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# Quantum Yield Correction for ACS/HRC and ETC implementation.

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## ABSTRACT

*In the ACS/HRC CCD a single UV photon may generate more than one photo-electron. We calculate the theoretical quantum yield and discuss the impact on the calculation of the S/N ratio for an observation in the UV. Without such correction the S/N can be overestimated up to ~18% in the F220W and ~26% at the bluest edge of PR200L. The implementation of the quantum yield correction in the ACS Exposure Time Calculator (ETC) is also described.*

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## Introduction

The first basic functionality of a CCD is the ability to intercept an incoming photon and generate an electric charge. Such a process is known as the photoelectric effect. When a photon is absorbed in the crystalline structure of the silicon, its energy is transferred to an electron that is then excited from the valence band to the conduction band, creating an electron-hole (e-h) pair. If the energy of the photon is less than the energy gap of the silicon ( $E_g$ ) there is simply not enough energy to elevate a valence electron to the conduction band and no e-h pair will be generated.

The energy of a photon of wavelength  $\lambda(\text{\AA})$  is

$$E(\text{eV}) = h\nu = \frac{hc}{\lambda} = \frac{12398.64}{\lambda} \quad (1)$$

Any photon with energy greater than  $E_g$  will generate at least one electron-hole pair during the absorption process. Photons with energy of ~1.1 to ~3.5 eV (11,000 – 3,500  $\text{\AA}$ ) will generate a single e-h pair. More energetic photons may generate multiple e-h pairs if the first generated

photo-electron has enough kinetic energy to generate a cascade of ionizations of other valence electrons (Wilkinson et al. 1983).

The average number of e-h pairs created per absorbed photon of energy  $E(\text{eV})$  is called the **quantum yield ( $\eta$ )**

$$\eta = \frac{E(\text{eV})}{w} \quad (2)$$

where  $w$  is the energy required to generate a single e-h pair and it depends on the temperature  $T$ . Values at room temperature (300K) have usually been in the range 3.62-3.68 eV/e-h. Given that the CCD is operated at cryogenic temperature, the correct value of  $w$  should be calculated. For the following discussion we will follow the same approach used by Don Groom (2004 - available in appendix).

$w$  can be expressed as a linear function band gap energy  $E_g(T)$ :

$$w = a \times E_g(T) + b. \quad (3)$$

Different values for the coefficients  $a$  and  $b$  can be found in the literature (Groom 2004). We will adopt  $a=2.12$  and calculate

$$\Delta w(T) = w(T) - w(300\text{K}) = a[E_g(T) - E_g(300\text{K})] \quad (4)$$

where we will assume  $w(300\text{K})=3.67$  eV and the band gap energy  $E_g(T)$  (in eV) is given by

$$E_g(T) = E_g(0) - \frac{\beta T^2}{T + \gamma} \quad (5)$$

where  $E_g(0)=1.1557$  eV,  $\beta = 7.021 \times 10^{-4}$  eV/K and  $\gamma = 1108$  K.

## The Quantum Yield Correction for HRC

Among the ACS CCD channels, only the HRC extends to the near UV, where the effects of the quantum yield should be taken into account. The operating temperature of the HRC CCD is -81 C (192 K). From Eq. 5 and 6 we can derive

$$E_g(192\text{K}) = 1.1358 \text{ eV}$$

$$\Delta w(192\text{K}) = 0.053 \text{ eV/e-h}$$

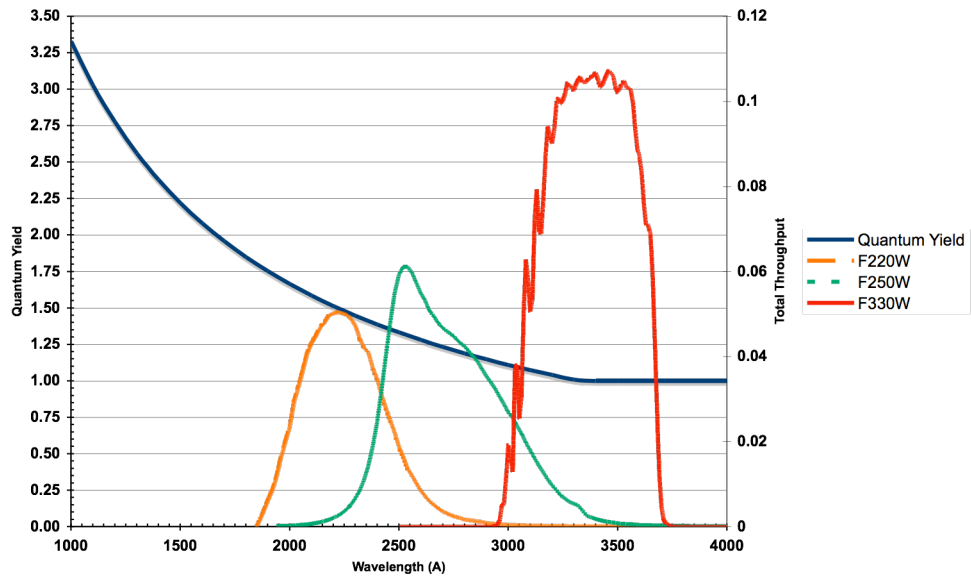
$$w(192\text{K}) = 3.723 \text{ eV/e-h}$$

With the correct value of  $w$  for HRC we can now use Eq. 2 to calculate the theoretical quantum yield listed in Table 1.

Wavelength (Å)	Energy (eV)	Quantum Yield
1000	12.399	3.33
1100	11.271	3.03
1200	10.332	2.78
1300	9.537	2.56
1400	8.856	2.38
1500	8.266	2.22
1600	7.749	2.08
1700	7.293	1.96
1800	6.888	1.85
1900	6.526	1.75
2000	6.199	1.67
2100	5.904	1.59
2200	5.636	1.51
2300	5.391	1.45
2400	5.166	1.39
2500	4.959	1.33
2600	4.769	1.28
2700	4.592	1.23
2800	4.428	1.19
2900	4.275	1.15
3000	4.133	1.11
3100	4.000	1.07
3200	3.875	1.04
3300	3.757	1.01
3400	3.647	1.00
3500	3.542	1.00
5000	2.480	1.00
10000	1.240	1.00

**Table 1 Quantum Yield Correction for HRC**

Only the prism, PR200L, and three broadband filters of the HRC are affected by the correction: F220W, F250W and F330W (Figure 1).



**Figure 1 HRC Quantum Yield Correction and NUV filters**

## Impact on S/N calculation

The Signal to Noise ratio (S/N) computed by the ETC is

$$S/N = \frac{S}{\sqrt{(S + Area * (Sky + Dark + RN^2))}} \quad (6)$$

where S is the source signal, Sky is the background level, Dark is the leakage current, RN is the read noise and Area is the number of pixel used for the photometry. This formula is valid if the noise associated to the quantities S, Sky and Dark is just shot noise. When more than one electron is generated by a single photon such formula is not valid anymore and Eq. 6 should be rewritten as:

$$S/N = \frac{S/\eta}{\sqrt{(S/\eta + Area * (Sky/\eta + Dark + RN^2))}} \quad (7)$$

where  $\eta$  is the quantum yield correction.

For observations that are not read-noise or dark current limited the effective S/N is

$S/N = \sqrt{S/\eta}$  and therefore the correction is  $\frac{1}{\sqrt{\eta}}$ . Such correction can amount up to ~18% in the F220W and ~26% at the bluest edge of PR200L.

## Calculation of the S/N with the ETC

The QE is the number of e-h pairs created and successfully readout by the CCD for each incident photon and it is defined as

$$QE = \eta QE_i \quad (8)$$

where the  $QE_i$  is the interacting quantum efficiency (always  $\leq 1$ ) and  $\eta$  is the quantum yield.

Above  $\sim 3350 \text{ \AA}$   $\eta = 1$  and therefore in the visual and near-IR  $QE = QE_i$ . In order to take into account the quantum nature of the incident flux of photons, the computation of the S/N ratio should be done using  $QE_i$ .

The Exposure Time Calculator for ACS relies heavily on SYNPHOT, the synthetic photometry software package of the Space Telescope Science Data Analysis System (STSDAS). Each request to the ETC is converted and submitted to the SYNPHOT server. By design, the output of SYNPHOT is an estimate of the total count rates expected on the image and such output is retrieved by the ETC and used for the final calculation of the S/N.

All SYNPHOT calculations use a provided QE (not  $QE_i$ ) curve and therefore S/N estimates are overestimated in the UV when based on SYNPHOT alone.

As of 01Sep 2006 the ACS ETC takes into account the quantum yield correction to improve the accuracy of the S/N ratio for UV observations with HRC by using  $\eta$  listed in Table 1 and the

effective wavelength ( $\lambda_{\text{eff}}$ ) of the observation.  $\lambda_{\text{eff}}$  is a source-dependent passband parameter which represents the mean wavelength of the detected photons and can be used to estimate shifts of the average wavelength due to source characteristics (e.g., temperature, reddening and redshift) and it is defined as:

$$\lambda_{\text{eff}} = \frac{\int f_{\lambda}(\lambda)P(\lambda)\lambda^2 d\lambda}{\int f_{\lambda}(\lambda)P(\lambda)\lambda d\lambda} \quad (9)$$

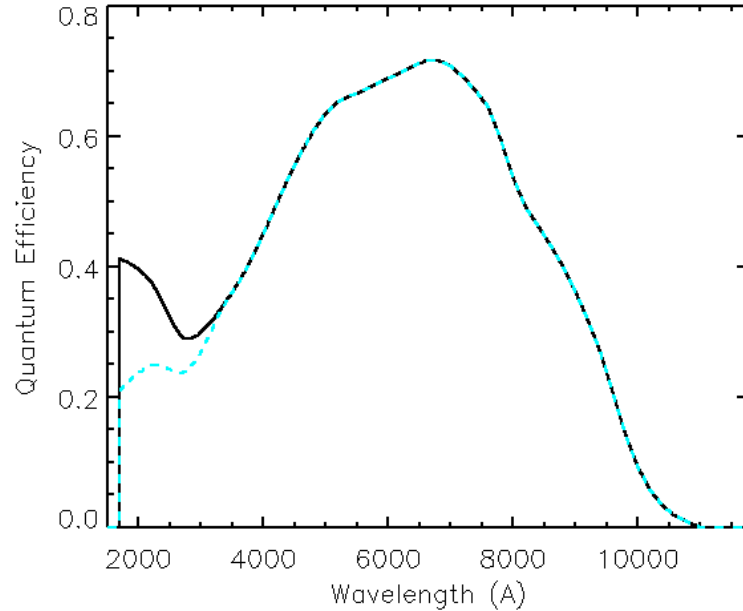
where  $P(\lambda)$  is the total passband transmission curve and  $f_{\lambda}(\lambda)$  is the flux distribution of the object.

For each observation,  $\lambda_{\text{eff}}$  will be used to calculate the value of  $\eta$  to apply in Eq. 7 for the calculation of the S/N. Table 2 shows the effective wavelength and the quantum yield correction for stars in the main sequence. Given that the effective wavelength for the hottest stars in the F330W is above 3350 Å, no correction is required in this filter. Finally, both F220W and F250W suffer from red leak to some extent. In some extreme cases the majority of the flux may be off-band and as a consequence the effective wavelength will be pushed into the red, where  $\eta=1$ . In such cases, no correction is applied to the UV part of the spectrum and the S/N will still be underestimated.

**Table 2 Effective wavelength and ETC Corrective Factor for MS stars**

Spectral Type	F220W		F250W		F330W	
	Effec. $\lambda$	$\eta$	Effec. $\lambda$	$\eta$	Effec. $\lambda$	$\eta$
O3V	2240.2	1.49	2692.4	1.23	3352.3	1.00
O5V	2241.2	1.49	2693.3	1.23	3352.6	1.00
O6V	2242.4	1.48	2695.0	1.23	3353.2	1.00
O8V	2244.3	1.48	2697.6	1.23	3353.9	1.00
B0V	2246.9	1.48	2698.5	1.23	3354.4	1.00
B3V	2256.9	1.48	2720.6	1.22	3360.4	1.00
B5V	2258.9	1.47	2733.8	1.22	3363.8	1.00
B8V	2264.5	1.47	2753.4	1.21	3369.9	1.00
A0V	2280.7	1.46	2779.5	1.20	3377.7	1.00
A5V	2303.2	1.45	2814.9	1.18	3381.8	1.00
F0V	2368.7	1.41	2870.6	1.16	3388.7	1.00
F5V	2505.3	1.33	2926.7	1.14	3396.5	1.00
G0V	2715.6	1.22	2964.2	1.12	3401.8	1.00
G5V	2988.7	1.11	2992.7	1.11	3404.9	1.00
K0V	4182.5	1.00	3078.7	1.08	3411.6	1.00
K5V	7152.0	1.00	3702.5	1.00	3458.6	1.00
M0V	7793.2	1.00	4352.5	1.00	3487.5	1.00
M2V	8068.3	1.00	4694.9	1.00	3493.9	1.00
M5V	8181.8	1.00	4877.9	1.00	3496.9	1.00

In the future, a better correction could be implemented by forcing the ETC to use the  $QE_i$  instead of the QE in SYNPHOT. Figure 2 shows the QE and  $QE_i$  for the HRC CCD.



**Figure 2 Quantum Efficiency (QE) curve (solid-black line) and Interacting Quantum Efficiency (QE<sub>i</sub>) (dashed-blue line) for the CCD of HRC ( $QE = \eta QE_i$ )**

## Testing of the ETC

The addition of a QE correction factor to the ETC affects the UV modes in the Imaging, Spectroscopic and Coronagraphic ETCs. The standard regression suite of tests was run in batch mode (see ISR03-08) for all three ETCs using the new  $QE_i$  curves, no discrepancies were found. The short wavelength filters (F220W, F250W, and F330W) effected by the  $QE_i$  were tested in the Imaging ETC by calculating the corrected source counts and S/N for an O5 and a B5 star and comparing it to the S/N obtained from Eq. 7. The results were consistent. Additional regression testing of the Imaging ETC was performed by calculating the SN for an M2 star and for filters F344N and F435W.

The ETC was used to calculate what S/N is achieved for a 1000 second exposure, using a 1x1 pixel aperture, a cr-split=1 and a gain=1. The standard Kurucz model spectra of O5V, B0V and M2V stars available in the ETC were used. The stars were normalized to 1.0e-18 flam at 5500

Angstroms. Table 3 lists the achieved S/N with the new  $QE_i$  curve with the ETC in column 7. For comparison the source counts and the sky counts obtained using the SYNPHOT QE curve are in columns 3 and 4 respectively. Column 5 lists the corresponding value for  $\eta$  for the effective wavelength of the star/filter combination (taken from Table 2). For all of these calculations the dark current value was 3.72 and the read noise was 4.6. Column 6 lists the calculated S/N from eq. 7 using the QE based values.

**Table 3 Imaging ETC Testing Results**

<b>Spectral Type</b>	<b>filter</b>	<b>Src</b>	<b>sky</b>	<b><math>\eta</math></b>	<b>S/N from Eq. 7</b>	<b>ETC Corrected S/N</b>
<b>O5V</b>	F220W	532.03	0.08	1.48	18.30	18.30
	F250W	453.44	0.25	1.23	18.55	18.55
	F330W	437.41	0.57	1.00	20.28	20.28
	F344N	42.22	0.06	1.00	5.15	5.15
	F435W	793.58	5.21	1.00	27.65	27.65
<b>B0V</b>	F220W	410.12	0.08	1.48	15.93	15.93
	F250W	367.54	0.25	1.23	16.60	16.60
	F330W	373.28	0.57	1.00	18.65	18.65
	F344N	36.13	0.06	1.00	4.62	4.62
	F435W	760.89	5.21	1.00	27.05	27.05
<b>M2V</b>	F220W	0.04	0.08	1.00	8.33e-3	8.33e-3
	F250W	0.18	0.25	1.00	0.04	0.04
	F330W	3.95	0.57	1.00	0.73	0.73
	F344N	0.42	0.06	1.00	0.08	0.08
	F435W	152.99	5.21	1.00	11.31	11.31

## Conclusions

We calculated the theoretical quantum yield for the ACS HRC CCD detector and discuss the impact on the calculation of the S/N ratio for an observation in the UV. Without such correction the S/N can be overestimated up to ~18% in the F220W and ~26% at the bluest edge of PR200L. A basic correction has been implemented and tested in the ACS Exposure Time Calculator (ETC).

## Acknowledgements

We thank Tom Brown for suggesting us to improve the accuracy of the ACS ETC. Donald McLean for the implementation of the quantum yield correction in the ETC and Kailsh Sahu, Ron Gillilands for helpful discussions and comments.

## References

Groom, D 1994 [www-ccd.lbl.gov/w\\_Si.pdf](http://www-ccd.lbl.gov/w_Si.pdf) (available in Appendix 2)

Wilkinson, F., Farmer, A., and Geist, J. 1983, J. Appl. Phys, 54, 1172.

## APPENDIX 1

### *Constants and Conversions*

h	$6.6262 \times 10^{-34}$	J sec	Plank's constant
C	$2.997925 \times 10^{10}$	cm sec <sup>-1</sup>	Speed of light
eV	$1.6022 \times 10^{-19}$	J	Electron volt

## APPENDIX 2 (attachment)

## Temperature dependence of mean number of of e-h pairs per eV of x-ray energy deposit

Don Groom  
14 December 2004

The conversion factor from ADU to e-h pairs in a CCD is commonly obtained using x-rays of known energy from a calibration source such as  $^{55}\text{Fe}$ . Absolute quantum efficiency (QE) is obviously dependent upon this number, so its systematic uncertainty is one of the many encountered in trying to make an absolute measurement QE. The factor is usually given as  $w = 3.65$  eV/e-h, but this is a room-temperature (300 K) value. It is dependent upon the silicon indirect bandgap energy, which increases significantly as the CCD is cooled. The room-temperature value is obviously not correct for CCD's operated at 130–170 K.

The conversion factor  $w$  has been measured for decades, usually at room temperature but sometimes at cryogenic temperatures. Values at 300 K have usually been in the 3.62–3.68 eV/e-h range. ICRU 31 (1979) [1] gives  $3.68 \pm 0.02$  without references. In a recent paper Scholze *et al.* report  $3.66 \pm 0.03$  [2]. Since there is no way to sensibly decide how to weigh the many results, we take these two as the more dependable and somewhat arbitrarily choose  $3.67 \pm 0.03$  eV/e-h.

Measurements of  $w$  at cryogenic temperatures are sparse. Ryan [3] reports  $w = 3.631$  eV/e-h at 300 K and 3.745 at 100 K. The EG&G Ortec catalog [4] gives 3.62 at room temperature and 3.72 at 80 K.

Both theoretically and experimentally,  $w$  can be represented by a linear function of the indirect bandgap energy, [5,6]

$$w = a E_g + b ,$$

which can conveniently be rewritten as

$$\Delta w(T) = w(T) - w(300 \text{ K}) = a [E_g(T) - E_g(300 \text{ K})] .$$

Varshi [7] proposed expressing the indirect bandgap energy  $E_g$  in silicon as a function of temperature  $T$  by \*

$$E_g(T) = E_g(0) - \frac{\beta T^2}{T + \gamma} .$$

For silicon,

$$\begin{aligned} E_g(0) &= 1.1557 \text{ eV} \\ \beta &= 7.021 \times 10^{-4} \text{ eV/K} \\ \gamma &= 1108 \text{ K} . \end{aligned}$$

With these constants,  $E_g(300 \text{ K}) = 1.1108$  eV. Many values very close to this, for example 1.12 eV (commonly) and 1.107 eV (Handbook of Chemistry and Physics) can be found.

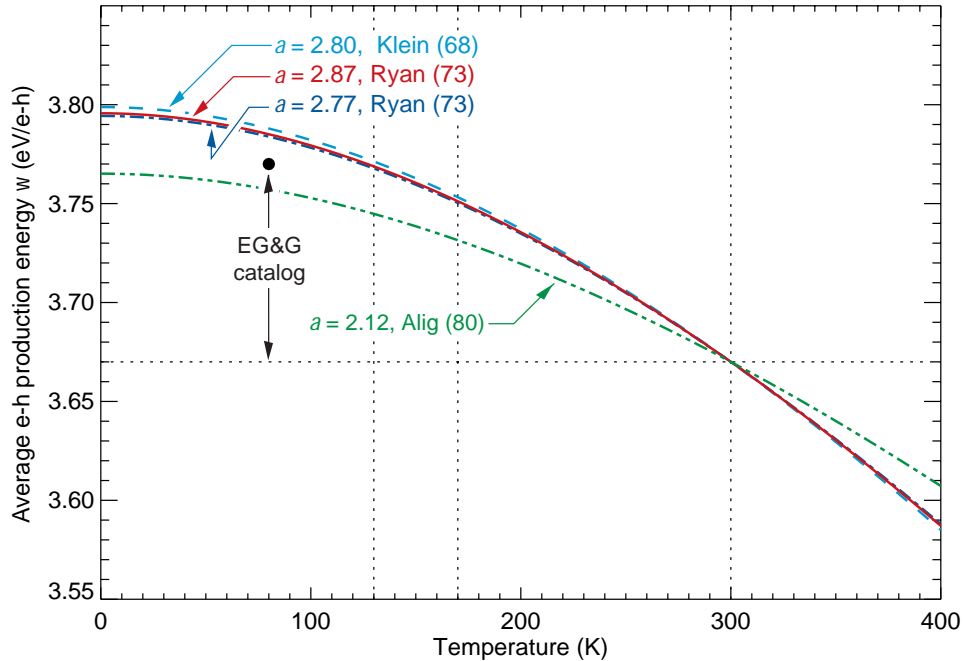
Different papers—most demonstrating the linear behavior of  $w(E_g)$ —find surprisingly different values for  $a$ .  $b$  is of course highly correlated with  $a$ , but since we are only interested in  $\Delta w$ , it doesn't matter much.

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\* His expression is a little more accessible in Refs. [8] and [9].

Table 1

Paper	Material	$a$	Plotted?	$\Delta w$ (130 K)	$\Delta w$ (170 K)	Comments
Klein 68 [5]	Many	14/5	Yes	0.099	0.081	Theory, fits data shown
Key 71 [10]	Si	2.80	No	0.099	0.081	$^{241}\text{Am}$ 5.48 MeV $\alpha$ 's
Canali 72 [11]	Si	2.15	No	0.076	0.062	$^{241}\text{Am}$ 5.48 MeV $\alpha$ 's
Ryan 73 [3]	Si	$2.87 \pm 0.07$	Yes	0.101	0.083	Detector 1, $^{207}\text{Bi}$ $\gamma$ 's
	Si	$2.77 \pm 0.08$	Yes	0.098	0.080	Detector 3, $^{207}\text{Bi}$ $\gamma$ 's
	Si	$1.83 \pm 0.08$	No			Detector 1, $^{241}\text{Am}$ $\alpha$ 's
	Si	$1.77 \pm 0.08$	No			Detector 3, $^{241}\text{Am}$ $\alpha$ 's
Alig 80 [6]	Many	2.73	No			Claimed from Klein (68) [5]
		1.6	No		1.89	Their calc., text, section III C
		2.12	Yes	0.075	0.061	My fit to data they show

Figure 1.  $w(T)$  for selected values of  $a$ .

A list of values for the coefficient  $a$  is given in Table 1. In some cases [5,6] a survey of room-temperature bandgap energies spanning 0.7–5.5 eV were used. In the case of silicon, data were obtained as a function of temperature for ( $T \leq 300$  K). Measurements were obtained by exposing a Si(Li) detector to either a  $^{207}\text{Bi}$   $\gamma$ -ray source or to a  $^{241}\text{Am}$   $\alpha$ -particle source. While it was first thought that the detector response should be the same, this is not the case. The mechanism is not understood. Part of it is probably recombination in the relatively long time it takes the very highly ionized column to disperse; to the extent this is true the unreported conductivity of the silicon is at play.

Nor are the results using  $\gamma$ - or  $\alpha$ -sources consistent among themselves. As can be seen from the Table,  $2.12 \leq a \leq 2.87$  for  $\gamma$  (or, equivalently, electron) irradiation and  $1.77 \leq a \leq 2.80$  for  $\alpha$ 's. Figure 1 shows  $w(t)$  for the cases marked as “Plotted” in the Table.

Experiments by Dodge *et al.* (66) [12] showed that  $w$  was constant to within about 0.02% for 6–77 K, which is more or less consistent with the slowly varying behavior of  $E_g$  in this range.

A 1994 EG&G-Ortec catalog [4] suggests  $w(300\text{ K}) = 3.62\text{ eV}$  and  $w(80\text{ K}) = 3.72\text{ eV}$ , or  $\Delta w(77\text{ K}) = 0.10\text{ eV/e-h}$ . References are not given. The value  $w(77) = 3.67 + 0.10$  is shown in the Figure.

A curious 1968 paper [13] by a Lawrence Berkeley Lab group presents beautiful data indicating a *linear* dependence of  $w(T)$  on temperature. This result is at variance with everything else in the literature, and we have been unable to find the resolution that must have occurred.

The situation is less than satisfactory, but it is probably safe to say  $2.12 \leq a \leq 2.80$  for x-rays,  $\gamma$ 's, and electrons incident on silicon. This reflect into  $\Delta w = 0.075$  to  $0.099\text{ eV/e-h}$  at  $140\text{ K}$  and  $\Delta w = 0.061$  to  $0.081\text{ eV/e-h}$  at  $170\text{ K}$ , the temperature range appropriate to CCD's used in astronomy. This is about a 2% effect if  $\gamma$ - or x-ray emitting radioactive sources are used, large enough to produce a significant systematic error in absolute quantum efficiency.

In conclusion: Based upon data presently available, I recommend  $w = 3.76\text{ eV/e-h}$  at  $-140^\circ\text{ C}$  and  $w = 3.74\text{ eV/e-h}$  at  $-100^\circ\text{ C}$ .

I thank Chris Bebek for suggesting the method and many of the references.

1. ICRU Report 31, "Average Energy Required to Produce an Ion Pair," (1979).
2. F. Scholze, H. Rabus, & G. Ulm, J. App. Phys. **84**, 2926–2939 (1998); F. Scholze, H. Henneken, P. Kuschnerus, H. Rabus, & G. Ulm, Nucl. Instrum. Methods **A439**, 208–215 (2000);.
3. R. D. Ryan, IEEE Trans. Nucl. Sci. **NS-20**, no. 1, 473–480, Feb. 1973.
4. EG&G Ortec, "Modular Pulse-Processing Electronics and Semiconductor Radiation Detectors," #95 (November 1994).
5. C. A. Klein, J. Appl. Phys. **39**, 2029 (1968).
6. R. C. Alig, S. Bloom, & C. W. Struck, Phys. Rev. **B22**, 5565–5582 (1980).
7. Y. P. Varshni, Physica **34**, 149 (1967).
8. K. Rajkanan, R. Singh, & J. Schewchun, Solid-State Elec. **22**, 793–795, (1979).
9. S. M. Sze, *Physics of Semiconductor Devices*, John Wiley & Sons, (1969).
10. J. R. Key & T. A. Rabson, IEEE Trans. Nucl. Sci. **NS-18**, no. 1, 473–480, 1971.
11. G. Canali *et al.*, IEEE Trans. Nucl. Sci. **NS-19**, no. 4, 9–19, Aug. 1972.
12. R. W. Dodge, S. R. Domen, T. F. Leedy, & D. M. Skopik, Phys. Rev. Lett. **17**, 653 (1966).
13. R. H. Pehl, F. S. Goulding, D. A. Landis, & M. Lenzlinger, Nucl. Instrum. Meth. **59** (1968).