Nuclear Instruments and Methods in Physics Research A 673 (2012) 10–15

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A varied shaping time noise analysis of $Al_{0.8}Ga_{0.2}As$ and GaAs soft X-ray photodiodes coupled to a low-noise charge sensitive preamplifier

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ARTICLE INFO

Article history:
Received 22 September 2011
Received in revised form
4 January 2012
Accepted 6 January 2012
Available online 17 January 2012

Keywords:
AlGaAs
Detector
Diode
GaAs
Photodiode
Preamplifier
X-ray

ABSTRACT

The noise sources affecting $Al_{0.8}Ga_{0.2}As$ and GaAs spectroscopic X-ray photon counting p^+–i–n^+ photodiodes connected to a custom low-noise charge sensitive preamplifier are quantified by analysing the system's response to pulses from a signal generator and varying the system's shaping amplifier's shaping time (from 0.5 μs to 10 μs). The system is investigated at three temperatures (-10 °C, $+20$ °C and $+50$ °C) in order to characterise the variation of the component noise sources and optimum shaping time with temperature for $Al_{0.8}Ga_{0.2}As$ and GaAs diodes. The analysis shows that the system is primarily limited by dielectric noise, hypothesised to be mainly from the packaging surrounding the detector, for both types of diode and at each temperature.

1. Introduction

Wide band gap compound semiconductor photodiodes for photon counting X-ray spectroscopy in high temperature and intense radiation environments have attracted increased attention in recent years, with $Al_{0.8}Ga_{0.2}As$ [1–4], GaAs [5] and SiC [6–12] among the materials which have had soft X-ray spectroscopic results reported at temperatures $\geqslant 20$ °C. High temperature and radiation tolerant soft X-ray detectors are likely to have terrestrial and space applications, including real time oil condition monitoring [13] in high value mechanical machinery (including railway locomotives, aircraft, ships, Formula 1 racing cars and military vehicles), in situ analysis of geological materials around active hydrothermal vents, planetary X-ray fluorescence spectroscopy missions to hot extraterrestrial environments such as the surface of Mercury and Venus and in extreme radiation environments such as those that would be encountered in missions to study the Jovian [14] or Saturnian [15] aurorae, or to study X-ray emissions from Jupiter's Galilean moons [16].

$Al_{0.8}Ga_{0.2}As$ and GaAs photon counting soft X-ray p^+–i–n^+ photodiodes operating at temperatures from -30 to $+90$ °C and from -30 to $+80$ °C have been previously reported by Barnett et al. [1,5]. In both cases the detectors were coupled to the same charge sensitive preamplifier electronics. The X-ray spectral performance, as measured by the FWHM of the Mn Kα (5.9 keV) peak from an ^{55}Fe radioisotope source, was reported as 0.9–2.5 keV and 0.8–1.6 keV for the $Al_{0.8}Ga_{0.2}As$ and GaAs diodes, respectively. The initial noise analyses presented in Refs. [1,5] indicated that the majority of the noise (spreading of the detected Mn Kα peak beyond that expected if the resolution was Fano limited) came from a source other than the parallel white noise from the leakage current of the diodes. It was reported that it was suspected that a significant portion of the noise was dielectric noise from the packaging of the diodes. However, this contribution was not separated from other sources, such as the series white noise, so the hypothesis was not tested.

Using a pulse generator and collecting spectra at various shaping amplifier shaping times (0.5 μs ≤ τ ≤ 10 μs) and temperatures (-10, $+20$ and $+50$ °C), we calculate the individual contributions of the parallel white, series white, $1/f$ and dielectric noises [17] for the $Al_{0.8}Ga_{0.2}As$ and GaAs diodes reported in Refs. [1,5].

2. Noise sources in X-ray photodiodes

The fundamental (statistically limited) X-ray spectral resolution (FWHM in eV) of a photodiode is

$$\Delta E\,[\text{eV}] = 2.35\omega\sqrt{\frac{FE}{\omega}} \qquad (1)$$

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doi:10.1016/j.nima.2012.01.009

where ω is the energy required to create an electron–hole pair in the diode material, E is the energy of the incident X-ray and F is the Fano factor [18], which quantifies the observed deviation in number of electron–hole pairs created from the absorption of a photon of given energy from that predicted by Poissonian statistics.

This fundamental spectral resolution is degraded by terms R and A, defined below, causing the practical spectral resolution of a semiconductor X-ray detector to become

$$\Delta E\ [\text{eV}] = 2.35\omega\sqrt{\frac{FE}{\omega}+R^2+A^2}. \tag{2}$$

The factor R is the equivalent noise charge (in r.m.s. e^-) introduced by the detector during the movement of the charge to the contacts (e.g. by charge trapping), and A is the equivalent noise charge (in r.m.s. e^-) introduced by the detector's leakage current, capacitance and the properties of preamplifier [17]. Assuming that peak broadening due to partial charge collection is negligible (the 5.9 keV peaks observed with the $Al_{0.8}Ga_{0.2}As$ and GaAs detectors are Gaussian (see Fig. 4 of Ref. [5]), which would be unexpected if partial charge collection or trapping were dominant factors [19–21]), the measured noise beyond that predicted by Eq. (1) can be attributed solely to A, which is a combination of the parallel white (N_{PW}), series white (N_{SW}), induced gate current, $1/f$ ($N_{1/f}$) and dielectric noise (N_D) contributions, defined below. A comprehensive introduction to the various electronics noise source contributions in photon counting X-ray photodiodes coupled to charge sensitive preamplifiers can be found in Ref. [17], the salient points of which are summarised in Sections 2.1–2.5 to give equations for the contributions of the different noise components. Further discussion and results regarding the disentangling of the noise components affecting semiconductor radiation detectors and their preamplifiers can also be found in Ref. [22].

2.1. Parallel white noise

The parallel white noise is from the shot noise of the currents flowing through the input node of the preamplifier. It is primarily dependent on the leakage currents of the detector, I_{LD}, and the preamplifier input field effect transistor (FET), I_{LT} [17].

The parallel white noise power spectral density, S_{PW}, can be expressed as

$$S_{PW} = 2q(I_{LD}+I_{LT}) + \frac{4kT}{r} \tag{3}$$

where q is the charge on an electron, k is the Boltzmann constant, T is the temperature (in K) and r is the resistance of the preamplifier feedback resistor (if the preamplifier has one) [17]. The preamplifier used in this work does not have a feedback resistor so the $4kT/r$ term is omitted. An example design of a charge sensitive preamplifier without a feedback resistor can be found in Ref. [23]. The contribution (measured in r.m.s. e^-) of S_{PW} to the equivalent noise charge A (Eq. (2)) is

$$N_{PW} = \frac{1}{q}\sqrt{(A_3/2)S_{PW}\tau} \tag{4}$$

where A_3 is a constant dependent on signal shaping function [24], and τ is the shaping time [17].

2.2. Series white noise

The series white noise primarily arises from the effect of thermal noise on the drain current of the input FET [17]. When secondary sources (e.g. stray resistance in series with the input FET's gate) are negligible, the series white noise power spectral density, S_{SW}, can be approximated to the thermal noise of the FET drain current [17]:

$$S_{SW} = \gamma\frac{4kT}{g_m} \tag{5}$$

where $0.7 \le \gamma \le 1$ depending on FET characteristics, and g_m is the transconductance of the FET [17]. The contribution (measured in r.m.s. e^-) of S_{ws} to the equivalent noise charge, A, (Eq. (2)) is

$$N_{SW} = \frac{1}{q}\sqrt{(A_1/2)S_{SW}C_T^2(1/\tau)} \tag{6}$$

where A_1 is a constant depending on signal shaping function [24] and C_T is the total capacitance at the preamplifier input ($=C_d+C_i+C_f+C_s$, where C_d is the detector capacitance, C_i is the input transistor capacitance, C_f is the feedback capacitance and C_s is the stray capacitance) [17]. The equivalent noise charge contribution from N_{SW} becomes increasingly significant at shorter shaping times because of the $1/\tau$ dependence.

2.3. 1/f noise

The noise from the drain current of the preamplifier input FET is also the main constituent of $1/f$ noise. The contribution to the equivalent noise charge A (Eq. (2)) is

$$ENC_{1/f} = \frac{1}{q}\sqrt{A_2\pi A_f C_T^2} \tag{7}$$

where A_f is a characteristic constant dependent on the FET and A_2 is a constant ranging from 0.64 to 2 depending on signal shaping function [17,24,25].

2.4. Dielectric noise

Dielectrics in close proximity to the preamplifier, such as the packaging of the FET and detector contribute

$$N_D = \frac{1}{q}\sqrt{A_2 2kTDC_{die}} \tag{8}$$

to the total electronics equivalent noise charge, A, where C_{die} is the capacitance of the dielectrics, D is the dielectric dissipation factor [17] and q, A_2, k and T have all been previously defined. It is therefore desirable to design the input FET and detector packaging to minimise exposure to dielectrics, for example by reducing the capacitance of the FET and detector assembly by integrating the FET onto the detector.

2.5. Induced gate current noise

Drain current noise (Section 2.2) causes charge fluctuations in the FET gate current, this gives rise to the induced gate current noise. The contribution from this to A is dependent on S_{SW} (Eq. (5)). Like the series white noise, the induced gate current noise becomes important at short shaping times because of the $1/\tau$ dependence. Bertuccio et al. state that Eq. (5) can be modified by a factor, G_c, ($\sqrt{G_c} \approx 0.8$) to take account of this noise in the FET's gate [17]:

$$S_{SWC} = S_{SW}G_c. \tag{9}$$

Consequently the contribution to A, becomes

$$N_{SWC} = \frac{1}{q}\sqrt{(A_1/2)S_{SW}G_cC_T^2(1/\tau)} = N_{SW}\sqrt{G_c}. \tag{10}$$

2.6. Electronic noise sources in combination

When considered together, the parallel white (Section 2.1) and series white (Section 2.2) noise contributions' dependences on τ