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Authors

Moses, W.W.

Kipnis, I.

Ho, M.H.

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A 16-CHANNEL CHARGE SENSITIVE AMPLIFIER IC FOR A PIN PHOTODIODE ARRAY BASED PET DETECTOR MODULE*

W. W. Moses, I. Kipnis, and M. H. Ho

Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720

Abstract

A 16-channel integrated circuit charge sensitive preamplifier has been developed for a PET detector module that uses an 8x8 array of PIN photodiodes to identify the crystal of interaction. The amplifier, which is made using 1.2 μm CMOS technology, produces an output of 100 mV per 1000 e^- input, and its noise performance is optimized for 10 pF detector capacitance. The rise time, fall time, bias current through the first FET, and detector current compensation are each controlled by a dc current applied to the 2 mm square chip. The Johnson noise (e^- fwhm at 1 μs peaking time) is $173 + 13C$, where C is the input capacitance in pF, and the shot noise (e^- fwhm) is $16.4\sqrt{IT}$, where I is the detector dark current in pA and T is the amplifier shaping time in μs . With this amplifier, the target noise of 300 e^- fwhm can nearly be met with 300 μm depletion thickness photodiodes (3 pF, 200 pA per 3x3 mm element).

1. INTRODUCTION

We have previously proposed a PET detector module that uses a silicon PIN photodiode array to identify the crystal of interaction [1, 2], and have extended the design to use the photodiodes to measure the depth of the 511 keV photon interaction on an event by event basis [3]. The low signal level (approximately 700 e^- per 511 keV photon interaction) and high density of elements (64 per square inch) place high demands on the noise and the size of the amplifier that services the photodiode array. In this paper we describe an integrated circuit developed for this application containing 16 low noise charge sensitive amplifiers on a 2 mm square die.

The proposed PET detector module, shown in Figure 1, consists of an 8 by 8 array of optically isolated 3 mm square by 30 mm deep BGO crystals, each coupled on one 3x3 mm face to a silicon photodiode and on the other 3x3 mm face to a photomultiplier tube. The photosensitive side of the photodiode array in Figure 1 actually faces the BGO crystal array – it is displayed on the incorrect side of the substrate for visibility.

When a 511 keV annihilation photon interacts in a BGO crystal, some of the scintillation light is detected by the photomultiplier tube and some is detected by the photodiode element coupled to that crystal. The photo-

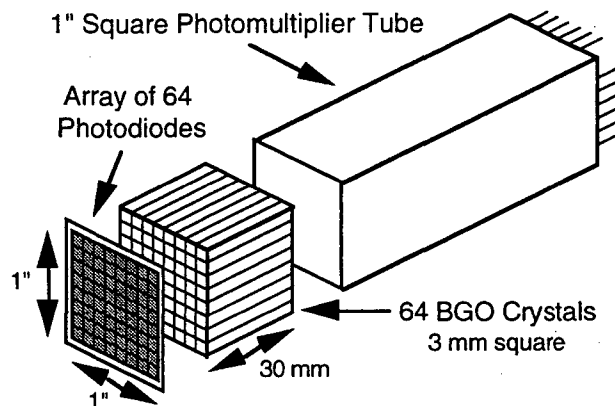


Figure 1: Exploded view of the proposed PET module. Each BGO crystal is attached to a photomultiplier tube, which provides a timing pulse and initial energy discrimination, and to a photodiode, which identifies the crystal of interaction and may also be used to measure the depth of interaction.

multiplier tube provides a timing pulse (typical accuracy is 2 ns fwhm) and initial energy discrimination (typical energy threshold is 250–350 keV). In the simple version of the detector module, the photodiodes are used only to identify the crystal of interaction. In the advanced module the photodiodes also measure the position in the BGO crystal (in the 30 mm long dimension) at which the 511 keV photon interacts by comparing their pulse heights to those observed in the photomultiplier tube.

2. DEVICE REQUIREMENTS

The design studies for the detector in Figure 1 [1–3] used a low noise charge sensitive amplifier constructed with discrete electrical components [4] that occupied 55 cm^2 of printed circuit board area. As each detector module requires 64 amplifiers and a typical PET camera would have 512 detector modules, a several order of magnitude size reduction is necessary for this design to be practical. The amplifiers also must be close to the photodiodes to minimize the capacitance from the leads connecting them (each lead must be < 2 pF).

An attractive solution is to place the amplifiers on the same substrate as the photodiode array, but on the opposite side. This requires that the each amplifier be smaller than a photodiode element ($\leq 0.09 \text{ cm}^2$). Even smaller area is desirable, as the tomograph design would be simplified if additional circuitry (e.g. calibration, identification of the crystal of interaction, readout of the address of the crystal of interaction) were also placed on the back side of the photodiode array substrate.

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The noise requirements for the photodiode / amplifier combination are set by the ability of the module to correctly identify the crystal of interaction. Previous work showed that for a 64 element detector, a signal to noise ratio of $\geq 2.25:1$ (where noise is in fwhm) will effectively eliminate events that are mis-identified because of noise fluctuations [2]. The average photodiode signal from a 511 keV energy deposit in the BGO crystal is $700 e^-$, implying that the noise from the amplifier / photodiode combination must be $\leq 300 e^-$ fwhm.

The design specifications are uncertain because the PIN photodiode array has not yet been manufactured, so its electrical properties are not known. The specified active area of each element is 2.8 mm square, with a depletion thickness of 300 μm , a maximum bias voltage of 100 V, and an operating temperature of $+25^\circ\text{C}$. Under these conditions, a capacitance of 3 pF and dark current of 200 pA are expected. The shaping time for the detector modules has not yet been determined, but will be $\approx 1 \mu\text{s}$. The main consideration for selecting the shaping time is noise minimization, but it will also be as short as possible (subject to a 0.5 μs minimum due to the 0.3 μs scintillation decay time of BGO) in order to minimize dead time.

3. AMPLIFIER DESIGN

Many integrated circuit amplifier arrays have been developed for silicon microstrip detectors [5]. As the parameters for these amplifiers (shaping time, gain, power dissipation, detector dark current, and detector capacitance) are similar to the requirements for this PET detector module, one such design [6, 7] was modified to meet the requirements specified above. To ease testing, four parameters (rise time, fall time, bias current through the first FET, and detector dark current sink) are adjustable via external dc current sources. This design has subsequently been modified for a synchrotron x-ray detector system [8].

The integrated circuit has 16 channels, each with a low noise, charge sensitive preamplifier, a RC-CR shaping amplifier capable of driving loads $>10 \text{ k}\Omega$, a gain (without shaping) of 100 mV per 1000 e^- , and a 0.16 pF test pulse capacitor coupled to its input. The circuit is fabricated with a standard 1.2 μm CMOS process, and fills approximately half of a 2 x 2 mm die. A photograph of the device is shown in Figure 2.

Figure 3 shows a simplified circuit diagram of one channel. The preamplifier input stage is a single stage common-source cascode amplifier with a cascode active load. A p-channel device is used for the input transistor M_1 because of its reduced white and $1/f$ noise compared to n-channel transistors, and its capacitance is optimized for a detector capacitance of 10 pF. Both noise and power dissipation depend on the bias current through this input transistor, so this current is controlled by an external current source via a current mirror (I_{M1}).

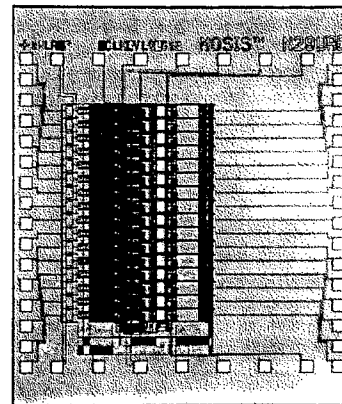


Figure 2: Photograph of the 2 mm wide, 16 channel integrated circuit amplifier chip. The chip is roughly half filled, so more circuitry can be added if necessary.

Very high open-loop gain ($>100 \text{ dB}$) is achieved using "active" cascode circuits, but insertion of a 20 fF feedback capacitor C_f gives the preamplifier a gain of 50 mV/fC. A differential amplifier (M_2, M_3) provides dc baseline restoration by forcing the output of the preamplifier to a reference voltage V_{ref} , differentiating with a time constant that is controlled by an external current source via a current mirror (I_{reset}).

The output of the preamplifier stage is amplified and shaped by a circuit of the same type as the preamplifier, the main difference being that an n-channel input transistor is used because of its higher gain. The shaping time constants are controlled from 500 ns to 50 μs by external current sources via current mirrors I_{rise} and I_{fall} . The ratio C_{s2}/C_{f2} determines the unfiltered voltage gain of this shaping amplifier, which is $250 \text{ fF} / 20 \text{ fF} = 12.5$.

4. AMPLIFIER PERFORMANCE

The integrated circuit is mounted on a Teflon printed circuit board to avoid $1/f$ noise due to lossy dielectrics [9] and wire bonded to traces that allow connection to larger components. A custom single width CAMAC module controls the integrated circuit amplifier array by providing power, the four control currents (rise time, fall

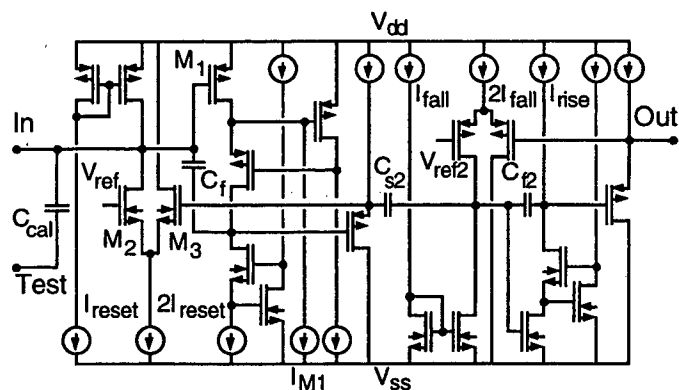


Figure 3: Simplified circuit diagram of a single preamplifier / shaping amplifier channel.

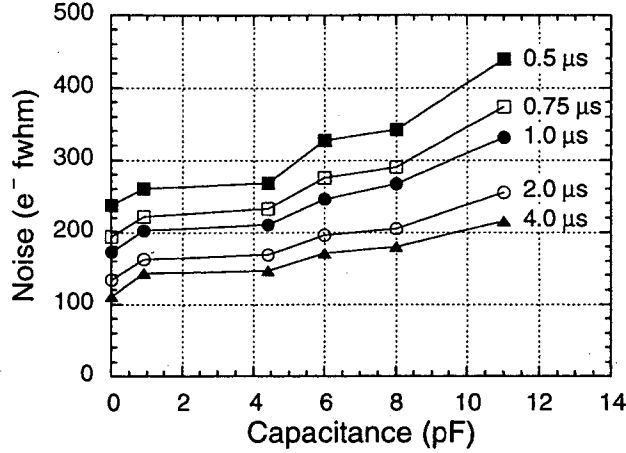


Figure 4: Amplifier noise (in e^- fwhm) versus input capacitance for several values of amplifier peaking time.

time, bias current through the first FET, and detector current null), as well as buffering and amplifying ($\times 10$) each of the 16 outputs. For all measurements quoted here, the operating voltage is 5 V and the power consumption is 5 mW per channel. As the first transistor dissipates most of the power in the circuit, the bias current through this device (M_1) is approximately 1 mA.

The noise is measured as a function of the capacitive load by setting the detector current null to a small value (< 30 pA), injecting a 2000 e^- test pulse by applying a 2 mV step to the 0.16 pF test capacitor C_{cal} , and accumulating the resulting pulse height spectrum using an analog to digital converter (ADC) read out by a personal computer. The fwhm of the distribution is calculated and the position of the centroid of the test pulse peak allows unit conversion from pulse height bins to e^- .

This measurement is made for several values of external capacitor, where the capacitance quoted includes the measured 0.9 pF capacitance of the printed circuit board trace and the measured value of the CK-05 capacitor attached to this trace (measurements at 0.0 pF are obtained by removing the bond wire connecting the amplifier input to the trace). The results of these measurements are plotted for several amplifier peaking times in Figure 4. The data at each shaping time are fit to a straight line, and the results displayed in Table 1. The data point at 0 pF is not included in this fit as it does not contain the noise from the printed circuit board dielectric.

Table 1: Straight line fit to amplifier noise (in e^- fwhm) as a function of capacitance (in pF) for several peaking times.

Peaking Time	Amplifier Noise (e^- fwhm)
0.5 μ s	$220 + 18 C$ (pF)
0.75 μ s	$188 + 15 C$ (pF)
1.0 μ s	$173 + 13 C$ (pF)
2.0 μ s	$142 + 9.2 C$ (pF)
4.0 μ s	$127 + 7.3 C$ (pF)

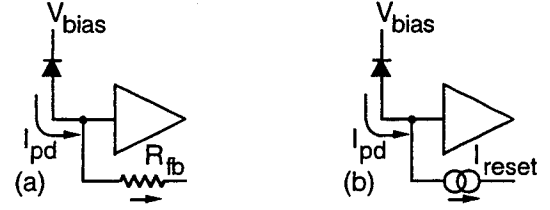


Figure 5: Methods for sinking the photodiode dark current: (a) through a large ($1\text{ G}\Omega$) feedback resistor R_{fb} or (b) nulling with a constant current source I_{reset} .

The shot noise contribution from the photodiode dark current depends on the method used to sink the dark current. In the discrete component amplifier, the amplifier feedback resistor R_{fb} sinks the dark current I_{pd} as shown in Figure 5(a), yielding a noise (in e^- fwhm) of $11.7\sqrt{IT}$, where I is the detector dark current in pA and T is the amplifier shaping time in μ s. Since this feedback resistor is connected to the amplifier input, its Johnson noise is amplified, so the resistor value must be as large as possible ($1\text{ G}\Omega$ typically) to minimize the Johnson noise. Resistor values this large are difficult to fabricate in an integrated circuit, so this integrated circuit amplifier nulls the dark current as shown in Figure 5(b) with a negative dc current source (*i.e.* a current sink) I_{reset} that is controlled externally. The preamplifier input is able to supply (but not sink) current, so the amplitude of I_{reset} is adjusted to be slightly greater than I_{pd} . The disadvantage of this method is that there are two independent sources of shot noise (the photodiode dark current I_{pd} and the nulling current $I_{reset} \approx I_{pd}$) so the shot noise is increased by a factor of $\approx \sqrt{2}$ over the design using a feedback resistor.

The amplifier array is evaluated by constructing a test module with a single $3\times 3\times 30$ mm BGO crystal having one end coupled to a 3 mm square PIN photodiode and the opposite end coupled to a photomultiplier tube. The PIN photodiode is a Hamamatsu S-2506 mounted in a special package to allow close coupling to the scintillator crystal. The active area of this device is 2.77 mm square, and the depletion thickness is 100 μ m (as opposed to the 300 μ m expected for the photodiode array). The photodiode is biased with +30 V and the assembly operated at room temperature ($+25^\circ\text{C}$). Under these conditions, the capacitance is 9 pF and the dark current is ≈ 100 pA (as opposed to the 3 pF and ≈ 200 pA expected for each element of the photodiode array).

The reset current I_{reset} is adjusted to compensate for the photodiode dark current I_{pd} by reducing the reset current until the amplifier saturates if I_{reset} is reduced further. The shot noise (in e^- fwhm) is expected to be $16.4\sqrt{IT}$, where I is photodiode dark current I_{pd} in pA and T is the shaping time in μ s. As explained earlier, this is larger than the $11.7\sqrt{IT}$ expected from an amplifier with a large feedback resistor because of the noise in the reset current source. The total noise at 2 μ s shaping time

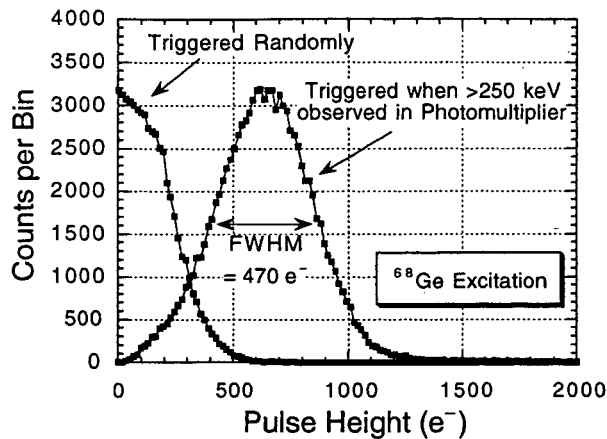


Figure 5: Pulse height spectrum measured by the amplifier / photodiode combination when the detector was excited with 511 keV photons and when triggered randomly.

is expected to be 280 e⁻ fwhm (225 e⁻ fwhm due to the 9 pF capacitive load and 164 e⁻ fwhm due to the shot noise from 100 pA dark current added in quadrature), which is significantly less than the 425 e⁻ fwhm measured when test pulsing with this photodiode connected.

The BGO crystal is irradiated with 511 keV photons from a ⁶⁸Ge source, and the amplifier output digitized whenever the photomultiplier tube detects a signal corresponding to an energy deposit ≥ 250 keV. The resulting pulse height spectrum, shown in Figure 5, has a clear peak centered at 650 e⁻ with a fwhm of 470 e⁻. Also shown in Figure 5 is the noise distribution, obtained by removing the excitation source and randomly digitizing the amplifier output. Although the signal is well separated from the noise, the noise is significantly larger than predicted from the photodiode capacitance and dark current. More work is necessary to identify and eliminate this additional source of noise.

5. CONCLUSIONS

A low noise, charge sensitive integrated circuit amplifier array has been developed as part of a PET detector module that uses an array of silicon photodiodes to identify the crystal of interaction and possibly measure the depth of interaction. Four operating parameters (rise time, fall time, bias current through the first FET, and detector current compensation) are controlled by dc currents applied to the 2 mm square chip. Each amplifier channel is small enough (0.00125 cm²) that the amplifier array and additional readout and control electronics can be mounted on the back of the 64 element, 1 in² photodiode array. The amplifier is characterized both by test pulsing with capacitive loads and with a test detector module excited by 511 keV photons. The predicted noise is sufficiently low at 1 μ s shaping time that the design goal of 2.25:1 signal to noise ratio (where noise is measured as a fwhm) can be met with 300 μ m depletion thickness photodiodes (expected capacitance of 3 pF and dark

current of 200 pA). Measurements with photodiodes indicate that while the signal resulting from 511 keV photon interactions in BGO is clearly separated from background, these photodiodes have an additional source of noise that must be eliminated for the design signal to noise ratio of 2.25:1 to be achieved.

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