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Arrays of silicon drift detectors for an extraterrestrial X-ray spectrometer

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ABSTRACT

Arrays of Silicon Drift Detectors (SDD) were designed, produced and tested. These arrays are the central part of an X-Ray Spectrometer (XRS) for measuring the abundances of light surface elements (C–Fe) fluoresced by ambient radiation on the investigated celestial object. The basic building element (or cell) of the arrays consists of a single hexagonal SDD. Signal electrons drift toward the center of the hexagon where a very low capacitance anode is located. The hexagonal shape of an individual SDD allows for a continuous covering of large detection areas of various shapes. To match the number of SDD cells with the external Application Specific Integrated Circuit (ASIC), two arrays, one with 16 and another with 64 cells were developed. One side of SDDs, called the window side, is a continuous thin rectifying junction through which the X-ray radiation enters the detector. The opposite side, called the device side contains electron collecting anodes as well as all other electrodes needed to generate the drift field and to sink leakage current produced on Si–SiO_2 interface. On both sides of the detector array there is a system of guard rings, which smoothly adjusts the voltage of the boundary cells to the ground potential of the silicon outside the sensitive volume. The drift voltage inside the detector is generated by an implanted rectifying contact, which forms a hexagonal spiral. This spiral produces the main valley where signal electrons drift as well as the voltage divider to produce the drift field. System performance is shown by a spectrum of Mn X-rays produced by the decay of ^{55}Fe.

1. Introduction

Measurement of X-rays from the surface of planetary bodies provides information regarding their surface elemental composition. Absorption of radiation results in characteristic fluorescence from the material being irradiated. By measuring the spectrum of the radiation and by identifying lines in the spectrum, the emitting element(s) can be identified. This technique works for any object that has no significant absorbing atmosphere and that has significant surface irradiation. Examples are: our Moon, the icy moons of Jupiter, the moons of Mars, the planet Mercury, asteroids and comets. Two objects of particular interest to NASA are (i) our Moon and (ii) Europa, an icy moon of Jupiter. Both are possible candidates for a future NASA mission that may involve surface elemental mapping using an orbiting spectrometer [1–3]. As such, Brookhaven National Laboratory (BNL) and NASA Marshall Space Flight Center (MSFC) have teamed together to design a novel X-Ray Spectrometer (XRS) that utilizes an array of hexagonal Silicon Drift Detectors (SDDs) coupled to an Application Specific Integrated Circuit of BNL design.

On the lunar surface, the fluorescence X-rays are produced by solar wind on the illuminated part of the Moon. The SDD XRS would be positioned on a satellite orbiting the Moon, and pointed towards its surface. The sensitive area on the lunar surface, called the footprint, is defined by a simple system of collimators, one for each SDD of the array. The timing of the detected X-ray is thus associated with the area being investigated. The Europa XRS would be similar; however, due to the large amount of ambient radiation around Europa there will be X-ray mirrors in front of the XRS rather than simple collimators. This paper reports on the XRS for the lunar mission, which has different requirements than the mission orbiting Europa. To achieve an effective lunar footprint of 5 km $\times$ 5 km from a satellite that is located 50 km above the lunar surface, a spectrometer with a total area of $\sim$500 cm^2 is required. The elements of interest are: Na, Mg, Al, Si, P, K, Ca, Ti, Cr and Fe. In other words the XRS has to provide energy resolutions better than 200 eV FWHM up to about 10 keV. The intrinsic (Fano) line width at 10 keV is 156 eV, which specifies the electronic width below 124 eV FWHM or a pulser width of less than 14 electrons

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r.m.s. This noise performance requirement has to be achieved under very strict maximum power dissipation, of less than 20 mW/cm^2. Detector cooling, not included in the power budget, is provided for operation down to about $-40\,^{\circ}$C.

The 500 cm^2 lunar XRS is based on pixelated SDD detectors each covering an area of 0.2 cm^2. The anodes are directly wire-bonded to the inputs of a low noise multi-channel ASIC developed in a commercial CMOS 0.25 μm technology. The decision not to integrate the first transistor onto the high-resistivity silicon of the SDD was justified on power dissipation and for economic reasons. At the present state of technology (2009) the lowest noise that can be obtained is by integrating the first transistor of the readout chain directly onto the detector [4,5]. The price to pay for this integration is (i) larger power dissipation in the transistor integrated on the detector when compared to the matching transistor in 0.25 μm CMOS technology, working slightly "below threshold" and (ii) a more complex production process of SDD related to the presence of the transistor, which decreases the yield of SDDs. Moreover, progress in the low noise main stream CMOS technology is such that the noise performance of cost-effective, fully external electronics approaches that of a system with the first transistor integrated into the detector. The noise specifications of the Lunar mission XRS were more than satisfied with SDD anodes bonded to the matched ASIC.

2. Design of spiral SDDs.

The decision to choose a spiral SDD [6] as an elementary cell for the lunar mission XRS was a consequence of the power constraints combined with the economical production of the SDDs. The spiral is made of a rectifying p-type implant on high-resistivity n-type silicon wafer. This serves a double purpose: firstly, it provides the p^+-n junction, which fully depletes the bulk of the SDD, and secondly, it acts as a voltage divider, which creates the drift field parallel to the large surface of the detector responsible for the transport of signal electrons toward the small area centrally located anode. The SDDs for the XRS must be fully sensitive to low energy X-rays down to several hundred eV. The side from which the radiation enters, henceforth called the window side, has to be a very thin continuous rectifying junction resulting in a constant potential on this side of the SSD. The opposite side of the detector, henceforth called the spiral side, has to provide the full drifting potential of the detector.

The problem of providing an optimal form of the potential on the spiral side (surface) of the detector to minimize the drift time and the diffusion of signal electrons within the body of the SDD was solved by method of calculus of variation in Ref. [6]. The resulting radial dependence of the potential at the spiral side written in Eq. 2.12 of Ref. [6] can be written in dimensionless variables as: $u(r)=1-\sqrt{1-r/R_{max}}$, where $u(r)$ is the ratio of the negative potential at r and the maximal applicable negative potential $U_{max}=qN_dt^2/(2\varepsilon_0\varepsilon_r)$ at the outside radius of the spiral R_{max}. N_d is the doping density of the wafer, q the absolute value of the charge of the electron, t the detector thickness, ε_0 the permittivity of vacuum and ε_r the relative dielectric constant of silicon.

Let us denote the total pitch of the spiral $p(r)$ (where r is understood to be a function of the angle ϕ), which is the sum of the width of the implanted spiral $w(r)$ and of the width of the left silicon dioxide $sd(r)$. We will constrain the spiral to keep the ratio of their widths $w(r)/p(r)$ to be constant C ($C=2/3$ in our case), so one spiral defines all spirals in an unambiguous way. We will search for the equation of the inner radius of the total spiral $r=r(\phi)$, ϕ having its usual meaning as the polar angle in the system of cylindrical coordinates. The current flows in the implanted spiral and the voltage drop along one loop of the spiral is $2\pi rI\rho/w(r)$, where I is the current flowing in the implanted spiral and ρ is the resistivity of the implant per square. The voltage drop in one loop of the spiral is related to the change in the desirable voltage in the radial direction by the expression $du/dr\times p(r)$. We can write the requirement of the desirable voltage drop along the spiral by the following equation:

$$2\pi r/p(r)=\alpha\frac{du}{dr}p(r), \tag{1}$$

where a new constant $\alpha=CU_{max}/(I\rho)$. From Eq. (1) the spiral width can be written explicitly as

$$p(r)=K\sqrt{r}\sqrt[4]{1-r/R_{max}}, \tag{2}$$

where we substituted for du/dr from the explicit form and introduced a new constant $K=\sqrt{4\pi R_{max}/\alpha}$.

The second condition to be satisfied by the spiral is the requirement that increase in spiral radius r after a full revolution ($\phi=2\pi$) should be the pitch $p(r)$. This condition can be written as the following equation:

$$r(\varphi+2\pi)=r(\varphi)+p(r). \tag{3}$$

Eq. (3) can be replaced by a somehow more restrictive differential equation

$$\frac{dr}{d\varphi}2\pi=p(r), \tag{4}$$

which assumes that the second and all higher-order derivatives of the radius of the spiral as a function of the polar coordinate are negligible when compared to its first derivative. Substituting Eq. (4) into Eq. (2) we obtain the separable differential equation from which the inverse of the equation for the spiral can be written explicitly as

$$\varphi-\varphi_0=2\pi\int_{r_0}^{r}\frac{dr}{K\sqrt{r}\sqrt[4]{1-r/R_{max}}}=\left[\frac{4\pi}{K}\sqrt{r}F\left(\left[\frac{1}{2},\frac{1}{4}\right],\left[\frac{3}{2}\right],\frac{r}{R_{max}}\right)\right]_{r_0}^{r}, \tag{5}$$

where $F([1/2,1/4], [3/2], x)$ is the generalized hyper-geometrical function of the variable x with the upper parameters [1/2,1/4] and the lower parameter [3/2]. To calculate the inverse of this function is not practical for routines of the graphics editor to be programmed to draw the spiral. A practical simplification can be obtained by approximating the function $F([1/2,1/4], [3/2], x)$ with 1 for $x<0.5$ or equivalently approximating $\sqrt[4]{1-r/R_{max}}=1$ in the denominator of the integral in Eq. (5). Arithmetic in Eq. (5) simplifies considerably and after easy manipulations we can obtain the explicit equation of the spiral

$$r(\varphi)=\left[\frac{K}{4\pi}(\varphi-\varphi_0)+\sqrt{r_0}\right]^2;\quad r(\varphi)\le R_{sw} \tag{6}$$

where R_{sw} is the largest radius for which the approximation leading to Eq. (6) is valid. Eq. (6) describes a simple quadratic spiral passing through the point (r_0, ϕ_0) given by the initial condition according the extent of the anode region of the SDD. The quadratic spiral ends at polar angle ϕ_{sw} where the radius of the spiral reaches the value R_{sw}. From that point (R_{sw}, ϕ_{sw}) on the rest of the spiral ($R_{sw}\le r\le R_{max}$) is approximated by a linear spiral

$$r(\varphi)=r_{sw}+\frac{p_{sw}}{2\pi}(\varphi-\varphi_{sw});\quad R_{sw}\le r(\varphi)\le R_{max} \tag{7}$$

where p_{sw} is the value of the width of the spiral reached by the quadratic spiral of Eq. (6). This value of the spiral width guarantees the smooth behavior of the radial electric field at the surface of the spiral side of the detector at the transition between the two approximations of the ideal spiral. The programmed hexagonal spiral has the values of the spiral calculated at all