TITLE MEASURING NEUTRON FLUENCES AND GAMMA/X-RAY FLUXES WITH
CCD CAMERAS

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Measuring Neutron Fluences and Gamma/X-Ray Fluxes with CCD Cameras

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Abstract

The capability to measure bursts of neutron fluences and gamma/x-ray fluxes directly with charge coupled device (CCD) cameras while being able to distinguish between the video signals produced by these two types of radiation, even when they occur simultaneously, has been demonstrated.

Volume and area measurements of transient radiation-induced pixel charge in English Electric Valve (EEV) Frame Transfer (FT) charge coupled devices (CCDs) from irradiation with pulsed neutrons (14 MeV) and Bremsstrahlung photons (4-12 MeV endpoint) are utilized to calibrate the devices as radiometric imaging sensors capable of distinguishing between the two types of ionizing radiation. Measurements indicate ≈ 0.5 V/rad responsivity with ≥ 1 rad required for saturation from photon irradiation. Neutron-generated localized charge centers or "peaks" binned by area and amplitude as functions of fluence in the 10^5 to 10^7 n/cm² range indicate smearing over ≈ 1 to 10% of CCD array with charge per pixel ranging between noise and saturation levels.

1. INTRODUCTION

We have determined empirically that solid state area arrays can be used to distinguish between pixel charge induced by high-energy neutrons and photons. For detectable flux levels (based upon cross-section criteria) and similar densities of neutrons and photons (neutrons or photons/unit area) the dominant observation is that neutrons induce localized charge in individual pixels or clusters of pixels whereas photons cause a basically uniform increase in average pixel charge

across the array. These fundamental differences in charge generation mechanisms in silicon associated with excitation by neutrons or photons are exploited in our technique.

Normally, radiation sensors are nonimaging. Typical designs are based upon radiation-to-light converters and photodiodes or photomultipliers, which integrate charge over their entire target area to measure total dose irrespective of type or location. For distinguishing between types of radiation, appropriate shielding is usually employed, but this makes it difficult to use one sensor to measure both types of radiation. Even area arrays lose ability to retain individualized charge centers if operated in charge-summing mode over the total array. Our technique, however, capitalizes not only on differences in charge generation but also on the preservation of spatially distributed charge patterns provided by image storage on the array followed by serial (pixel-by-pixel) readout of the FT CCD video, which is digitized for later analysis.

We have developed a computer algorithm that interrogates the digitized CCD image (pixel-by-pixel) to quantize each pixel's charge. For photon-generated charge, increases in average levels above background noise levels are measured to give a figure of merit (video volts/rad) for the CCD. For neutron-generated charge centers (or "stars"), each is individually measured and tabulated for affected area (quantity of pixels involved) and amplitude (digitized units above background noise) to obtain volume. From these data we can give two figures of merit (% of area or volume affected versus fluence) for the CCD.

For these experiments, the EEV CCDs were operated in either standard RS-170 Photon Model PS46510 or Asynchronous resettable RS-170 Model P45380 EEV cameras.

Experimental Set-Up

Because we are exploring transient effects, pulsed sources of radiation are required. Short-duration pulses of high-energy Bremsstrahlung photons are produced by bombarding a tungsten target with electrons from a LINAC as shown in Fig. 1. The system uses pulse widths in the range from 50 ns to 2 μ s and controllable current in the incident electron pulse

Fig. 1. Set-up for measuring EFV CCD gamma/x-ray responsivity. Components are not to scale. The CCD is shielded from the 2p flux by 6 inches of lead with tapered collimator aperture. For sampling a smaller diameter beam is provided by 3/16" aperture in the 2-inch thick lead collimating plug

in the range from 0.05A to 2A to provide doses in the CCD image plane of 50 millirads to 5 rads.

Two different collimators were used to restrict irradiation to the central area of the CCD array. The collimation was required for two reasons: (1) to provide irradiated and non-irradiated areas on the images to give contrast for signal definition and measurement of background versus radiation-induced signals, and (2) to shield reference pixels in the CCD imagers that are used for dark current or quiescent levels for DC restoration in the camera electronics.

The (original) collimator used is shown in Fig. 2a. The second (improved) collimator used is shown in Fig. 2b. Their transmission was measured by using gamma/x-ray photons from the linac and measuring dose transmission/attenuation characteristics with TLDs and radiochromic film. The measurements were repeated using Co-60 gamma flux with essentially the same results.

Typical CCD video amplitude at the aperture and along the shoulders are indicated in Fig. 3 for the improved collimator.

The neutron irradiation setup is shown in Fig. 4. Bursts ($\approx 1-10 \mu$ s) of neutrons from D-T reactions produced in a triggerable generator provided peak fluences in the CCD image plane approaching 10^7 n/cm². Fluence levels were varied by controlling the source to CCD distance as shown in Fig. 4 (d).

Fig. 2a. Transmission profile for pulsed gamma/x-ray radiation for improved aperture butted against lead shield tapered collimator with 1.18 in. (30 mm) entrance diameter and 1.57 in. (40 mm) exit diameter.

Fig. 2b. Transmission profile for pulsed gamma/x-ray radiation for improved aperture butted against lead shield tapered collimator with 0.63 in. (16 mm) entrance diameter and 0.75 in. (19 mm) exit diameter

In order to synchronize the CCD cameras with the arrival of radiation, an instantly resettable sync generator was designed. The generator is used to "slave" the CCD camera, using "gen lock" techniques by providing vertical and horizontal sync pulses to drive the camera's internal sync circuitry. A precisely timed "integrate" pulse is also generated to time phase the CCD imager with the radiation. For the experiments, a pretrigger from the radiation sources is used to reset the sync generator as shown in Fig. 5. The sync circuitry is shown in Fig. 6.

II. ANALYSIS OF GAMMA/X-RAY DATA

The gamma/x-ray responsivity for one EFV CCD camera (EEV #1) was measured by generating a transfer curve (Fig. 7)

Fig. 3. Transmission profile for improved collimator (aperture) indicating pulsed gamma/x-ray dose and corresponding EEV CCD video.

Fig. 4. Set-up for measuring EFV CCD neutron responsivity. Components not to scale. No collimation was used. The CCD was immersed entirely in beam.

Fig. 5. Timing diagram illustrating key waveform phasing of EFV camera to assure synchronism with randomly occurring transient light or radiation pulses.

of video amplitude versus incident dose from LINAC excitation of the Bremsstrahlung target. Doses from 40 to 793 mR were used for this experiment. The amplitudes used for plotting the curve correspond to peak transmission through the collimator aperture (Fig. 2) with background or pedestal level subtracted. The technique is illustrated in Fig. 8. Two independent readers were used to minimize subjectivity in the amplitude readings. The lower boundaries of the curve obtained from one reader are $\approx 73\%$ the value of the higher boundaries from the second reader. The high readings indicate ≈ 0.562 V/rad and the low readings are closer to

≈ 0.415 V/rad. An average "best-fit" indicates ≈ 0.489 V/rad, which is rounded off to give 0.5 V/rad.

The experiment was repeated at a later date to look for consistency from EEV #1 camera. The aperture signal amplitude falls on the "best-fit" curve as shown by two entries for 588 mR and 669 mR doses. Other measurements along the curve also essentially repeated the earlier data set but are omitted for clarity in the figure.

For this latter experiment, the aperture amplitude readings were augmented by also reading pedestal amplitudes (see Fig. 8). These correspond to transmission outside of the collimator

Fig. 6. Circuitry of instantly resettable sync generator used for synchronizing FFV camera to random radiation or light pulses.

Fig. 7. Typical EEV CCD gamma/x-ray responsivity transfer curve.

aperture, principally in the "shoulder" areas as indicated in Fig. 2. The combined aperture and pedestal level give a larger amplitude (see Fig. 7 aperture plus pedestal entry at 588 mR), which is a more nearly correct measure of absolute responsivity for the CCD camera. However, the relative responses as functions of dose obtained from the aperture readings only are adequate for characterizing linearity in a given CCD camera. We have used the same technique to characterize several other solid-state cameras [1-3].

Also in the latter experiment, the EEV #1 responsivity was measured without using any collimator. The use of a collimator was two-fold: (1) to give contrast between irradiated and unirradiated areas on the CCD array, and (2) to provide gamma/x-ray attenuation of reference pixels and storage areas of the FT CCD. The reference pixels are opaque to visible light and are used to determine the "black" level or "dark" condition for the CCD. The camera DC restoration circuits require such a reference to operate properly. At the lower flux levels (40 mR to 360 mR on Fig. 7) the pedestal signal appears linear (transfer curve slope of $\delta = 1$) but with different gain than observed for the aperture signal. However, at higher doses, the pedestal appears depressed, probably due to improper DC restoration as larger "area-under-the-curve" video waveforms are generated. This is indicated as "ped loss" in Fig. 7.

To ascertain typical EEV CCD responsivity, two additional cameras, EEV #2 and EEV #3, were also measured. The data plotted for EEV #2 were obtained at the same time as one of the EEV #1 experiments. Only a single responsivity

Fig. 8. Typical field (top) and scan line (bottom) waveforms from EEV camera illustrating video amplitude measurement technique for characterizing gamma/x-ray responsivity

data point was measured for EEV #3 because only charge dumping of the radiation-induced charge was emphasized for this camera during a separate series of experiments.

Later experiments used the improved collimator of Fig. 3. The aperture data for the new collimator and a fourth Co-60 camera (EEV #4) produced ≈ 425 mV/rad from 793 mR dose as noted in Fig. 7.

Reciprocity measurements were performed to investigate rate effects. This parameter was measured by controlling the LINAC pulse duration and current to produce nearly the same total energy in different "increments" of time. The time range was from 200 ns FWHM to 2.1 μ s FWHM. The EEV #1 video linescans and the LINAC pulses for these two conditions, as shown in Fig. 9, give essentially the same result. Some reciprocity data from all three EEV CCD cameras are tabulated in Table 1.

Auxiliary data for EEV #1 and EEV #2 were obtained by integrating the steady-state flux from a Co-60 isotopic source over the EEV CCD camera's 16.66 ms field period. Because the camera was operated interlaced, the radiation-induced integrated charge from continuous irradiation was read out in two consecutive fields. For comparison with the pulsed response (where all the charge was read out in one field) the video from both fields was added. These normalized data are also in Table 1. To substantiate the validity of the normalization, EEV #4 was operated noninterlaced and gave approximately twice the responsivity noted for the interlaced data from EEV #1 and EEV #2. This is shown in Fig. 7 and in Table 1.

Fig. 9 Reciprocity measurements of EEV CCD for similar total doses at two rates. Part a shows ≈ 669 mR dose from ≈ 2.1 μ s FWHM gamma/x-ray pulse with video amplitude ≈ 320 mV shown in part b. Similar dose of ≈ 588 mR from ≈ 200 ns FWHM pulse is shown in part c with resultant video ≈ 290 mV in part d. The respective responsivities are 0.478 and 0.493 V/rad.

Table 1. Reciprocity Effects

Camera	Source	Rate	Dose		Responsivity (V/R)	
			Total (mR)	Video (mV)	Raw	Normalized
EEV #1	Cs-60 ^a	29.87 R/S	496	160	0.323	0.646
	Bremsstrahlung	Unknown	525	295	--	0.562
	Bremsstrahlung ^b	600 ns	675	280	--	0.415
	Bremsstrahlung ^c	200 ns	588	290	--	0.493
	Bremsstrahlung ^d	2.1 μ s	669	320	--	0.478
EEV #2	Cs-60 ^a	29.87 R/S	496	120	0.242	0.484
	Bremsstrahlung ^e	1.3 μ s	575	300	--	0.522
	Bremsstrahlung	Unknown	440	200	--	0.452
EEV #3	Bremsstrahlung	Unknown	500	325	--	0.650
EEV #4	Cs-60 ^a	7.75 R/S	130	70	0.539	0.539
	Bremsstrahlung ^e	675 ns	793	425	--	0.536

^a29.87 R/S flux integrated for 16.66 mS for 1 interlaced field and normalized upward 2X for full field

^b600 ns FWHM, 90 mA, 675 mR.

^c200 ns FWHM, 400 mA, 588 mR.

^d2.1 μ s FWHM, 45 mA, 669 mR.

^e1.3 μ s FWHM, 50 mA, 575 mR dosimetry.

^f7.75 R/S flux integrated for 16.66 mS for 1 noninterlaced field.

^g675 ns FWHM, 90 mA, 793 mR.

The indicated responsivities from the Table 1 entries show no rate effects. Within experimental accuracy, in the range from tens of nanoseconds to tens of milliseconds, no reciprocity problems were observed.

Analysis of Neutron Data

The dominant observation from particle (neutrons or protons) irradiation is the creation of localized charge centers or peaks referred to as "stars" by us [1-3] and as dark current "spikes" by others [4,5]. Our data indicate that the quantity, magnitude, and area of stars generated is a function of fluence, with larger fluences creating not only a larger number of stars, but also higher amplitude (greater charge) and area for affected pixels. The different physical mechanisms involved with electron-hole production from neutron and gamma irradiations is covered in a later section.

During these experiments as with the gamma/x-ray experiments, the camera was operated in the dark without a lens and the imager was masked with opaque tape to prevent light from reaching the pixels. Therefore, all signal produced by the camera was due entirely to ionizing radiation. Figure 10 shows typical star patterns generated by neutrons. To simplify implementation of our computer-based star counting algorithm, a search area corresponding to a square 3×3 millimeters on the CCD surface was defined. This area illustrated or outlined in the white box of Fig. 10 comprises 13,776 pixels. In this manner, observations are qualified per unit area and can be extrapolated to the total CCD area. The stars are categorized (Table 2) by size (quantity of pixels involved) and by amplitude (digital counts from noise level to saturation).

Typical line scan profiles from EEV #3 camera following irradiation with 14-MeV neutrons are shown in Fig. 11. Fluences of 9.88×10^6 n/cm², 2.47×10^6 n/cm², and 6.17×10^5 n/cm² were selected by controlling the distance

Fig. 10. EEV CCD TV field picture following exposure with $\sim 1\text{-}10 \mu\text{s}$ FWHM burst of 14 MeV neutrons

("d" of Fig. 4) between the neutron generator and the CCD image plane. Corresponding line profiles are shown in Figs. 11a, b, and c, respectively. To avoid counting noise (as stars), several thresholds are selected as illustrated in Fig. 11.

Table 3 (a, b, and c) shows tabulated data at one threshold for each of the three fluences. From these data average volume charge per pixel can be estimated. However, a simpler figure-of-merit model involving area only was developed. This model uses the criterion that affected pixels, regardless of amplitude, are useless because of the uncertainty in magnitude of neutron-induced charge. Subsequent light-induced charge is superimposed on neutron-induced charge, making it impossible to distinguish the source except if structural differences are known beforehand. In effect, pixel dynamic range is reduced by an unknown amount for affected pixels limiting their usefulness as radiometric (*calibrated*) sensors. The summary of area effects as a function of the three neutron fluences is found in Table 3.

Calculated average volume charge corresponding to the three fluences is found in Table 4. These were derived using the amplitude data from Table 2 and the area data from Table 3. The average charge per pixel varies misleadingly as a function of threshold with higher thresholds resulting in higher charge because fewer stars are usually counted. However, there does appear to be a definite bias towards higher total charge as fluence increases. This indicates that using affected area only to predict fluence is not sufficient.

The volume entries for a given fluence and threshold indicated in Table 4 (footnote b) correspond to total volume charge from the search area obtained by subtracting a dark (unirradiated) background field from the data field containing neutron-generated stars. Values obtained in this manner are approximately 2.5X larger than values obtained by our technique. This is probably an error in our method of conservative selection of thresholds. A lower selection threshold would obviously yield higher charge levels but at the risk of counting noise spikes that are not related to neutron irradiation. Conversely, the background subtraction method relies on the exact same noise structure between irradiated and nonirradiated fields, which is unlikely. Both methods seem to track reasonably well (linearly with fluence) with the exception of absolute values obtained.

A new star counting algorithm was designed that quantifies individual stars by area and amplitude so discrete packets of volume charge can be measured for individual stars. The algorithm used for the data presented in this report only identifies amplitude and area distributions from analyzing all stars. The new algorithm has been successfully used on a limited subset of these data and will be presented in future reports on this subject.

Charge Categorization from Unknown Radiation

An example of distinguishing signal charge resulting from simultaneous irradiation with neutrons and gammas is illustrated in Fig. 12. The gamma-induced signal is derived by

Table 2. Frequency of stars by peak amplitude (drystal units) and by area (pixels) versus fluence.

a. 9.88×10^6 n/cm ² fluence							
Area	Freq	Ampl	Freq	Ampl	Freq	Ampl	Freq
1	205	42	126	68	1	108	1
2	63	43	60	69	2	109	1
3	30	44	49	70	2	111	1
4	28	45	22	71	2	113	2
5	15	46	16	73	1	117	1
6	13	47	6	74	1	118	1
7	15	48	2	76	2	120	1
8	7	49	8	77	3	126	1
9	3	50	6	78	1	128	1
10	3	51	5	80	2	133	1
11	5	52	4	81	2	135	3
12	1	53	7	82	1	136	2
13	2	54	3	83	1	137	3
14	1	55	3	84	2	141	1
15	1	56	3	86	2	142	1
16	1	58	3	87	3	143	1
17	4	60	3	88	1	145	1
18	1	61	4	90	1	147	1
19	1	62	4	93	1	180	1
21	1	63	3	99	1		
40	1	64	1	101	2		
196	1	67	3	106	2		

b. 2.47×10^6 n/cm ² fluence							
Area	Freq	Ampl	Freq	Ampl	Freq	Ampl	Freq
1	164	39	116	61	1	85	2
2	66	40	68	62	1	88	1
3	26	41	42	64	2	89	1
4	22	42	16	66	1	90	2
5	11	43	15	67	2	96	1
6	12	44	4	68	1	97	1
7	8	45	5	69	1	100	2
8	3	46	4	71	2	106	1
9	2	49	1	72	1	112	1
10	7	51	1	73	1	114	1
11	1	54	1	74	2	116	1
16	1	56	2	77	1	135	3
		57	3	78	3	136	1
		58	1	80	1	138	1
		59	2	83	2	197	1

Table 2 (continued)

c. 6.17×10^5 n/cm² fluence

Area	Freq	Ampl	Freq	Ampl	Freq	Ampl	Freq
1	60	34	36	48	1	78	1
2	13	35	17	55	1	87	1
3	11	36	15	56	2	129	1
4	4	37	7	60	1	134	1
5	3	38	2	61	1		
6	5	39	3	64	1		
7	3	40	3	67	1		
13	1	42	1	75	2		
15	1	44	2	76	1		

Fig. 11a. EEV CCD scan line showing threshold magnitude selection for neutron star counting measurements from high-level fluence.

Fig. 11b. EEV CCD scan line showing threshold magnitude selection for neutron star counting measurements from intermediate-level fluence.

Fig. 11c. EEV CCD scan line showing threshold magnitude selection for neutron star counting measurements from low-level fluence.

Table 3. Summary of area effects at three fluences. The CCD search area used for star counts was 13,776 pixels with start coordinates row 76, column 80, and stop coordinates row 187, column 202.

14 MeV Fluence $\approx 6.17 \times 10^5$ n/cm ² (file EEV 10 inch)				
Threshold (CNTS)	33	34 ^a	35	36
No. of Stars	298	101	65	48
No. of Pixels	868	229	152	117
% of Area	6.3	1.7	1.1	0.85
14 MeV Fluence $\approx 2.47 \times 10^6$ n/cm ² (file EEV 5 inch)				
Threshold (CNTS)	38	39 ^a	40	41
No. of Stars	369	323	210	138
No. of Pixels	1491	784	490	343
% of Area	10.8	5.7	3.6	2.5
14 MeV Fluence $\approx 9.88 \times 10^6$ n/cm ² (file EEV 2.5 inch)				
Threshold (CNTS)	42 ^a	43 ^a	44	45
No. of Stars	402	312	258	201
No. of Pixels	1404	973	762	568
% of Area	10.2	7.1	5.5	4.1

^aBest estimate based upon "most similar" thresholds for comparing CCD response at various fluences.

subtracting the scan line pedestal level of a background (unirradiated) field from increased pedestal level after irradiation. For this exposure we measured ≈ 100 mV, which corresponds to ≈ 200 mR gamma dose from the transfer curves of Fig. 7. The neutron-induced charge is obtained by using the star-counting algorithm and comparing results with those obtained during laboratory neutron fluence measurements. This exposure corresponds to $\approx 1 \times 10^7$ n/cm².

Radiation Factors Relating to CCD Structures

There are two aspects to the effect of "radiation" upon silicon semiconductor based optical imaging devices:

- Spurious signal generation when operating in a radiation field, and
- Permanent damage.

High-energy photons (ionizing radiation), e.g., gamma rays, x-rays, cosmic rays, etc., cause the generation of electron-hole pairs. Such generation within the bulk silicon causes spurious signals in the form of photocharge but no permanent damage. Within an oxide layer, however, the holes remain trapped and with increasing dose can lead to a significant shift of flat band voltage (causing a change of optimum dc bias) [4,5] and an increase of surface generation rate (i.e., background build-up or dark current) [1,4,5]. High-

energy particles, e.g., neutrons and protons can cause lattice displacement giving rise not only to large transient signals upon impact causing localized dark current spikes [4] or neutron stars [1-3] as they are often referred to, but also the possibility of permanent damage in either the silicon or oxide interface. Several reactions of neutrons with silicon nuclei that produce ionizing particles include elastic and inelastic scattering, (n,p) and (n, α). The particles create electron-hole pairs as they pass through the silicon substrate. Carriers produced in device depletion regions, or within a diffusion length of these regions, are stored as photocharge, which is read out later as video signal from the CCD. Because of the short range of scattering recoils and charged secondary particles, most of the energy deposited as ionization occurs within the material where the reaction occurs. Consequently, a single reaction can show up as a local effect or a star in one or a few contiguous pixels on the CCD.

Our neutron fluence test excitation levels were not shown to cause permanent damage effects under irradiation conditions to the EEV CCD devices. This is probably because we used a pulsed source of neutrons, thus restricting total dose to the CCD. In this paper we are principally concerned with transient irradiation effects upon the CCD devices. Permanent damage effects have been assessed more rigorously by other authors [4,5].

In a conventional CCD light absorbed by the silicon gives rise to an electron hole pair of which the electron is

Table 4. Calculated average volume charge per pixel for several thresholds for the three fluences.

6.17×10^5 n/cm² fluence				
Threshold	# of Pixels	# of Ampl. Units	Avg Chg/Pixel	
			(Ampl. Units/Pixel)	(volts/pixel)
34 ^a	229	847	3.7	0.058
35	152	766	5.0	0.078
36	117	683	5.8	0.091
2.47×10^6 n/cm² fluence				
Threshold	# of Pixels	# of Ampl. Units	Avg Chg/Pixel	
			(Ampl. Units/Pixel)	(volts/pixel)
39 ^a	784	2916	3.7	0.058
40	490	2648	5.4	0.084
9.88×10^6 n/cm² fluence				
Threshold	# of Pixels	# of Ampl. Units	Avg Chg/Pixel	
			(Ampl. Units/Pixel)	(volts/pixel)
42 ^a	1404	5151	3.7	0.058
43 ^a	973	5162	5.3	0.083
45	568	4754	8.4	0.131

^aBest estimate based upon "most similar" thresholds for comparing CCD response at various fluences.

^bVolume measurements obtained from background subtraction of a dark field from an irradiated field are 1847 units for threshold 34, 6411 units for threshold 39, and 12827 units for threshold 42.

subsequently collected by the polysilicon electrode structure within the device and generates a signal. The depth at which the carriers are generated are dependent upon the wavelength of light but 90% of all light at 400 nm is absorbed within the first 25 μ m of silicon and 90% of all light at 900 nm is absorbed within the first 60 μ m of silicon. It can thus be seen that only a thin silicon layer is required to absorb and detect the visible illumination.

In respect to radiation sensitivity the magnitude of the transient pickup depends essentially on the active volume of the semiconductor associated with each element. The relative magnitude then depends on the active volume and the absolute magnitude of the read-out noise. Because these factors also influence optical sensitivities and dynamic range, it is an inevitable tradeoff that as optical sensitivity increases so does the apparent sensitivity to radiation induced pickup.

The key point is that the capture cross-section of silicon for ionizing radiation detection is much lower (when compared

with the visible spectrum) and electron-hole pairs are generated throughout the whole of the silicon wafer. The question then arises whether these carriers are collected by the classical CCD polysilicon/depletion electrode CCD structure.

Mobility of these carriers is determined by equivalent diffusion lengths or carriers lifetimes. Diffusion length is dependent upon many parameters, but is dominated by the doping concentration of the silicon [6-8].

In an EEV device the base silicon or substrate on which the epitaxial silicon is grown is very highly doped (*low resistivity*) giving a low carrier lifetime so most carriers generated within the substrate will be lost before they reach the classical CCD structure within the epitaxial layer. As a comparison, we understand that Fairchild makes their CCD devices on bulk silicon of appropriate resistivity to provide storage for typical field times of tens of milliseconds. Because the whole of the wafer would be of *high resistivity* (relative to that of the EEV CCD substrate) then carriers generated deep

Fig. 12. EEV CCD scan lines for nonirradiated conditions (background) and irradiation with both neutrons and gamma/x-rays. The two components of total radiation-induced charge are identified as illustrated.

within the wafer would be collected by the CCD structure. The EEV design provides *high resistivity* appropriate for storage requirements only in the epitaxial layer.

On a comparative test, complementary to the results reported in this paper, measurements indicated a much higher susceptibility ($\approx 15\times$) for a Fairchild 222 CCD device to ionizing radiation (gamma) when compared with an EEV device. Also, measurements taken on CIDs, which are also of epitaxial structure, indicate even higher radiation immunity than the EEV CCDs. This supports the view that one of the major keys to good radiation hardness is the epitaxial approach with attendant resistivity and thickness parameters of the silicon appropriately defined.

CCD structures could be optimized in respect to minimizing the ratio of radiation to optical sensitivity. In theory, the susceptibility of any silicon device to radiation noise should be independent of type, i.e., interline transfer, full frame, photodiode provided the ratio of volume of silicon available to radiation detection (within carrier diffusion lengths of collection) to volume of silicon available to photon detection is the same. EEV frame transfer devices utilize pixel structures that virtually cover the entire image area without loss of detection area between pixels and thus optimizes the above ratio but an interline transfer device would necessarily cause some image area to be lost (due to vertical registers) and thus only a percentage of the image area would be available for

photon detection, however, all of the image (wafer) area would be available for radiation detections.

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