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AND9198/D

Conversion of Light to Electronic Charge

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APPLICATION NOTE

Introduction

This primer is intended for those involved with CCD image sensing applications wishing to obtain additional insight into the mechanisms of CCD sensor principles and operations. It is not intended to provide an exhaustive study into the detailed theory behind the subject and it is assumed that a silicon based CCD is used unless otherwise stated. It is also assumed that a conventional front illuminated detector system is employed. Further reading references are listed.

The conversion of light or photons to electronic charge is dependent on many factors. Electronic charge in this case represents electrons that are excited from the silicon valence band to the conduction band due to a reaction between the silicon and the impending light. There are many factors in determining how much charge is generated for a given source of light. A description of the major dependent factors proceeds as follows.

Dependence on Wavelength or Photon Energy – First Order Analysis

An electron can be excited to the conduction band and thus become mobile from an incoming photon if the energy of the photon (*Eph*) is greater than or equal to the band gap energy (*Eg*) of the material. Specifically:

$$E_{ph} \geq E_g \qquad \text{(eq. 1)}$$

and

$$E_{ph} = hv = \frac{hc}{\lambda} \qquad \text{(eq. 2)}$$

where *h* is Planck's constant, *v* is the frequency, λ is the wavelength and *c* is the speed of the light. This is known as the photoelectric effect. An important aspect of this effect is that a critical wavelength exists (λ_c) in which no electrons can be created for a given material. This critical wavelength is given by:

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{\lambda E_{g(eV)}}\ [\mu m] \qquad \text{(eq. 3)}$$

For $\lambda \geq \lambda_c$, the photon has insufficient energy to excite an electron from the valence band to the conduction band and is illustrated as hv_7 in Figure 1.

In this case the photon passes completely through the material. For intrinsic silicon:

$$E_g = 1.12\ eV \text{ and } \lambda_c = 1.11\ \mu m\ [infrared] \qquad \text{(eq. 4)}$$

For extrinsic or doped silicon, energy levels can exist within the forbidden region thereby decreasing the effective band gap. This enables longer wavelength photons sufficient energy to generate a free electron.

The number of electrons created for a given wavelength of light, therefore, will be a linear function of the number of photons per unit time and per unit area. To first order we can assume that for every photon $\lambda \leq 1.11\ \mu m$ reaching a piece of silicon, a corresponding electron is created.

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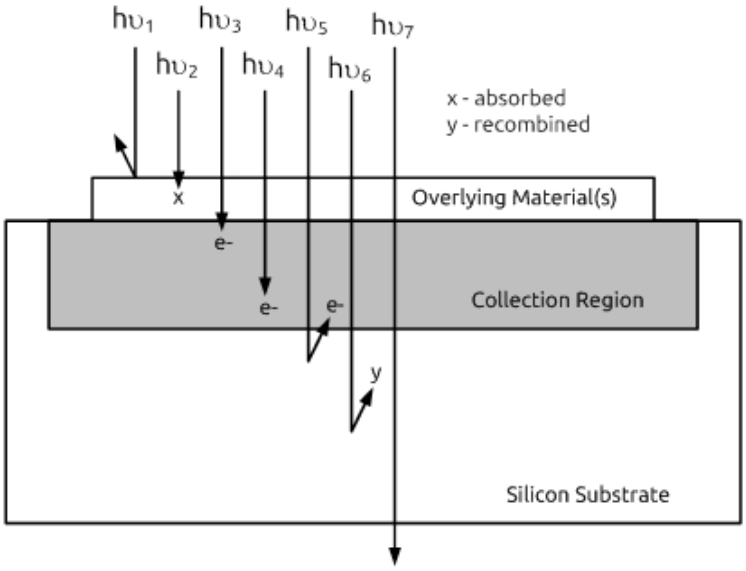

Figure 1. Photon Interactions with Silicon

Non−Linearities in the Conversion Process − Second Order Effects

There are deviations in the pre−described theory which degrade the efficiency of the charge generation process such that an incomplete conversion of photons to signal electrons occurs. This degradation is characterized by a figure of merit called the Quantum Efficiency (η). Quantum efficiency is one of the most important parameters used to evaluate the quality of a detector and is often called the spectral response to reflect its wavelength dependence. It is defined as the number of signal electrons created per incident photon. In some cases it can exceed 100% (i.e. more than one electron created per incident photon). For silicon based CCD's incorporating traditional photosensing elements (photocapacitors or photodiodes) the quantum efficiency is generally assumed to be limited to 100% at wavelengths greater than ~400−450 nm. At wavelengths less than this value, the photon energy is sufficiently large to excite multiple electrons into the conduction band and is sometimes referred to as an electron 'cloud'.

Quantum Efficiency is used to calculate the detector's responsivity which is typically represented in terms of Amps/Watt or $e^{-}/\mu J/cm^2$. The conversions from quantum efficiency to responsivity are shown below.

$$R = \frac{q\lambda\eta}{hc}\ [\text{Amps/Watt}] \qquad \text{(eq. 5)}$$

or

$$R = \frac{\lambda\eta A_p}{hc}\ [e^{-}/\mu J/cm^2] \qquad \text{(eq. 6)}$$

where q is the electronic charge, η is the quantum efficiency and A_p is the pixel area.

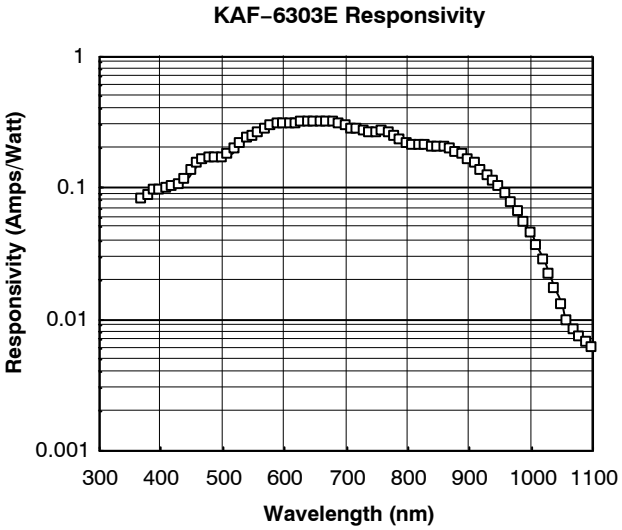

Figure 2.

Examples of quantum efficiency and responsivity curves of a photocapacitor device are shown in Figure 3 and Figure 4 In both of these cases, the KAF−6303 Image Sensor (a Full−Frame Transfer CCD) is represented. Figure 4 shows a representative quantum efficiency curve of a small aperture photodiode detector taken from the KLI−2113 Image Sensor (a Linear CCD). Note the differences. The quantum efficiency can vary drastically depending on many factors such as:

Absorption Coefficient (α)

This parameter is expressed in units of cm^{-1} and relates to how far into the material an incident photon will travel

before being absorbed by the lattice, creating an electron. α is strongly dependent on wavelength. The shorter wave−lengths (higher energy) photons are absorbed nearer the material's surface than the longer wave−length (lower energy) photons. For deep blue light (400 nm), α for silicon is 50,000 cm^{-1} and penetrates or is absorbed at an average depth of about 0.2 μm from the silicon surface – see hv_3 of Figure 1. For red light (650 nm), α = 3000 cm^{-1} and is absorbed at an average depth of about 3.33 μm from the surface – see hv_5 of Figure 1. If the absorption coefficient is too high or too low, the electron may be created in a region where it cannot be eventually collected as usable signal thus reducing quantum efficiency.

Recombination Lifetime (τ)

Photon−inducted electrons have a finite time in which they are mobile within the silicon lattice before they transition back into the valence band. The time constant for this process is called the recombination lifetime τ and is dependent on the quality of the silicon and its dopant density. Longer lifetimes increase the probability of signal electrons to be captured and readout of the device thereby increasing quantum efficiency.

In the case of an electron being generated outside of the collection region (see hv_5 of Figure 1), thermal diffusion, coupled with long recombination lifetimes, enable the signal to be collected. Recombination can occur directly by a transition from the conduction band to the valence band yielding a photon. Direct recombination, however, has low probability in silicon devices compared to indirect recombination which occurs through impurity dopants, phonons and lattice defects in the silicon. This process yields heat rather than a photon.

Typically a sensor has, as part of its design, a 'denuded zone' region within the first few microns of the silicon surface which are free of lattice defects and oxygen precipitates. This region has high recombination lifetimes. The bulk however, is heavily populated with crystal defects and has very short lifetimes. Long wavelengths, which generate electrons deeper in the bulk, then have high probability of being recombined because of short lifetimes thus reducing quantum efficiency. This is illustrated by hv_6 of Figure 1.

At the silicon surface, which is always populated with additional defect sites due to incomplete lattice bonds, the electron lifetime is significantly reduced in this region as well. This is an effect called surface recombination and greatly reduces the quantum efficiency of the lower wavelength photons.

Diffusion Length (L_n)

The diffusion length, L_n, represents the average distance a photo−induced electron will travel before recombining. A situation can occur in which an electron is created in a region that supports high lifetime but needs to be moved to the predefined collection area. In this case, one must depend on transport mechanisms for the electron to reach the desired region. These mechanisms consist of thermal diffusion (via carrier gradients) and drift in the presence of electric fields.

Carrier gradients occur when excess carriers of one kind (electrons in this case) are localized in a region at which point they have a tendency to move or diffuse to regions of lower concentrations. As the temperature increases, this process is accelerated. The expression for thermal diffusion can be expressed as:

$$J_{diff} = qD_n \frac{dn(x)}{dx} \ [A/cm^2] \qquad \text{(eq. 7)}$$

where J_{diff} is referred to as the diffusion current density of electrons, q is the electronic charge, D_n is the electron diffusion coefficient and $n(x)$ represents the electron density as a function of distance. Drift, on the other hand, refers to the migration of carriers due to an electric field and can be expressed as:

$$J_{drift} = q\mu_n n(x)E(x) \ [A/cm^2] \qquad \text{(eq. 8)}$$

where J_{drift} refers to the drift current density of electrons, μ_n represents the electron mobility in silicon and $E(x)$ is the electric field as a function of position. Therefore, a sensor can improve quantum efficiency by tailoring the doping profiles and electric fields allowing electrons to migrate to the desired collection regions. This, again, can be illustrated by hv_5 and hv_6 in Figure 1 where the photon generated electron drifts and diffuses before reaching the collection region (hv_5) or recombining (hv_6).

In the neutral substrate, the recombination lifetime (τ) and electron diffusion length (L_n) are related by:

$$L_n = \sqrt{D_n \tau} \ [cm] \qquad \text{(eq. 9)}$$

Overlying Material(s)

CCD image sensors are fabricated with materials (e.g. silicon dioxide, polysilicon, nitrides, etc.) overlying the silicon. These materials are added to keep unwanted impurities out of the silicon or, in the case of frame transfer or full−frame transfer architectures, are necessary for reading the collected charge out of the device. Ideally, one would want these materials to be transparent, but the light (depending on wavelength) can be absorbed or reflected by the material, thus decreasing the number of photons that actually reach the silicon. This reduces quantum efficiency and is illustrated by hv_1 and hv_2 in Figure 1 where the photons have been reflected or absorbed, respectively. The absorption or transmittance of the material varies with the thickness and refractive index. Thus, it is common to optimize the material's optical parameters to obtain the highest transmittance for the desired spectral region.

Other overlying materials could be color filter arrays (CFA) which act as bandpass filters and are designed to absorb or reflect wavelengths outside of the predetermined wavelength band. Within the band, the material is intended to be transparent within the limits of the optical properties of the material.

In summary, the quantum efficiency can be affected by many factors. These include the absorption depth of the photon before creating the electron, the recombination lifetime of the photon induced electron (which is related to the diffusion length), and the effect of any overlying material(s). Without the aid of sophisticated modeling programs, it becomes difficult to predict the overall quantum efficiency of the sensor.

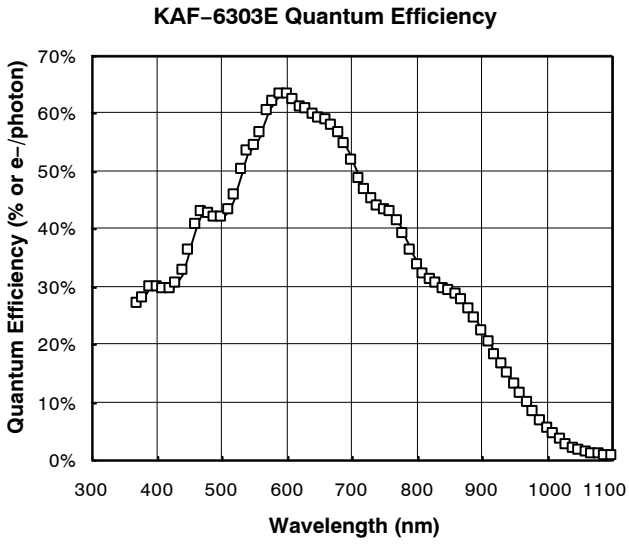

Figure 3. KAF−6303 Quantum Efficiency Curve

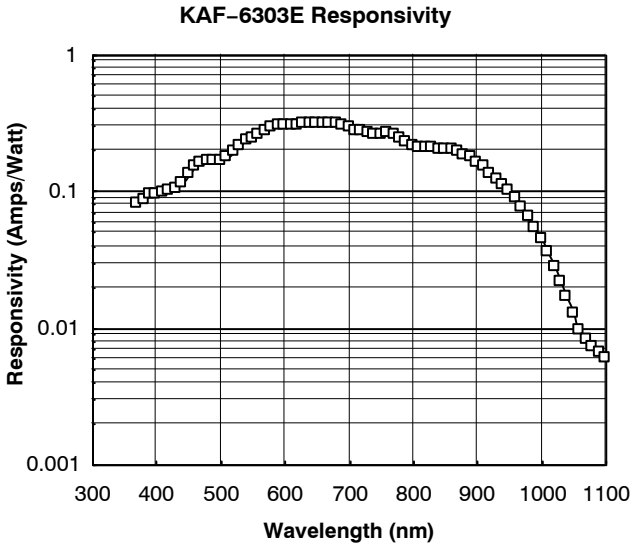

Figure 4. KAF−6303 Responsivity Curve

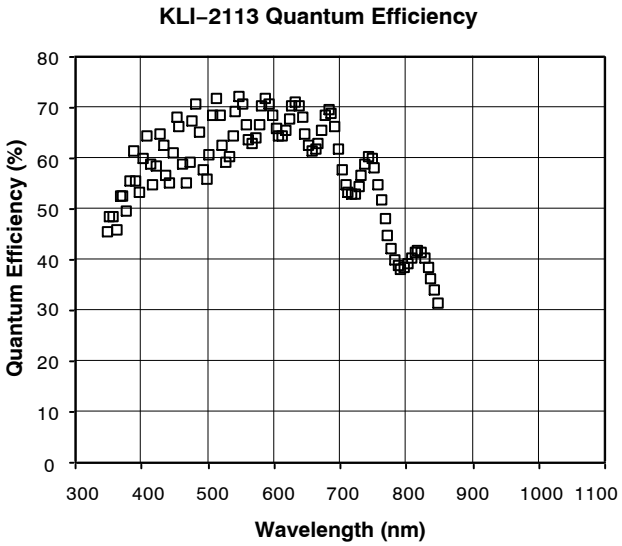

Figure 5. KLI−2113 Quantum Efficiency Curve

References

S.M. Sze, Physics of Semiconductor Devices, 2nd Edition, Wiley−Interscience, 1981, ISBN 0−471−05661−8

B.G. Streetman, Solid State Electronic Devices, 2nd Edition, Prentice Hall, 1980, ISBN 0−13−822171−5

E.L. Dereniak, D.G. Crowe, Optical Radiation Detectors, John Wiley & Sons, 1984, ISBN 0−471−89797−3

R.S. Muller, T.I. Kamins, Device Electronics for Integrated Circuits, John Wiley & Sons, 1977, ISBN 0−471−62364−4

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