Charge-coupled-device charge-collection efficiency and the photon-transfer technique

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Abstract. The charge-coupled device has shown unprecedented performance as a photon detector in the areas of spectral response, charge transfer, and readout noise. Recent experience indicates, however, that the full potential for the CCD's charge-collection efficiency (CCE) lies well beyond that realized in currently available devices. In this paper we present a definition of CCE performance and introduce a standard test tool (the photon-transfer technique) for measuring and optimizing this important CCD parameter. We compare CCE characteristics for different types of CCDs, discuss the primary limitations in achieving high CCE performance, and outline the prospects for future improvement.

Subject terms: charge-coupled devices; charge diffusion; x-ray events; frontside illumination; backside illumination.

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1. INTRODUCTION

CCDs in recent years have become the premier detector for use in many spaceborne and ground-based astronomical instruments. They were selected for use in the Hubble Space Telescope Wide Field Planetary Camera (WF/PC), the Galileo Jupiter Orbiter's Solid State Imager (SSI), and many ground-based imaging and spectroscopic applications. Proposed space applications include an x-ray imager on NASA's Advanced X-ray Astronomical Facility (AXAF), a Space Telescope Imaging Spectrometer (SIS), the Solar Optical Telescope (SOT), and the Comet Rendezvous/Asteroid Flyby Imaging Subsystem (CRAF ISS).

The fundamental parameters that ultimately limit CCD performance are (1) read noise, (2) charge-transfer efficiency (CTE), (3) quantum efficiency (QE), and (4) charge-collection efficiency (CCE). At their present stage of development, it is possible to fabricate devices that have low read noise (in the 4 to 15 e- range), excellent CTE performance (<10 e- deferred charge), and unsurpassed QE performance over the entire spectral range from 1 to 11,000 Å.1-3 However, the full potential of charge-collection efficiency lies well beyond that of currently available devices. Optimization of this important parameter represents a new challenge for the CCD manufacturer and user. High CCE performance is required for many applications over all regions of the spectrum to which the CCD is sensitive. In the visible range, for example, CCDs are used in star trackers that demand high sensitivity (charge collection without loss) in conjunction with high geometric accuracy (collection without significant charge diffusion). In the x-ray and EUV regions of the spectrum, applications require confinement of signal charge to a single pixel without loss in order to accurately determine the energy of the incoming photon.

The means of measuring and achieving high CCE performance is the subject of this paper. In Sec. 2 we present a useful definition for CCE performance in terms of parameters that are readily found when testing the CCD. The definition is divided into the two primary factors that are responsible for the degradation of CCE performance, namely, charge loss and charge diffusion. In Sec. 3 we introduce the concept of photon transfer, a technique used as a standard way of measuring CCE characteristics, and develop the theoretical foundations upon which the photon-transfer method is based. We show the strengths and limitations of the photon-transfer technique as it is used in measuring CCE characteristics of the CCD. In Sec. 4 we apply the photon-transfer technique in measuring
CCE performance for frontside- and backside-illuminated CCDs and discuss the primary factors that ultimately limit CCE for each device. Finally, in Sec. 5 we discuss future considerations for further improving CCE for the CCD.

2. CHARGE-COLLECTION EFFICIENCY

CCE is a relatively new CCD performance parameter that has been defined, measured, and optimized at Jet Propulsion Laboratory (JPL) and elsewhere. CCE measures the ability of the CCD to collect all signal charge generated from a single photon event into a single pixel. High CCE performance is especially critical for EUV and soft x-ray applications (e.g., soft x-ray imaging spectrometers), where the ability of the CCD to accurately determine the energy of the photon depends upon collecting the photogenerated charge properly. Experience has shown that complete charge collection requires that two criteria be met: (1) There must be no trapping centers within the CCD to cause signal charge to be lost by recombination, and (2) the charge of an individual photon must be collected within a single pixel and must not be allowed to divide among several pixels. Charge loss causes the photon energy to be underestimated, while charge splitting degrades the precision of charge measurement by requiring the summation of several noisy pixels.

The degree of charge loss and charge splitting depends upon where in the pixel the photon is absorbed. Photons that are absorbed within the frontside depletion region (see Figs. 5 and 8) of a given pixel are typically seen as the ideal event and are called "single-pixel events." Photons absorbed below the depletion region, where the electric field is weaker, create a charge cloud that thermally diffuses outward until it reaches the rapidly changing potential wells at the lower boundary of the pixel array. At that point, the charge cloud may split into two or more packets, which are collected in adjacent pixels. Events of this type are called "split events." Events in which charge is not conserved have been named simply "partial events" and are usually generated in regions deep within the CCD, where loss of carriers through recombination occurs.

From this discussion, a definition for CCE for an individual photon event I can be presented through the formula

\[
\text{CCE}_I = \frac{\xi_{\text{pe-1}}}{\eta P_{\text{se-1}}},
\]

(1)

where CCE_I represents the fraction of signal electrons, generated by a particular interacting photon I, that is collected in any single affected pixel; \(\xi_{\text{pe-1}}\) refers to the partial event and represents the number of signal carriers generated by a photon and collected by all pixels (the rest being lost to recombination); \(P_{\text{se-1}}\) refers to the split event and represents the number of pixels that collect signal electrons generated by a photon; and \(\eta\) is defined as the ideal quantum yield, a quantity equal to the total number of electrons generated for an interacting photon of energy \(E_\lambda\) (eV). The ideal quantum yield \(\eta\) is directly proportional to the photon energy and is found according to the relationship

\[
\eta = \frac{E_\lambda}{3.65} \quad (\lambda < 1000 \text{ Å}).
\]

(2)

As an example of using Eq. (1), assume that an interacting photon generates 1000 e\(^-\) (\(\eta\)), with 200 e\(^-\) lost to recombination and the 800 e\(^-\) remaining (\(\xi_{\text{pe-1}}\)) split between and collected by two pixels (\(P_{\text{se-1}}\)). For this event, a CCE_I of 0.4 is calculated no matter in what proportion the 800 e\(^-\) are split between the two affected pixels.

To determine the average CCE performance of a CCD for a large number of interacting photons of the same energy, many events are measured for charge loss and splitting and then averaged using the equation

\[
\text{CCE} = \frac{1}{N\eta} \sum_{i=1}^{N} \frac{\xi_{\text{pe-1}}}{P_{\text{se-1}}},
\]

(3)

where \(N\) is the number of photon events sampled.

Equation (3) is used regularly in the laboratory in characterizing the two mechanisms (the partial and split events) responsible for degrading CCE performance of the CCD. However, measuring CCE in the manner described by Eq. (3) requires a considerable amount of data reduction since many events must be integrated. Also, Eq. (3) is usable over only a limited spectral region (typically, \(\lambda < 30 \text{ Å}\)) because for longer wavelengths the signal generated by an individual photon becomes too small compared to the CCD read noise floor to reliably resolve the individual event and determine the amount of charge lost and the number of pixels affected.

In this paper we describe another approach to evaluating CCE performance for the CCD that is applicable to all wavelengths of interest. The new technique (discussed in Sec. 3) is based on the formula

\[
\text{CCE} = \frac{\eta_E}{\eta},
\]

(4)

where \(\eta_E\) is called the effective quantum yield, a quantity that measures the average number of electrons collected by an affected pixel for an interacting photon of energy \(E_\lambda\). The effective quantum yield \(\eta_E\) is related to the partial and split events through

\[
\eta_E = \frac{\xi_{\text{pe}}}{P_{\text{se}}},
\]

(5)

where \(\xi_{\text{pe}}/P_{\text{se}}\) is the average value of the term \(\xi_{\text{pe-1}}/P_{\text{se-1}}\).

3. PHOTON-TRANSFER TECHNIQUE

The ideal CCD, which does not generate split or partial events but exhibits perfect CCE performance, will deliver an effective quantum yield equal to the ideal quantum yield (i.e., \(\eta_E = \eta\)). Today's CCDs are rapidly progressing toward this ultimate goal; however, very strict conditions are placed on the CCD in obtaining such performance, as we shall see in Sec. 4. Because of the various CCD technologies and manufacturers involved in fabricating CCDs, a standard "test tool" for evaluating CCE performance over a very large spectral range is required.

In this section we discuss the technique of photon transfer, a test tool that was used in the past to evaluate CCD performance characteristics in absolute units. It was realized only recently that the photon-transfer technique also can be applied as a standard method for evaluating the CCE performance of a CCD. In the discussion that follows, we first develop the equations necessary to describe the technique.
assuming that we have an ideal CCD camera with no partial
or split event generation. We show that the ideal quantum
yield \( \eta \) can be determined through the photon-transfer
approach. We next examine a typical CCD camera, which
includes partial and split event generation, and show that the
photon-transfer technique gives a reasonable approximation
for the effective quantum yield \( \eta_{\text{eff}} \) defined in Eq. (5), which in
turn is used to calculate the CCE performance of the CCD
[Eq. (4)], at least in a relative sense.

3.1. Ideal CCD camera

Figure 1 is a schematic representation of the overall transfer
function of an ideal CCD camera. The camera can be de-
scribed in terms of five transfer functions, three that are
related to the CCD and two that are related to the external
CCD signal processing circuitry. The input to the camera is
given in units of incident photons, and the final output of the
camera is achieved by encoding each pixel’s signal into a
digital number (DN), typically using 12 to 16 bits. The output
signal \( S(\text{DN}) \) resulting from a given exposure of the CCD
camera shown in Fig. 1 is given by

\[
S(\text{DN}) = P\eta S_{\text{v}} A_{1} A_{2},
\]

where \( S(\text{DN}) \) represents the average signal (DN) over all
affected pixels, \( P \) is the mean number of incident photons per
pixel on the CCD, \( Q_{E} \), is defined as the interacting quantum
efficiency (interacting photons/incident photons), \( \eta \) is the
ideal quantum yield defined by Eq. (2), \( S_{\text{v}} \) is the sensitivity
of the CCD on-chip circuitry (V/e^-), \( A_{1} \) is the electronic gain
of the camera (V/V), and \( A_{2} \) is the transfer function of the
analog-to-digital converter (DN/V).

The quantities \( Q_{E} \) and \( \eta \) are related through

\[
Q_{E} = \eta Q_{E},
\]

where \( Q_{E} \) is the average quantum efficiency (electrons collected/incident photon).

To convert the output signal \( S(\text{DN}) \) into fundamental
physical units, it is necessary to find the appropriate factors to
convert DN units into either interacting photons or signal
electrons. The constants that do this conversion are defined by the
equations

\[
K = (S_{\text{v}} A_{1} A_{2})^{-1},
\]

\[
J = (\eta S_{\text{v}} A_{1} A_{2})^{-1},
\]

where the units of \( K \) and \( J \) are e^-/DN and interacting pho-
tons/DN, respectively. Note that Eqs. (8) and (9) are related
through \( \eta \) by

\[
\eta = \frac{K}{J}.
\]

It is possible to determine the factors \( K \) and \( J \) by measuring
each transfer function in Fig. 1 separately and then combining
these results as in Eqs. (8) and (9). However, because of the
uncertainty in a number of parameters of the CCD (which
prevents us from knowing \( Q_{E}, \eta, \), and \( S_{\text{v}} \) independently), we
cannot in practice directly determine \( K \) or \( J \) to any great
accuracy. Instead, we have developed a simple technique that
requires no knowledge of the individual transfer functions to
determine the factors \( K \) and \( J \).

3.2. Evaluation of constant \( K \)

For the CCD stimulated with photons that generate only one
electron-hole (e-h) pair for each interaction (i.e., \( \eta = 1; \lambda > 3000 \text{ Å} \) ), Eq. (6) reduces to the form

\[
S(\text{DN}) = P\eta_{\text{eff}} S_{\text{v}} A_{1} A_{2},
\]

where \( P = P Q_{E} \) represents the number of interacting
photons per pixel.

The constant \( K \) can be determined by relating the output
signal \( S(\text{DN}) \) to its variance, \( \sigma_{S}(\text{DN}) \). The variance \( \sigma_{S}^{2}(\text{DN}) \)
of Eq. (11) is found using the propagation of errors, which
yields the following equation for the ideal CCD (i.e., perfect
collection and charge transfer):

\[
\sigma_{S}^{2}(\text{DN}) = \sigma_{\eta}^{2} + \sigma_{\text{v}}^{2} + \sigma_{A_{1}}^{2} + \sigma_{A_{2}}^{2} + \sigma_{\text{DN}}^{2},
\]

where we have added in quadrature the read noise floor
variance \( \sigma_{\text{R}}^{2}(\text{DN}) \) [see Fig. 1; \( \sigma_{\text{R}}^{2} = \sigma_{\text{R}}^{2}(e^{-}) K^{-2} \)]

Performing the required differentiation on Eq. (12) and
assuming that the constant \( K \) has negligible variance (i.e.,
\( \sigma_{K}^{2} = 0 \)), we find the following expression for the variance in
\( S(\text{DN}) \):

\[
\sigma_{S}^{2}(\text{DN}) = \left( \frac{\sigma_{\eta}}{K} \right)^{2} + \sigma_{\text{R}}^{2} + \sigma_{\text{v}}^{2} + \sigma_{A_{1}}^{2} + \sigma_{A_{2}}^{2} + \sigma_{\text{DN}}^{2}.
\]

Since \( \sigma_{\eta}^{2} = P \) because of photon statistics, the following
expression for the constant \( K \) in terms of \( S(\text{DN}) \) and \( \sigma_{S}^{2}(\text{DN}) \)
results:

\[
K = \frac{S(\text{DN})}{\sigma_{S}^{2}(\text{DN}) - \sigma_{\text{v}}^{2}} (\lambda > 3000 \text{ Å}).
\]

Equation (14) is a useful expression and can be used, with no
further calibration, to convert output measurements in DN
directly into units of electrons.

3.3. Evaluation of constant \( J \)

For wavelengths longer than 3000 Å, the constants \( K \) and \( J \)
are equivalent [Eq. (10), \( \eta = 1 \) ]. However, as we move into
the UV, EUV, and x-ray regions of the spectrum, multiple e-h
pairs are generated by each interacting photon, resulting in
\( \eta > 1 \) and a decrease in the value \( J \). For these conditions, the
constant $J$ also can be found by relating the output signal $S(DN)$, given by Eq. (6), to its variance $\sigma^2_{S(DN)}$. Through propagation of errors, the variance in the signal for the ideal CCD can be expressed by

$$\sigma^2_{S(DN)} = \left[ \frac{\partial S(DN)}{\partial P_1} \right]^2 \sigma^2_{P_1} + \left[ \frac{\partial S(DN)}{\partial \eta} \right]^2 \sigma^2_{\eta} + \left[ \frac{\partial S(DN)}{\partial K} \right]^2 \sigma^2_{K} + \sigma^2_{S(DN)}.$$

Equation (15) and assuming that the quantum yield $\eta$ has negligible variance (i.e., no partial or split event; $\sigma^2_{\eta} = 0$), we find

$$J = \frac{S(DN)}{\sigma^2_{S(DN)} - \sigma^2_{K}(DN)} \quad (\lambda \leq 3000 \text{ Å}).$$

Equations (14) and (16) form the basis for the photon-transfer technique. By simply measuring the mean signal and its variance for both visible photons and photons at any other specific wavelength of illumination, we can determine the values $K$ and $J$. Once the constants $K$ and $J$ are known, the ideal quantum yield for photons at the wavelength under consideration can be calculated through Eq. (10).

### 3.4. Partial and split events included

Up to this point, we have assumed no partial or split event generation within the CCD (i.e., $\eta_e = \eta$). We now show that the ratio $K/J$ with partial and split events included gives an upper limit for the effective quantum yield $\eta_E$, which in turn gives an upper limit for CCE performance for the CCD as defined by Eq. (4). We also show that as the number of partial and split events within the CCD decreases, the ratio $K/J$ approaches the real value of $\eta_E$ and in the limit $\eta_E$ equals $\eta$, when perfect CCE is achieved.

To analytically solve for the constant $J$ under these conditions, we must give Eq. (6) a new form so that the variances of the partial and split events are included when we consider the overall variance of the signal is calculated. Such an equation for the average signal in any given pixel can be written in the form

$$S(DN) = \Pi_1 M \left( \frac{\tau_{pe}}{P_{se} \eta} \right) K^{-1},$$

where $M$ is the average number of interacting photons per pixel.

It is informative to compare the behavior of the signal given by Eq. (17) to the signal given in Eq. (6) for the ideal CCD camera without partial or split events. The signal described in Eq. (6) is proportional to $\eta$ and is not influenced by CCE characteristics since CCE is assumed to be perfect. In the case of Eq. (17), we find that the signal is proportional to $(\tau_{pe}/P_{se})$ when the number of interacting photons per pixel is small (i.e., $M \approx 1$) and interactions are not adjacent to each other in the CCD array. In this case, the amount of signal measured is dependent on both partial and split event behavior. However, when the number of interacting photons per pixel is large (i.e., $M \approx P_{se}$), the signal is dependent only on the partial event [i.e., $S(DN) = \Pi \tau_{pe} K^{-1}$] and the effects of the split event are averaged out.

It can be shown, again using propagation of errors, that the signal $S(DN)$, given by Eq. (17), and its variance $\sigma^2_{S(DN)}$ are related to the effective quantum yield by

$$\eta_E = K \left[ \frac{S(DN)}{\sigma^2_{S(DN)} - \sigma^2_{K}(DN)} \right]^{-1},$$

where $\sigma^2_{S(DN)}$ is the event-to-event variance in the number of pixels that collect signal electrons per interacting photon and $\sigma^2_{K}$ is the event-to-event variance for the total number of electrons collected. Here, we have assumed that the average of $\tau_{pe-1}/P_{se-1}$ is equal to the average of $\tau_{pe-1}$ divided by the average of $P_{se-1}$, which becomes nearly correct for large numbers of photon events.

Equation (18) also can be written in the form

$$\eta_E = \frac{K}{\epsilon J e},$$

where $\epsilon$ is $P_{se} + 2(\sigma^2_{K}/P_{se}) + P_{se} P_{se} / \epsilon(\sigma^2_{K})$ and $K$ and $J$ are as defined in Eqs. (14) and (16), which we normally measure using the photon-transfer technique.

The true value of the effective quantum yield $\eta_E$ given by Eq. (19) is less than $K/J$ by the factor $\epsilon^{-1}$. As the number of partial and split events decreases, the accuracy of $K/J$ improves and in the limit is exact when $\epsilon = 1$ (i.e., $\eta_E = \eta$). Therefore, when measuring the effective quantum yield using the photon-transfer technique in the presence of partial and split events, the ratio $K/J$ gives an upper limit for $\eta_E$.

For example, for the Texas Instruments (TI) 3PCCD (a CCD type discussed in Sec. 4), we find experimentally that for individual 5.9 keV (Fe$^{55}$) photon events, one out of 11 events splits between 2 pixels, with only a few partial events observed. For this CCD we calculate an average $P_{se}$ of 1.09 pixels with variances $\sigma^2_{P_{se}} = 0.166$ and $\sigma^2_{P_{se}} = 0$. Assuming these values, we find that $\epsilon^{-1} = 0.72$. Therefore, the true value of $\eta_E$ is actually smaller by 0.72 than the value of $\eta_E$ measured using the photon-transfer method (i.e., $K/J$).

Even though the ratio $K/J$ does not give an exact value for the effective quantum yield, this quantity still is useful in evaluating and optimizing CCE performance of the CCD, as we shall see in Sec. 4. Therefore, unless otherwise indicated, we use the ratio $K/J$ as found through the photon-transfer method as our standard measuring tool in comparing $\eta_E$ and CCE performance for different CCDs under different operating conditions, while keeping in mind that the absolute values of these quantities are lower (by $\epsilon^{-1}$).

### 3.5. Photon-transfer curve

The constants $K$ and $J$ can be found directly through Eqs. (14) and (16). We examine the graphical approach first because the method gives insight into the mechanics of the photon-transfer technique.

The constants $K$ and $J$ can be found graphically by plotting a curve (called the "photon-transfer curve") of noise $\sigma_S(DN)$ as a function of signal $S(DN)$, typically for a 20X20 pixel array on the CCD. One such photon-transfer curve is shown in Fig. 2. For this curve we use 7000 Å illumination, which guarantees that $\eta_E = \eta = 1$ and therefore can be used in finding the constant $K$. The abcissa, $S(DN)$, is the average signal level of the 400 pixels with the array uniformly illuminated at some level. (Here, we assume that electrical offset and
dark current were subtracted from the data before the signal level was determined.) The ordinate, σ_D (DN), is the standard deviation of the signal of those 400 pixels at each exposure. The standard deviation is found after the CCD pixel-to-pixel nonuniformity has been removed. This can be accomplished by differencing (pixel by pixel) two frames taken at the same light level, calculating the standard deviation of the resultant difference, and dividing by 2, which yields the desired σ_S (DN).

The read noise σ_R (DN), indicated in Fig. 2, represents the intrinsic noise associated with the readout circuitry, i.e., the CCD on-chip amplifier and any other noise sources that are independent of the signal level. As the signal is increased, the noise eventually becomes dominated by the shot noise of the signal and is characterized by a line of slope 1/2. From Eq. (14) we note that the intersection of the slope 1/2 line of the signal axis [i.e., σ_S (DN) = 1] represents the desired conversion constant K.

The same graphical approach can be used in determining the constant J when η_η > 1 [Eq. (16)]. For example, in Fig. 3 we show three photon-transfer curves (taken with the same CCD camera and CCD) generated from flat fields at wavelengths of 7000 Å, 1216 Å, and 2.1 Å. The corresponding intersections on the signal axis at each of these wavelengths are 2.3, 0.77, and 1.62×10^-3. Since η_η = η_η = 1 for 7000 Å illumination, the signal at σ_S (DN) = 1 for this photon-transfer curve represents the value of constant K (i.e., K = 2.3 e^-/DN). The other two intersections, for the wavelengths 1216 Å and 2.1 Å, represent values for J that can be used in conjunction with K to find η_η (= K/J), yielding an average of 3 e^- and 1420 e^- per affected pixel per interacting photon, respectively.

In the case of 2.1 Å (E_λ = 5.9 keV; η_η = 1610 e^-), the photon-transfer technique yields a K/J of 1420 e^-). An actual η_η of 1215 e^- is readily determined by measuring individual photon events [Eq. (5)], which gives a value for e^- in Eq. (19) of 0.85. From Eq. (4), an upper limit of 0.88 for CCE performance is calculated using K/J found from the photon-transfer curve, while a true CCE of 0.75 is calculated using individual photon events. This level of CCE performance is quite good by today's CCD standards.

### 3.6. Photon-transfer histogram

The accuracy of determining K and J can be improved by using Eqs. (14) and (16) directly (as opposed to the graphical approach used in Sec. 3.5). The signal S (DN) and the noise σ_S (DN) are found from the CCD in the same manner as for the photon-transfer curve discussed above. The read noise σ_R (DN) is found from a dark image. After applying these formulas to many different 20×20 pixel subarrays across the sensor, the resulting values of K (or J) are compiled into a form we call a "photon-transfer histogram." An example histogram using 4000 Å illumination is shown in Fig. 4. It produces a very accurate value of K = 1.5 e^-/DN. Using many 20×20 pixel subarrays allows elimination of those regions on the device that contain blemish artifacts, which give erroneous values for K. Areas that are not well behaved can be easily recognized as data points outside the main histogram, as Fig. 4 shows. A similar histogram also can be generated over the entire CCD array for η_η (= K/J) at a specific wavelength of interest. This type of histogram is quite valuable in characterizing the variability of CCE performance across the array of the CCD. In Sec. 4 we depict the use of histograms of η_η under different operating conditions of the CCD.

### 4. PHOTON-TRANSFER USE

In this section we apply the photon-transfer technique to measuring CCE performance for two different types of CCDs, namely, the thick Ti frontside-illuminated virtual-phase CCD (TI VPCCD) and the thin Ti backside-illuminated three-phase CCD (TI 3PCCD). These devices are discussed in considerable detail elsewhere. The CCDs used in tests discussed here have approximately the same read noise floor, charge-transfer efficiency, and quantum efficiency performance for
the wavelengths used. However, we show that CCE performance for the two CCDs is significantly different owing to the number of partial and split events generated in each device.

4.1. Frontside illumination (TI VPCCD)

In general, we find numerous partial and split events for the thick frontside-illuminated epitaxial CCD. Such a device is schematically represented in Fig. 5, which shows the primary regions within the CCD that are responsible for generating split and partial events. Photons that interact in the substrate region produce a charge cloud that has a high probability of recombination owing to the high concentration of holes in this region and the existence of bulk interface states at the epitaxial interface. The physical size of the charge cloud also is likely to span the boundary between adjacent pixels. Such interactions tend to result in split and partial events. Photons that interact between the epitaxial interface and frontside depletion region also generate split events due to charge diffusion in the field-free region and partial events due to signal charge diffusing through the weak field produced by the p⁺ diffusion into the bulk traps at the epitaxial interface (see Fig. 5).

Figure 6 shows the response of the TI VPCCD uniformly illuminated by an Fe⁵⁵ x-ray source with a mean flux of approximately 1 x ray per 500 pixels. The DN of each pixel on the CCD containing signal charge is measured and appropriately binned in histogram form. Ideally, the response of Fig. 6 should show only two prominent peaks, located at 1150 electron-charge units below these two lines are the result of split and partial events and constitute the majority of the events observed.

Figure 7 shows a histogram of effective quantum yield $n_E$ for a thick frontside-illuminated CCD, showing numerous partial and split events.

4.2. Backside illumination (TI 3PCCD)

For the backside-illuminated CCD, in which the substrate and epitaxial interface are removed (Fig. 8), the number of partial and split events is significantly reduced. It has been demonstrated that an internal QE of 100% can be achieved (i.e., $\eta_i / \eta_i = 1$) for the CCD that is properly thinned and backside treated. The main factor that determines CCE performance for the backside-illuminated CCD is the split event.

To minimize the number of split events for the backside-illuminated CCD, it is important that an electric field of greater than $10^5$ V/cm be provided throughout the entire photosensitive depth of the CCD. Regions in which the field
differences in $\eta_f$ are the result of thinning nonuniformities, where the four corners are physically thinner than the middle of the array because of the thinning method employed.

Figure 14 shows $\eta_f$ histograms for a different TI 3PCCD biased with different frontside depletion voltages ($V_{np}$) across the n-channel and p-substrate. The distance that the edge of the depletion region extends into the substrate is proportional to $V_{np}^2$ and therefore influences the field-free region of the CCD. From these figures we see that the effective quantum yield decreases significantly as $V_{np}$ is lowered due to an increase in field-free material, which causes more diffusion and charge splitting. Figure 15 shows an $\eta_f$ image over the CCD array for $V_{np} = 7$ V; note two distinct areas that correspond to the thin and overly thin regions indicated in Fig. 14(b).

The last $\eta_f$ histogram, shown in Fig. 16, is similar to that of Fig. 10 but has an elevated frontside depletion voltage of $V_{np} = 27$ V and represents the best CCE performance achieved for the TI 3PCCD. For the overly thin region, an average quantum yield of $1420 \text{ e}^- \text{ e}^- \text{ DN}$ was measured, which yields a relative CCD = 0.88. We believe that this limit in CCE performance for the TI 3PCCD is due primarily to two factors: First, the initial cloud diameter size for a 5.9 keV photon event is significant (cloud diameter $\approx 0.6 \mu m$); therefore, charge splitting between the TI 3PCCD’s 15 $\mu m$ pixels occurs even if there is no field-free material. Second, it is known that a field-free region exists beneath the channel stop regions, which allows charge diffusion and charge splitting to occur. Both of these effects are discussed in detail in Ref. 7, where it is shown that increasing the size of the pixel improves the CCE performance further because of these two factors.

5. FUTURE IMPROVEMENTS IN CCE

At this time in the development of the CCD, the backside-illuminated device is superior to the frontside-illuminated device in achieving high CCE performance. This is because the backside-illuminated CCD allows field control over most of the photosensitive volume and elimination of neutral bulk and trapping centers at which photogenerated charge can diffuse and recombine to produce partial and split events.

Improvements in CCE for the backside-illuminated CCD will be made principally in two areas. The first area for
improvement will come from depleting the entire photosensitive volume of the CCD. Although complete depletion already has been demonstrated for the TI 3PCCD in certain regions on the array, depletion extends only a maximum of 7 \( \mu \text{m} \). Therefore, high energy efficiency and cosmic ray background rejection characteristics are still poor for this sensor. Increasing the thickness of the CCD and depleting it fully through deep depletion technology (high resistivity silicon) in conjunction with backside treatment should yield both high CCE and high energy sensitivity for the CCD. Work at several CCD manufacturers has been initiated to accomplish this goal.

Second, larger pixels (\( \sim 30 \mu \text{m} \)) would increase CCE performance further by making a larger “target” for the incoming photon and reducing the effects of the initial event cloud diameter. In addition, a smaller fraction of the pixel is devoted to “overhead” functions such as the channel stop regions, which tend to increase the number of split events by diffusion.
The authors acknowledge many rewarding conversations on the subject of CCE with Morley Blouke (father of the TI 3PCCD), Taher Daud, Andy Collins, Dave Campbell, James DeWitt, Arsham Dingizian, and James McCarthy. We also thank Deborah Durham for reviewing this paper. The research described was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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7. REFERENCES


James R. Janesick: Biography and photograph appear with the Guest Editorial in this issue.

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