high frequency), output signals are subject to the dielectric constant (ε′) at 20 °C (D_k) and the dissipation factor (D_f) of the substrate materials, leading to slower rise time signals. In addition, even in the case in which substrate materials have the same D_k, the amplitude loss of output signals will be lower when D_f

<table>
<thead>
<tr>
<th>Materials (composition)</th>
<th>Dielectric Constant (ε′) at 20 °C (D_k)</th>
<th>Dissipation factor @ 1 GHz (D_f tanδ)</th>
<th>Effective dissipation factor (D_f/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FR4</td>
<td>4.5</td>
<td>0.018</td>
<td>0.0113</td>
</tr>
<tr>
<td>Teflon (PTFE-Glass)</td>
<td>3.5</td>
<td>0.0016</td>
<td>0.0021</td>
</tr>
<tr>
<td>Ceramic (Al_2O_3 92%)</td>
<td>8.7</td>
<td>0.003</td>
<td>0.006</td>
</tr>
<tr>
<td>eV-5093 [8]</td>
<td>&gt;10</td>
<td>0.002</td>
<td>-0.002</td>
</tr>
</tbody>
</table>

Fig. 6. (a) Equivalent noise charges represented in keV FWHM of a Si detector and (b) sensitivity of PA1 on 3 different substrate materials for various detector capacitances.

Fig. 7. Equivalent noise charges in keV FWHM of a Si detector and sensitivities of Teflon-based PA2 represented in terms of: (a) shaping time and (b) feedback capacitance.
The velocity \( v' \) of the signal and the effective capacitance \( (C_{\text{eff}}) \) of the transmission line on the substrate have the following relationships [15]:

\[
v' = \frac{c}{\sqrt{\varepsilon_r}} \tag{5}
\]

\[
C_{\text{eff}} = \frac{\varepsilon_r}{H} \cdot \frac{W}{L} \tag{6}
\]

where \( c \) is the velocity of light in free space \( (3 \times 10^8 \text{ m/s}) \), \( \varepsilon_r \) is the relative permittivity of material between signal lines, \( W, L, \) and \( T \) are the width, the length and the thickness of the transmission line \( (W \) is 0.5 mm and \( T \) is relatively lower than \( W \)), and \( H \) is the thickness of the substrate. The lower the dielectric constant \( (\varepsilon_r) \), the higher the characteristic impedance, with less crosstalk and propagation delay [16], which leads to a faster rise time and larger signal gain of CSA. Thicker substrates for CSA will have lower input capacitance, and thus, make the sensitivity higher.

### 3. Results and discussion

We compared the ENC and the sensitivity of CSAs designed on 3 different substrate materials for various detector thicknesses, i.e.
for various detector capacitances. Fig. 6 shows the ENC result represented in terms of the full-width at half-maximum (FWHM) of the test pulse peak in keV and the sensitivity of PA1 before irradiation. Teflon- and ceramic-based PA1 show better noise performance than the FR4-based one, but the Teflon-based PA1 shows better sensitivity than the ceramic-based one.

ENC was measured with respect to the shaping time and calibration capacitance when feed (test) pulses were 2 and 4 mV. ENC was improved at lower calibration capacitances and shaping times. ENC was 54, 46, 49 electrons in RMS, which are equal to 0.47, 0.41, and 0.43 keV FWHM (of the Si detector response) for FR4-, Teflon-, and ceramic-based CSAs without an input capacitor ($C_I$), when 500 ns-peaking-time of the unipolar shaping amplifier was used. When the detector capacitances were increased from 1 pF to 1000 pF, ENC was increased to 642, 655, and 695 electrons in RMS, corresponding to 5.6, 5.8, and 6.1 keV FWHM (of the Si detector response), respectively. The ENC increased with respect to the detector’s capacitance in a proportional manner (Fig. 6a). In order to minimize electronic noise of the detection system which enhance energy resolution, one would prefer to use low capacitance detectors. And this is why the radiation sensor and CSA are closely connected with respect to reducing the total input capacitance.

In addition, the sensitivity of FR4-, Teflon-, and ceramic-based CSAs, when the testing condition was the same for ENC measurements, was 4.21, 4.97, and 4.63 mV/fC, respectively. They decreased to 1.25, 3.1, and 2.2 mV/fC, respectively, with an increase of the detector’s capacitance up to 1000 pF, as shown in Fig. 6b. Since the dissipation factor of Teflon is smaller than others, which leads to a small capacitance in the total input capacitance, the sensitivity of Teflon-based CSA could be higher than other substrate material based ones when the detector capacitance is under 1 nF.

Noise characteristics of Teflon-substrate-based PA2 design with zero input capacitance, before irradiation, is shown in Fig. 7. PA2 design has a twofold greater gain than PA1, but it showed 1.5 times higher noise properties and higher sensitivity of 7.2 mV/fC without input capacitance when 500 ns peak time of the unipolar shaping amplifier was used. Because higher sensitivity can reduce noise factors from the other signal-processing chains, particularly from the shaping amplifier that amplifies the signal and the noise at the same time before the DAQ system, the energy resolution can be enhanced. When the shaping time was increased, ENC increased, but the sensitivity slightly decreased. In addition, when the feedback capacitance ($C_{feedback}$) was increased with the same 2 μs peak time for the shaping amplifier, ENC increased and the sensitivity decreased by $1/C_{feedback}$. If the electronic noise of CSAs is to be minimized and the energy resolution of the detector system be enhanced, a short shaping time and a small feedback capacitance would be preferred for better signal-to-noise ratio (SNR). The developed CSA of PA2 design showed high sensitivity, good SNR and energy resolution when we compared energy resolutions of two CSAs that have the same ENC value.
In order to investigate energy resolution of a detector system using developed CSAs, the energy spectra of $^{57}$Co and $^{133}$Ba were measured with a Si PIN detector [17] as shown in Fig. 8. The measurement was done before the high dose gamma-ray irradiation. Using a Teflon-based PA2 that has ultra-low noise (~50 e$^{-}$) and high sensitivity (7.2 mV/FC), and a low-noise Si PIN-type radiation detector showing a leakage current of 0.7 nA at ~40 V, we obtained gamma-ray energy spectra of $^{57}$Co and $^{133}$Ba. Energy resolutions (FWHM) of the spectra were 219 eV (0.18%) at 122 keV peak of $^{57}$Co and 259 eV (0.32%) at 81 keV of $^{133}$Ba, respectively. When the same detector was tested with a Teflon-based PA1 CSA with a similar ENC value (~46 e$^{-}$) but lower sensitivity (5.1 mV/FC), the energy resolution (FWHM) of the spectra were 231 eV (0.19%) at 122 keV peak of $^{57}$Co and 284 eV (0.35%) at 81 keV peak of $^{133}$Ba, respectively. This shows that a higher sensitivity preamplifier is favorable for lowering total noise and enhancing energy resolution of the detection system as it requires less gain at the shaping amplifier which may also amplify the noise, as well as the signal.

For the investigation of radiation damage to the CSAs on various substrate materials — FR4, Teflon, and Al$_2$O$_3$ ceramics — $^{60}$Co irradiators (MDS Nordion, Canada) were used to deliver low and high dose rates. Detailed specifications for the irradiators are shown in Table 2. For the delivery of doses from 10 to 100 Gy, a dose rate of 100 Gy/h was used, and for $10^3$ to $10^5$ Gy, the dose was delivered with 3600 Gy/h. After irradiation, gamma-ray energy spectra of $^{133}$Ba were obtained with the same 3 x 3 x 0.68 mm$^3$ Si PIN detector, and the result is shown in Fig. 9.

ENC and sensitivity characteristics of the developed CSAs on three different substrate materials were also studied as the result shown in Figs. 8 and 9. The energy resolution at 81 keV got worse from 0.35% to 0.71% FWHM after $10^5$ Gy irradiation in association with the increase of the ENC value from 46 e$^{-}$ to 98 e$^{-}$ as shown at Fig. 10a. All other CSAs showed similar behavior after the irradiation in terms of their ENC characteristics.

According to the results for the ENC measurement before and after the high dose ($10^5$ Gy) gamma-ray irradiation, ENC increased twice after irradiation, and the energy resolution (FWHM) was degraded to 575 eV (0.71%) at the 81 keV peak of $^{133}$Ba spectrum as shown in Fig. 9, using a Teflon-based PA1-design CSA As we increased the irradiation dose, ENC also increased, notably from 100 Gy, but the sensitivity did not show any significant degradation until $10^4$ Gy as shown in Figs. 10 and 11. Note that, although the noise characteristics and sensitivity of PA1 and PA2 are different, the tendency of noise and sensitivity variation after irradiation is almost the same for PA1 and PA2, not because of the influence of the integrated active components circuits (ICs) such as transistors and amplifiers, but because of the effective dissipation factor of each substrate. Therefore, the deviation of ENC and sensitivity is caused due to substrate radiation exposure because all CSAs use the same IC component. These results show that developed CSAs exhibit good performance in terms of ENC and sensitivity even with $10^4$ Gy irradiation. Furthermore, for detectors of larger capacitances (>10 pF), ceramic-based CSAs show better noise performance and stability; however, Teflon-based CSAs show better noise characteristics at a lower detector capacitance.

4. Conclusions

Ultra-low noise single charge sensitive amplifiers (CSAs) developed based on various types of substrate materials such as FR4, Teflon, and ceramics with two kinds of design, PA1 and PA2, were developed and studied in terms of noise and sensitivity. Many different types of CSAs were tested to examine the effects on noise property by the dielectric loss of the substrate capacitance before and after irradiation.

If the electronic noise of the CSAs is to be minimized and the energy resolution of the detector system be enhanced, an optimal shaping time and a small feedback capacitance would be preferred for better signal-to-noise ratio (SNR). Teflon- and ceramic-based PA1 CSAs showed better noise performance than FR4-based ones owing to the high dielectric constant per unit thickness of the
substrate material. For the PA2 design, the equivalent noise charge and the sensitivity were 0.52 keV FWHM (of Si detector response) and 7.2 mV/fC, with 2 μs peaking time and 0.1 pF detector capacitance.

For the results after gamma-ray irradiation, ENC started to increase from 100 Gy irradiation according to the absorbed dose, but the sensitivity started to degrade from 10^4 Gy. These results show that developed CSAs reveal good performances in terms of the ENC and the sensitivity even with 1000 Gy irradiation. For larger detector capacitances (>10 pF), ceramic-based CSAs showed better noise performance and stability, whereas Teflon-based CSAs show better noise characteristics at lower detector capacitances only. To conclude, we have successfully developed a robust charge-sensitive preamplifier for a radiation detector system which we plan to exploit for the development of Compton camera, PET, and XRF systems in our subsequent research projects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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