ON A PHOTON-COUNTING ARRAY USING THE FAIRCHILD CCD-201

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Current work on the evaluation of certain performance parameters of the Fairchild CCD-201 and the proposed method of operation of an electron-bombarded charge-coupled device will be described. This device will be used in two different applications in the multi-aperture amplitude interferometer now being fabricated at the University of Maryland. The first application uses an array of sensors in the aperture plane of a telescope. The requirements are: discrimination between single, double, and triple photoelectron events in a pixel frame scan time of a few milliseconds, and an array of at least 60 × 30 pixels. The second application, which is in the focal plane and operates with very high contrast illumination, should have a single photoelectron sensitivity and a minimum of blooming and lag. Theory of operation of a device which uses the Fairchild CCD-201 and satisfies both of these requirements will be discussed. The expected blooming characteristics will also be considered. Work in progress at the University of Maryland on the evaluation of the parameters relevant to remote, low-noise operation of the Fairchild CCD-201 will be described. These tests have been conducted using light input. The video data from the CCD are amplified, digitized, stored in a minicomputer core memory, and then recorded on magnetic tape. The frames of data are then analyzed on a Univac 1108 using a set of specialized programs which permit a statistical analysis of the variation of the single level across a single frame. These programs also permit evaluation of the performance of a given pixel in a sequence of frames, followed by an "across the frame" evaluation of the statistical properties. To handle the data from the ICCD, a circulating semiconductor memory has been designed and fabricated to handle five frames of data with an accuracy of 16 bits at a 4-MHz data rate. This operates in conjunction with a minicomputer, which controls the operation of the circulating semiconductor memory and serves as an intermediate data storage.

I. INTRODUCTION

In the following, we discuss the work being done at the University of Maryland on the internally intensified charge-coupled device (ICCD). The details of the actual tube, which is being fabricated by the Electronic Vision Company, are described in detail in the paper by John Choisser (Proceedings of this Symposium). The ICCD will be operated as a photon-counting array detector.

An incident photon is converted to a photoelectron with a standard photocathode (S-20, for example). This photoelectron is then accelerated to an energy of about 15 keV and electrostatically focused onto the front surface of a Fairchild CCD-201. Within a particular photosite on the CCD, the photoelectron creates many hole-electron pairs by ionization. These charges for a single photoelectron are collected and produce an easily detectable charge packet. These charge packets are "scanned" from the CCD by the conventional clock pulse trains. After on-chip amplification, the signals leave on a single video output line. This data is then electronically processed to detect the charge packet produced by each photoelectron. The information is then processed on-line and stored in a special memory, which can operate at video data rates.

II. PHOTO SENSOR REQUIREMENTS

This development effort with the ICCD is motivated by two different applications with significantly different requirements.

A. Amplitude Interferometer Requirements

The primary application of the ICCD will be as the light sensor for a special instrument, the multi-aperture amplitude interferometer (MAAI). This instrument is a multi-channel version of a similar instrument, which has been used in an astronomical observation program over the last few years (Refs. 1, 2, 3). Basically, this application requires an array of photosensors, each of which acts as a photomultiplier. Thus, the requirements are:

(1) The ability to discriminate on single photoelectrons
(2) The scan of an entire frame in a few milliseconds
(3) Very low lag, or memory from one frame to the next frame
(4) Minimal crosstalk between spatial channels (or pixels)
(5) The ability to distinguish reliably among zero, one, two, or more photoelectrons per pixel per scan.

B. Imaging Camera Requirements

The other application, which is related to the MAAI, consists of an imaging camera in the focal plane of the telescope. For this application, the requirements consist of items 1, 2, 3, and 4 listed in Section A, as well as

(1) Very large dynamic range
(2) Very low blooming

The electronic operating conditions for the ICCD will be somewhat different in order to satisfy the different requirements of the two applications.

III. METHOD OF CCD OPERATION

A. Theory of Operation of the CCD

The Fairchild CCD-201 will be bombarded by electrons arriving in the front of the CCD. The transfer registers, which carry the charge from the photosensitive sites to the on-chip preamplifier, operate independently and at the same time as the integration of charge at the photosites. Thus, the transfers or "scanning" can take place during the integration period, and eventually the array is sensitive all the time. These transfer registers are protected by a layer of aluminum, so that the bombarding electrons cannot produce any ionization or "noise" in the registers. In the operational data system, the scanning procedure is controlled by an external device [the circulating semiconductor memory (CSM)], which may be programmed to scan a portion of the 100 × 100 array, or the entire array.

B. Operation of the CCD

In order to operate the light sensor on the telescope, a long cable from the electronics to the camera head is required. To handle this, a special camera head has been fabricated which minimizes the crosstalk and coherent noise. The pulse trains are transmitted to the telescope on high-impedance lines. These are converted to the required high-current pulses by clock drivers in the camera head. The camera head also contains amplifiers, a sample and hold circuit, and a discriminator.

C. Noise Sources in the Charge-Coupled Device

There are three types of electronic noises which are most significant with respect to ideal photoelectron discrimination operation. These are "random charge noise," "thermal leakage charge," and the variation of the thermal leakage current or the "thermal leakage noise."

1. Random Charge Noise. The random noise is indicated by the variation of the voltage level, from one frame to the next, at a given pixel. For measurements of the random noise, the illumination is presumed to be constant or, as for most of these tests, no illumination. The random noise is characterized by the standard deviation of the voltage at a given pixel for a number of successive frames. This type of noise behaves as if it were Johnson noise dominated by the capacitive input of the on-chip preamplifier. The value of the random noise is essentially independent of temperature (more precisely, it varies inversely as the temperature). At a data rate of 0.5 MHz, the random noise has been measured by Dyck and Jack (Ref. 4) to be about 300 electrons per pixel per scan.

2. Thermal Leakage Current. This "dark current" or thermal leakage current is due to thermally generated charge pairs which are created within the active silicon. The leakage current is parameterized by the average number of electrons which collect at a given pixel during the integration interval (usually the scan or frame time). The value of the thermal leakage charge varies across the frame from pixel to pixel. It decreases by a factor of two when the temperature of the CCD is reduced by 6 or 7°C and decreases

linearly as the integration time is decreased. The average leakage charge across the frame does not significantly affect the ICCD operation, but its variation across the chip may create a problem. The variation of the thermal leakage charge from frame to frame (Poisson noise) would properly be a component of the random noise, but its value is negligible for normal ICCD operation.

3. Thermal Leakage Noise. The thermal leakage noise is the variation of the thermal leakage charge across the array. This will be parameterized by the standard deviation of the thermal leakage charge across the array. More precisely, it is the variation of the mean (over many frames) thermal leakage charge across the array. This latter form of the definition removes the random noise as a component of the thermal leakage noise. It should decrease with temperature at the same rate as the thermal leakage charge and decrease in proportion to the increased data rates. In order to permit single photoelectron discrimination without a change of discriminator level for each pixel, this noise must be reduced by about 100 photoelectrons. This may safely be accomplished by cooling to approximately -20°C.

D. Array Display

In order to study these quantities, an image processing system has been developed at the University of Maryland which permits computer processing of many scanned frames and the determination of these quantities by a standard procedure.

IV. OPERATION OF INTENSIFIED CCD

A. Theory of Intensification

The photoelectron is accelerated to 14.6 keV prior to impact on the CCD. This value is sufficient to produce a large enough charge by ionization to permit the detection of a single photoelectron, but is not sufficient to penetrate the aluminum (and other) layers which form the protection for the transfer registers. Since different regions covering the transfer registers have different thicknesses, the accelerating voltage is chosen so the photoelectron cannot penetrate the thinnest region. In fact, the energy has been further reduced so the photoelectron will not penetrate into the final layer of SiO_2 insulation above the active silicon of the transfer registers. For a photoelectron which impacts the CCD over a photosite, some of the energy is lost in the layers of silicon and silicon dioxide which lie over the photosite. The 14.6-keV electron will encounter either of two regions over the photosites, which have different thicknesses. Therefore, the photoelectron may have either 8.5 or 9.6 keV upon entry to the active silicon. These detailed calculations are based on a specific model of the CCD architecture which was obtained from R. Dyck of the Fairchild Corporation. For any given device from a particular run, it is expected that there will be significant variations. Thus, these numbers may be considered as a sample calculation.

As a result of the energy of the photoelectron entering the active silicon, we will have the production of charge packets containing 2300 or 2600 electrons, depending on how many layers it has penetrated. The variation of these numbers is relatively small, especially when compared to noise in the on-chip amplifier of 300 electrons.

V. ADVANTAGES OF SINGLE PHOTOELECTRON DISCRIMINATION

In this section, we distinguish between single photoelectron sensitivity and single photoelectron discrimination in a photodetector. In a conventional photomultiplier, this distinction is the difference between operating in an analog or "DC" mode and operating with a discriminator set to trigger at the single photoelectron level. In order to illustrate this distinction more clearly for a television or scanning system, several parameters will now be defined. The nominal CCD-201 has a saturation level of 75 millivolts, which is equivalent to 0.4×10^6 electrons. Under operating conditions similar to those discussed in the previous section, a single photoelectron will produce a charge packet of 2000 electrons.

We presume for the sake of discussion that the thermal leakage charge and the thermal leakage noise are zero. Let us now consider the dynamic range and the noise level for such a detector system. The maximum number of photoelectrons per pixel version is thus 200. If the "random noise" has a value which is larger than 2000 electrons, then the dynamic range is linearly related to the noise level. However, as the noise level decreases, we have the option of a different type of detection based upon the discrete character of the photoelectron. Thus, we may introduce the discriminator and operate in a mode in which, intuitively, the discriminator will never be tripped when there are no photoelectrons. The dynamic range would then be infinite.

From a more practical point of view, a finite noise distribution has a "tail," so there are occasional times when the discriminator is actuated, producing an "electronic dark current." However, the value of the electronic dark current or the probability of tripping this discriminator decreases far more rapidly than linearly with a decreasing noise level. Thus, if the discriminator is set equal to 1000 electrons and the random noise has a value of 1000 electrons (giving an effective collection efficiency of 84%), the probability of tripping the discriminator by the noise in each pixel in a given scan is about 0.16, so the dynamic range is about 1300. If the random noise level is one half as large (500 electrons), then collection efficiency is 98% and the probability of tripping the discriminator is about 2.3%. Thus, the dynamic range is increased by a factor of seven to 2,000,000. This general relation presumes Gaussian statistics for the random noise. Thus, we see the critical importance of decreasing the noise and operating in a single photoelectron discrimination mode, since small reduction in random noise increases the dynamic range by several orders of magnitude rather than by proportional factors.

VI. SATURATION, BLOOMING, AND LAG

In this section, we briefly mention several problems which normally affect scanning sensors.

A. Saturation

Saturation is defined as the departure from a linear relation between input light intensity and output electrical signal. For the moment, we ignore the processes analogous to the computer processing methods which are used to get "linear" results from film by unfolding an H-D curve. The single photoelectron discriminator curve which relates input to output has a break point at 1 photoelectron per pixel per scan. Actually, for normal MAAI operation, this break point occurs at 3 photoelectrons per pixel per scan. This value then parameterizes the single photoelectron discrimination (SPD) saturation. However, if a parallel analog channel is used, the break point for the "analog saturation" is defined by using the nominal 75-millivolt saturation of the CCD-201. For the parameters of the earlier section, this occurs at about 200 photoelectrons per scan per pixel.

B. Blooming

The term "blooming" is used in this discussion to describe the appearance of apparent photo response in pixels which receive no light but are located near pixels which are receiving illumination. There are three types of blooming:

(1) Radial bloom is normally seen in conventional low-light-level devices. It is caused by various mechanisms, including the electron beam spread. There is almost no radial bloom in the CCD due to internal structures in the silicon and the lack of an electron beam.

(2) Vertical bloom occurs due to spilling of charge from an overloaded photosite into the transfer register locations which are "passing by." This occurs at an illumination beyond the analog saturation level, which, in turn, is well beyond the normal operating levels for single photoelectron discrimination.

(3) Horizontal bloom occurs primarily due to a lower transfer efficiency for the horizontal transfer registers operating at 4 MHz. This type of blooming occurs as apparent light in one horizontal line only. Existing data may be used to place an upper limit on the magnitude of this effect. It will produce excess light in a horizontal line which is fainter than the "diffraction spikes" which occur due to the spider in a reflecting astronomical telescope.

C. Lag

Lag describes the residual charge left at a photosite from the previous frame. This is not significant below saturation and should be small above saturation, but it has not yet been measured.

VII. DAMAGE MECHANISMS

When a CCD is bombarded on the front surface by photoelectrons with an energy of 10 to 20 keV, there may be radiation damage which interferes with proper semiconductor operation. While there are a variety of different damage mechanisms, proper operating conditions and some of the special properties of the CCD-201 will prevent a number of these problems. The mechanism which remains most important is related to the effect of holes left in the SiO_2 when the photoelectron causes ionization in the insulating layers. General radiation damage measurements which have been conducted at the Naval Research Laboratory (Ref. 5) indicate that this type of damage will result in a significant operational lifetime problem. The actual lifetime will depend upon details of operating procedures and conditions. Several further techniques are now being investigated for extending the operating life of the ICCD. One of these techniques consists of increasing the thickness of the aluminum protection. This is one aspect of reducing, as much as possible, the amount of ionization in the critical layers. In addition, there are several procedures that have shown promise in annealing or removing the damage. These techniques have been successful in other types of devices but have not been properly tested on the CCD-201.

VIII. TEST SYSTEM DESCRIPTION

A basic description of the single-scan data system is presented in this section. The voltage sequences which are required to drive the CCD are developed in the video driver unit. This is a separate rack-mounted unit. In addition to the high-impedance pulse trains, this unit also develops the required voltages for driving the CCD. Clock drivers within the camera mount, on the video drive board, convert the high-impedance pulse train into the high-current pulse trains required for the CCD. The actual performance of the CCD, as well as a detailed description of the electronic system will appear in a separate report.

In the Mark II camera head (upgraded), the video output from the CCD is processed in a separate chamber, which is electrically isolated from the chamber in which "scanning" pulse currents are generated. This video processor card contains a preamplifier, a sample and hold amplifier which is gated from the video driver unit, a second amplifier, and a DC restoration circuit.

The output of the video processor card may be amplified and used for a direct CRT display, using special outputs from the video driver unit to provide the proper voltages to form a raster.

The video signal from the video processor card then proceeds to an input/output card in the NOVA 2/10 computer. Here the signal is again sampled and converted from analog to digital form. A special multiplexing circuit then compacts the 8-bit or 4-bit data from the A/D converter into 16-bit NOVA words. This permits the use of the NOVA direct memory data rate of 1.2 MHz for 16-bit words or a CCD data rate of 4.8 MHz with 4-bit digitization (2.4 MHz for 8-bit digitization).

The control of the NOVA, which includes the storage and selection of the array data, is handled by a Lexiscope CRT terminal. While this data is stored in the NOVA 2/10 core, with the Lexiscope terminal, one can command a bar chart display of a single line in the array. This permits the inspection of the data within the NOVA core prior to recording on magnetic tape. Following this inspection, on command from the Lexiscope, the data is transferred from the NOVA core to the Precision Instruments magnetic tape unit for recording on 9-track magnetic tape.

The magnetic tape is then read by a special program written for the UNIVAC 1108 which unpacks the NOVA words into FORTRAN-readable 36-bit words and/or writes these pictures into an image processing system picture format file. The arrays of data are then processed by the image processing system (IPS), which has been written for the Amplitude Interferometry Program. The output for the IPS employs several of the I/O devices of the Computer Science Center, in particular, teletype display, CRT display, line printer output, or the Computer Science Center digital optical scanner. The image processing system will be described in more detail in separate publications.

The entire single-scan data system is rack-mounted in special shipping containers to permit convenient field operation.

IX. OPERATING DATA SYSTEM

For normal operation of the ICCD on a telescope, there are several additional requirements placed on the data processing system. Since we expect to operate the ICCD at a data rate of 4 MHz, this will require some method of data storage and successive frame addition which has a cycle time of 350 nanoseconds. In order to satisfy the requirements for the MAAI application, a circulating semiconductor memory (CSM) has been fabricated. This unit has five independent tracks, each of which has an ultimate capacity of 12,288 words containing 16 bits. The data is entered through five arithmetic units, which are presently programmed either to add the new data word to the existing word or to produce a zero. However, the arithmetic unit has the capability of being programmed for a total of 32 logical operations on its two inputs. The data which is circulating in the CSM may be removed on data buses. The data buses from each of the five tracks are multiplexed to a common data bus. This common data bus is connected to the NOVA 2/10 minicomputer core by the direct memory access mode. Thus, the data can be transferred directly from the CSM to the NOVA 2/10.

In this mode, the CSM is serving as a temporary high-speed storage device. However, it serves another purpose. By placing a "skeleton" of control words in the CSM and certain logic and control functions in the hardware, the CSM controls, in detail, the voltages used in scanning of the CCD. In this mode, the CSM controls the horizontal and vertical scanning and inserts the data words between the control words in the CSM. Since this "skeleton" is entered to the CSM via a program contained in the NOVA 2/10, one may enter special skeletons to cause special scanning modes (i.e., scanning a small rectangle in the CCD array). These control modes are defined by interjecting a new control skeleton into the CSM from the NOVA 2/10. The CSM has been completed and presently is operating in stand-alone mode. The interface to the minicomputer has been completed and is being tested. With a modification in a control card, the CSM can also do real-time subtraction of sky background.

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