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Operating Temperature Optimization of CCD 236 X-Ray Fluorescence Detector

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Abstract

Scientific Charge Coupled Device, CCD 236, designed to be used in Chandrayan II mission as high sensitive large area X-ray Fluorescence detector. CCD refers to an array of closely spaced MOS capacitors formed on a continuous oxide layer grown on a semi conductor substrate. The operation of a CCD is based on, the photo generation of charges within the pixels, charge collection, charge transfer and integration, when photons incident on its surface. Charge transfer efficiency (CTE) and bulk dark current are important parameters that determine the performance of a CCD. Both of them are expected to be affected by temperature variation. Hence an optimum temperature for the desired performance is to be determined. The resolution of CCD for 5.9 KeV Mn K_α *and 6.4 KeV Mn* K_β *lines were studied over a temperature range of -15 to -30 degree Celsius. The clock frequency was varied over a frequency range of 90-130 KHz at clock bias of 7 .0 volts. It is found that, the resolution of the device increases considerably as the temperature is decreased in the above temperature range. Under the given condition the optimum temperature range is found to be -20 to -30 at desired clock frequency of 100 KHz.*

Keywords: Scientific CCD, charge transfer efficiency, CCD bias, flat band shift, X ray fluorescence detector.

Introduction

One of the Objective of Chandrayan-2 mission is the mapping of elemental abundance on the surface of the moon while traversing the lunar polar orbit at a distance of 200 Km above the surface[1]. Swept Charge Device (CCD 236), a large area X ray Fluorescence detector, is used for this purpose. Charge coupled device (CCD)[2] refers to an array of closely spaced (<2.5µ m) MOS capacitors formed on a continuous oxide layer of thickness (100-200 nm) grown on a semi conductor substrate. MOS capacitors are closely built to one another, so that the minority carriers stored in the inversion layer associated with one MOS capacitor pixel can be transferred to the surface channel region of the adjacent pixel. The operation of a CCD is based on storage and transfer of minority carriers between potential well created by the voltage pulses applied to the Gate electrode of MOS capacitor. The sequence of clock pulses will bias the MOS capacitors in CCD on to deep depletion. Charge packets from input signal can be stored and transferred from one potential well to another in a controlled manner across the semi conductor substrate. CCD 236 has 4 identical quadrants and a central channel. Each quadrant has Silicon MOS capacitor based 2D Pixel arrays. The charge generated during the passage of X ray photon through the pixels are gathered in to a single point by the help of a synchronous 2 phase clock bias of suitable frequency . Thus the charges generated at any point in any of the quadrants in this large area detector are swept in to the central channel of the detector which has the electronics to convert the charge in to voltage. CCD 236 has a reasonably good performance for the spectral resolution.

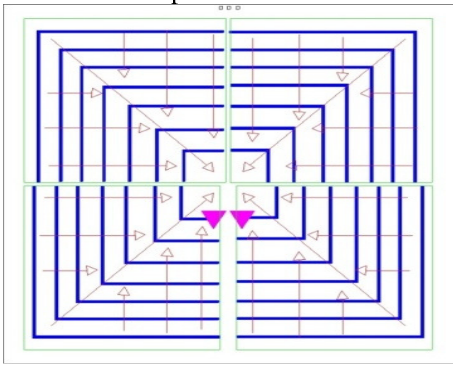


Figure-1
CCD- Pixel Structure

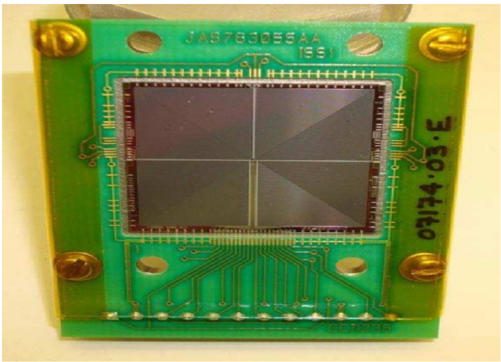
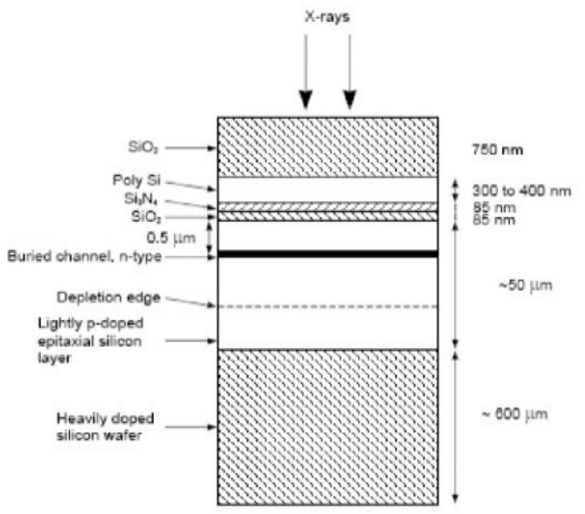


Figure-2
SCD 236 Overview

SCD (CCD54) Structure

Drawn from information provided by Peter Pool (e2v) on 27 March 2008.



The depletion edge is estimated to be 5 to 10 µm from the SiO$_2$ / epitaxial Si boundary based on the device bias voltages.

Figure-3
SCD [CCD 236] Prototype

This work is aimed to determine the ability of the spectral resolution of SCD in terms of FWHM of the spectral peak at various operating parameters of the device and find out the optimum operating temperature when the other operating parameters are pre-fixed. The device is likely to degrade[3] during the course of its use in the space mission due to the expected space radiation damage caused by protons. The device should have enough power to resolve the various spectral peaks. The Charge Transfer Efficiency[4] (CTE) and Dark current and are some of the performance parameters of a SCD that determine the resolution of the SCD. Charge Transfer Inefficiency (CTI = 1-CTE) is the portion of the charge left behind the pixel during the charge transfer process. Thermal diffusion, self induced drift and Fringing field effect[5] are responsible for charge transfer which are dependent on temperature. Dark Current is a natural phenomenon by which CCD produce a current even when the CCD is not illuminated and depends on the temperature. For a given SCD, the only way to reduce dark current is device cooling during the operation. The optimum operating parameters of such devices are usually determined by trial and error methods for the particular situation. Hence it is required to determine the optimum Operating Temperature of SCD, for a given Clock bias voltage and Clock frequency for the best resolution.

In this work, we have done a systematic approach to optimize the operating temperature of SCD for the use in space as an X-ray Fluorescence Detector with an acceptable resolution. The spectral resolution of the SCD is determined for the K-α and K-β X ray spectral peaks emitted from Fe^{55} Source by measuring the FWHM of the peaks. The experiment is done by varying the temperature while keeping the values of the bias voltage and clock frequency at constant value. The optimum operating temperature which satisfy the targeted spectral resolution for the above spectral lines is determined for the given values of the other parameter.

Material and Methods

The experimental setup consists of a Source of X-ray provided by Fe^{55}, a Vacuum Pump connected to a Vacuum Chamber., a Temperature Controlling System and SCD Controller and Data Acquisition System. SCD is kept inside vacuum Chamber. Vacuum chamber is required for two reasons. The first is to prevent water vapors condensing on SCD during cooling and Secondly, to prevent attenuation of X rays by air before falling on to SCD. Vacuum system consists of a Turbo Molecular Pump with a cascaded backing pump to produce a vacuum up to 10^{-4} mbar. SCD is clamped to an Aluminum cold finger kept on the top of a Thermo Electric Cooler (TEC) which is attached to a copper heat exchanger. TEC has a semiconductor Thermo Electric Plate which can cool the device up to- 40°C.

Heat produced by TEC is removed by heat exchanger by circulating cold water through it. Temperature of the device cooled by thermoelectric plate is continuously sensed by PT 1000 temperature sensor. A PID Controller ensured high degree of temperature stability (~0.1°C). PT 1000 temperature sensor is fixed on the cold plate. The connection leads from the driver board, temperature sensor and tubes of the circulating water etc. could be taken out of the chamber through proper vacuum sealed fixtures.

SCD with its driver board is kept on the top of the cold plate at the centre of the vacuum chamber The SCD driver electronics can pass the CCD data to PC. The SCD driver provides the voltage sequence for the SCD for the operation. SCD drive box and Software provided by X- CAM Ltd., is used to control the device. The spectral data is obtained figure-4 from SCD through X-CAM driver electronics box and the associated software. X-CAM provides various settings such as sequential file, voltage file, delay etc. which may need to be varied to obtain the optimized values. For studying the dependence of FWHM on temperature, the sequential file, voltage file and delay are kept constant and the temperature is allowed to change by predetermined value. Figure-4 is the schematic of the experimental arrangement.

Fe^{55} source is held in front of the mylar window on the vacuum chamber above SCD to illuminate the SCD with Mn-Kα and Mn- Kβ lines. The air inside the chamber is evacuated first. The SCD is positioned such that, X ray alls on the top left quadrant of SCD.

The module was cooled slowly till the temperature reaches -5°C. The temperature is maintained for 30 minutes to stabilize at -5°C. Clock speed is set to 90 KHz and the frames are chosen to be 300. Settings of the clock speed, clock voltage and the frame number are made using X CAM Software. Data is captured by X-CAM Software and stored in a PC. The data corresponding to isolated single pixel events and split events are separated using Software The data consists of the density of counts against channels number as shown in figure-5. The whole process is repeated to record the spectrum keeping the device at the temperature-5°C and at frequencies 100 KHz to 130 KHz in steps of 10 KHz.

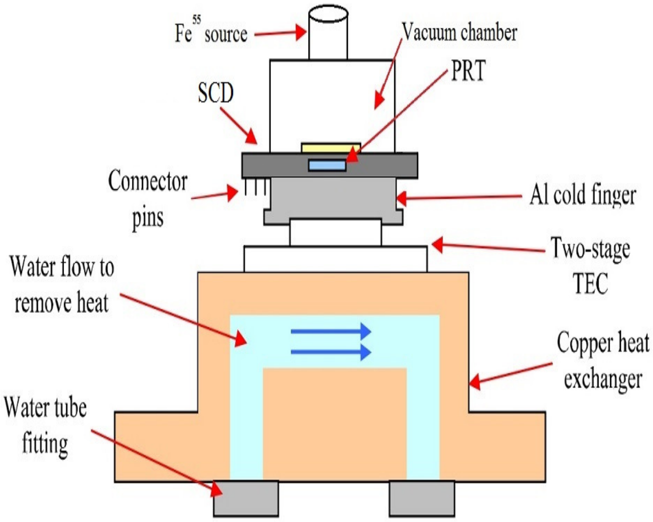


Figure-4

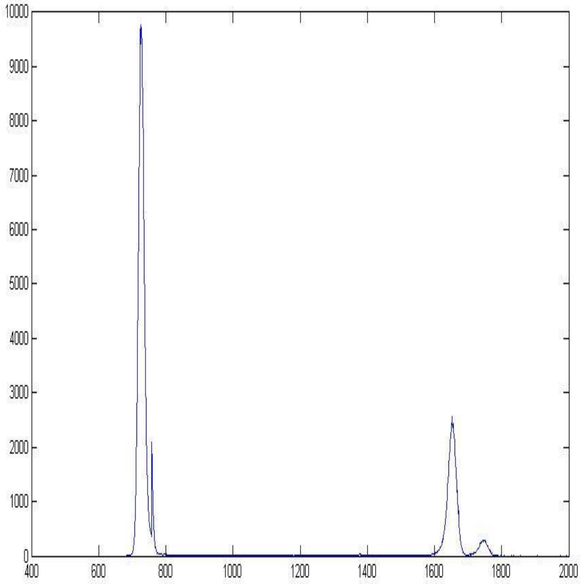


Figure-5

Now, the whole process above is repeated for different temperature ranging from -5°C to -30 degree in steps of - 5 degree for various frequencies keeping the bias voltage constant at 7.0 V.

In each spectrum, three prominent peaks are seen. The first and the tallest peak is the noise peak (zero energy peak). Second peak correspond to Mn K-α at the energy 5.9 KeV and the third smallest peak is the Mn K-β at the energy 6.4 KeV. The data corresponding to spectral peaks are identified and a Gaussian fit is made on the isolated data and FWHM is found using code written in MATLAB. FWHM is found in all the cases corresponding to noise peak, K-α peak and K-β peak and tabulated.

Results and Discussion

The variation of FWHM with clock frequency at a constant bias voltage of 7.0 volts at various temperatures is plotted in figures figure-6-8. There are 4 curves in this figure corresponding to temperatures -15°C- -30° C. FWHM Vs Frequency curves for -5°C and -10°C are not plotted as the values are beyond comparison in the present discussion.

All the curves show a dependence of FWHM on temperature. This is due to the variation of CTI and dark current with temperature. CTI has an exponential dependence[6] on time't' after the transfer, ($CTI_D = e^{-t/\tau}$) where τ is the diffusion time constant. The overall diffusion time increases because of temperature. Hence CTI will increase with temperature.CTI is also affected by the Clock Voltage and Clock Frequency.. Dark current is originated mainly from three regions. The neutral bulk material below the potential well, the depleted region within the semiconductor and the Si-SiO$_2$ interface states. Dark current carriers are generated through intermediate levels near the intrinsic Fermi level caused by the impurities or imperfection in the semi conductor or Si-SiO$_2$ interface. All the three forms of dark currents increase with temperature. The final dark current formula[7] is $D_{R\,(e^-)} = 2.5\text{x}10^{15} P_s D_{FM} T^{1.5} e^{-Eg/(2KT)}$ where $D_{R\,(e^-)}$ is the average dark current generated (electrons /seconds/pixel) at the operating temperature T, P_S is the pixel area and D_{FM} is the dark current figure of merit at 300 K(nA/cm^2).

Figure-6 corresponds to variation of FWHM of the noise peak. FWHM values of these curves will be helpful for understanding device deterioration in future when the device is actually put to use for measurements. In figure-7, all the four FWHM Vs Clock frequency curves are belonging to Mn-Kα line from X ray source at various temperatures. We found that the curve drawn for -25°C has the FWHM values less than 150 eV. As the clock frequency is increased the FWHM value is found to decrease almost linearly with frequency with an exception at 120 KHz. The curve drawn at -30°C has a flat region over a range of 110 KHz-140 KHz. At extreme frequencies, ie, at 100 KHz and 150 KHz the FWHM curve shows a deviation. Still the values are all below 150 eV. At -30°C the device offer lowest

FWHM for the curve. In Figure-8, all the four FWHM Vs Clock frequency curves are belonging to Mn-Kβ line from X- ray source at various temperatures. We found that the curve drawn for -25^{o}C has the FWHM values less than 160 eV. As the clock frequency is increased the average FWHM value is found to be almost stable at this temperature. At -30^{o}C the resolution is found to be better.

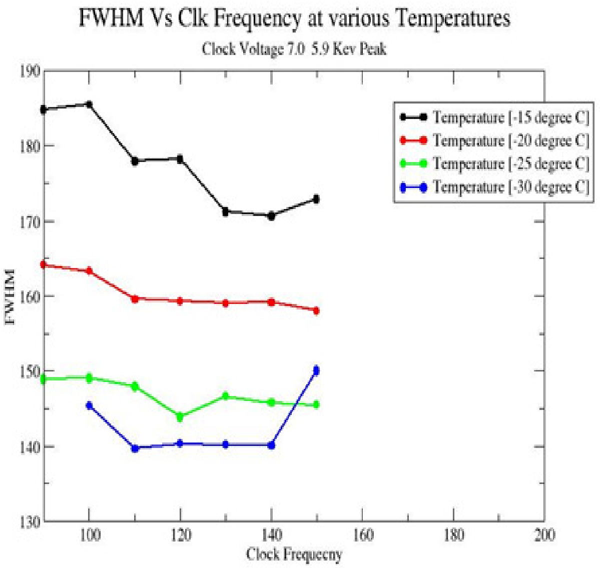


Figure-6
FWHM Vs, Clock Frequency at different temperatures. [Noise Peak Clock Voltage 7.0V]

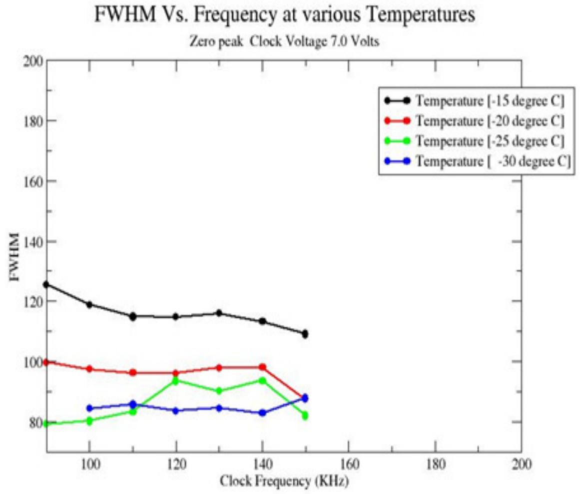


Figure-7
(FWHM Vs, Clock Frequency at different Temperatures:5.9 KeV Peak; Clock voltage 7.0V)

The analysis of the graph clearly shows that, at the desired clock frequency of 100 KHz, a resolution 150 eV per 5.9 KeV can be achieved for Mn-Kα peak at temperatures -25^{o}C and below. Similarly for Mn-Kβ peak, the resolution is 160 eV per 6.4 KeV at temperatures -25^{o}C and below. Both, being, within the targeted resolution at the respective energies the optimum operating temperature range of SCD is found to be -25 to -30^{o}C at 100 KHz and at a bias voltage of 7.0 V.

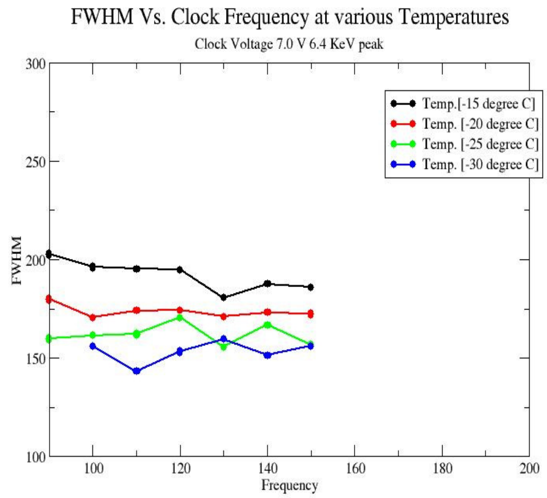


Figure-8
FWHM Vs, Clock Frequency at different temperatures [6.4 KeV peak; Clock Voltage 7.0V]

Conclusion

The experiment has satisfactorily determined the optimum operating parameters of the device for better performance in the space. Considering the nature of the variation of the curves with frequency, and the economy of cooling the device to a stable temperature and the value of FWHM at these temperatures, the operating temperature of the device is recommended to be at-25^{o}C.

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