Design and Fabrication of Integrated Image Sensors

Richard Hornsey

Electrical and Computer Engineering

University of Waterloo

Waterloo, Ontario, Canada

Course Overview

- **Course aimed at wide coverage**
  - » draws together all aspects, from fundamental principles to system level
  - » enough background for the general audience
  - » with up-to-date examples from the literature for the specialist
  - » in order to provide, as far as possible, a self-contained reference
- **Part I – background material**
  - » applications & general requirements
  - » optical detection with semiconductors
- **Part II – technology and pixel design**
  - » CMOS technology & scaling
  - » passive & active pixels; photodiodes & photogates
- **Part III – noise and noise reduction**
- **Part IV – single-chip imaging systems**
  - » basic array operation, electronic shutter, A-to-D
  - » advanced focal plane processing; colour sensors, dynamic range enhancement, motion detection
  - » artificial retina, biologically inspired architectures

Part I:
Background
and
Principles of Optical Detection

Introduction

- **In this first section of the course, we will consider some of the applications of electronic cameras in general**
  - » from this, we will gain an idea of the factors that will be important when it comes to the camera design
- **This section also serves to illustrate the motivation for studying electronic cameras, and integrated cameras in particular**
  - » of course, specific requirements will depend on the application, but we still need to know what design trade-offs we are making
- **Subsequently, we will examine how light is detected by semiconductor devices**
  - » firstly, the general principles
  - » then the photodiode and MOS capacitor in particular
- **In the next section of the course, we will discuss the detailed design of these sensors, and how they are fabricated**

Why use electronic cameras at all?

- **The main reason for choosing a solid-state camera is to interface it with other machines, in particular digital analysis, recording or transmission systems, and which are very limited in the type and speed of operations they can perform**
    - » although humans seem to manage well enough ...
- **In many cases, we are also seeking “super-human” performance from the camera, e.g.**
    - » high speed and repeatability
    - » precise metrology (i.e. high resolution)
    - » extended wavelength sensitivity
    - » harsh operating conditions
    - » small size and power consumption
- **In essence, a solid-state camera has analogous advantages and limitations in comparison to the human eye as a digital computer has in comparison to the human brain**

Video

- **For CCDs, the annual market is more that 10 million units, mostly for consumer electronics such as camcorders, with Sony being the major manufacturer**
- **For this type of application, important features include:**
  - sensitivity to low light levels (no control over environment)
  - reasonable image quality
  - low power consumption
- **The Handycam has a sensitivity of about 10 lux**
  - 1 lux ≈ 300 photons/(s μm^2)
  - typical office illumination ~ few hundred lux
  - the range of photon fluxes (ratio of max. to min. values) in a typical scene is approximately 10^6
- **However, the sensor itself occupies only a small part of the camcorder; we also need:**
  - clocking and other timing signals, amplifiers, encoding to standard TV formats
- **It is this need for several components in the imaging “chain” that makes the idea of a fully integrated camera-on-a-chip so appealing**

- **The major manufacturer of basic integrated video chips is currently VLSI Vision Ltd. from Edinburgh, UK**
    - approx. 100,000 chips per month
    - all timing, control, and encoding circuitry on-chip
    - colour versions available
    - cost is <$10 per chip
    - main markets are toys, and other low-cost applications
- **The number of companies offering similar products is increasing rapidly, and major players include Kodak/ Motorola, Toshiba, Olympus, Fuji, Hewlett-Packard, Intel, AT&T, Rockwell, National Semiconductor ...**

Digital Still Camera

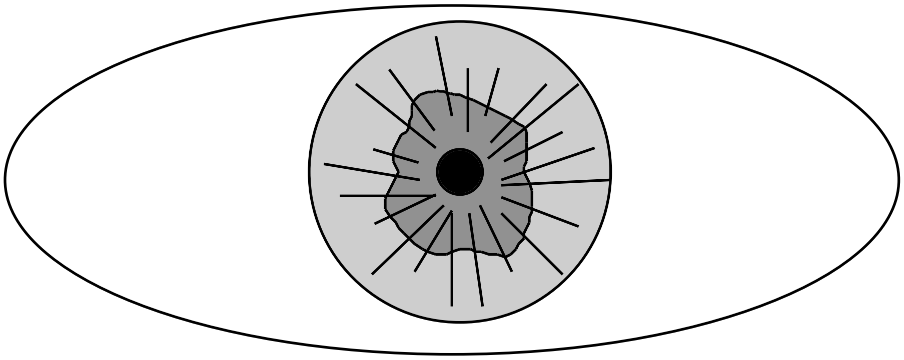
- **It is estimated that the market for digital replacements for regular film cameras is now about US$2 billion per year**
- **For this to be acceptable, the resolution must be > ~1000 x 1000, so-called “mega-pixel” arrays**
  - » approx. 2000 x 2000 needed to compare with film
- **CCD cameras are typically 1024 x 1024; CMOS integrated cameras chips announced include:**
  - » 1024 x 800 colour (VLSI), 2048 x 2048 mono (IMEC), 1318 x 1030 (Toshiba)
- **In these applications, the main difficulty with such large arrays is getting a high enough yield to keep the cost reasonable**
- **The first consumer colour CMOS digital camera was announced in November 1997 by SoundVision Inc., named the SVmini-209**
  - » uses VLSI vision 1000x800 CMOS chip
  - » 1MB DRAM & 1MB memory, DSP and noise reduction
  - » 4 - colours: RGB and “teal”, to correct for the dyes in this process not being a good match to the human eye
- **Advantages over CCD-based systems are lower cost, integration, and extended battery life**

Security Applications

- **Most security systems are some form of video camera system, so the above comments still apply**
- **However, there is a move to "remote" security**
  - » e.g. dial-up cameras in bank ATM rooms
- **If the image capture system could be made cheap enough, the applications expand**
  - » camera in every bank ATM
  - » 80% of bank machine frauds are by people borrowing cards from family members!
- **So here speed and image quality are secondary to integration, cost, and perhaps some signal processing/compression**
- **Military research by the US Army aims to produce a chip that:**
  - » stores 10,000 images on-chip
  - » smart circuits and image processing
  - » battery powered
- **Something like this would clearly have many civilian uses as well!**

Biometrics

- **One of the “holy grails” for security applications is biometric measurement**
  - » fingerprints (early VLSI Vision design ...)
  - » facial recognition
  - » measurements of patterns in the iris of the eyes
  - » retinal measurements
  - » infrared measurements of veins in the hands
- **Salient features of the image are extracted and stored as records**
  - » which may be only ~256 bytes long for irises
  - » And maybe 1kbyte for fingerprints



- **It is widely believed that CMOS integrated cameras offer the best hope for widespread biometric security systems**

Video Communications

- **For a long time, one of the most advertised applications for integrated cameras has been for video conferencing and video-phones**
- **The integration would allow built-in data analysis and compression**
  - » compression for moving images is difficult in hardware. MPEG is too complex
  - » the solution proposed is to use JPEG encoding (which is available in hardware) and later to re-build the moving image
- **Another possible data-reduction technique is to detect and transmit only regions of the image that have changed since the last frame**
  - » thus backgrounds are only transmitted infrequently
  - » but the speaker is seen at full speed
- **Current video phones operate at about 4 frames per second**
  - » mainly limited by the restricted bandwidth of the telephone line (H.26x communication standard)
- **Video conferencing and “telepresence” – remote office environments – are also becoming popular**

Industrial Inspection

- **The range of application of industrial inspection is truly staggering – almost everything you buy will have been inspected by machine**
  - presence and orientation of labels etc. (important for store shelf display)
  - presence of contents & caps (e.g. pills in bubble packs, bottle caps)
  - size, shape and colour of fruit & vegetables
  - damage to glass bottles (indicating possible splinters in the bottle)
- **But before this final stage, the objects themselves will probably have been checked**
  - Sorting of objects on conveyors
  - Quality control (e.g. defects on rolls of paper, cloth)
  - Alignment and orientation of objects for assembly
  - Contamination and surface defects (e.g. optical components, semiconductor wafers)
  - Checking of welds and solder joints
  - Optical Character Recognition (e.g. postal codes on mail)

Space Applications

- **Solid-state cameras are particularly attractive for the space industry because**
  - » small and lightweight
  - » robust (10g acceleration on launch!)
  - » low power consumption
- **Usually, the cameras were monochrome, and used coloured filter wheels to build up colour images. Now full-colour cameras are used**
  - » e.g. Mars Pathfinder in 1997
- **Many space applications are more for guidance than for photography**
  - » inter-satellite communications (laser & camera keep satellites correctly oriented)
- **Satellite attitude control can be carried out with respect to fixed objects, such as the stars or the Earth**
  - » e.g. CMOS electronics for readout of IR detectors
- **Electronics for space applications must be “radiation hard”**

So What is Important?

- **From the above brief overview of some of the applications of solid-state cameras, what types of performance figures of merit might be relevant?**
  - for camera system?
  - for array itself?
- **Physical parameters:**
  - mass, volume
  - power consumption
  - radiation hardness
- **System specifications:**
  - resolution, array dimension (& pixel size)
  - A-D conversion accuracy
  - readout speed
  - on-chip control & signal processing
  - overall system noise levels
- **While all of these are important, the fundamental limitations often arise from the performance of the imaging array itself**

Array Figures of Merit

- **Sensitivity to low light levels**
  - » characterised by quantum efficiency: ratio of the number of electrons collected by the pixel to the number of incident photons
  - » depends on the wavelength of the light – i.e. there is a non-uniform spectral response
  - » also depends on the proportion of the pixel area that is light-sensitive – the “fill factor”
  - » so design and fabrication of the pixels is crucial
- **The ultimate limit on minimum resolvable signal is the noise introduced both within the pixel and in the external circuits**
  - » noise comes from many sources, which we will discuss later
  - » noise level may be around 10 electrons rms
- **Maximum measurable signal is also a function of pixel design**
  - » often called the “full well capacity” both for CCDs and other sensor types
  - » may typically be in the region of 10^5 electrons

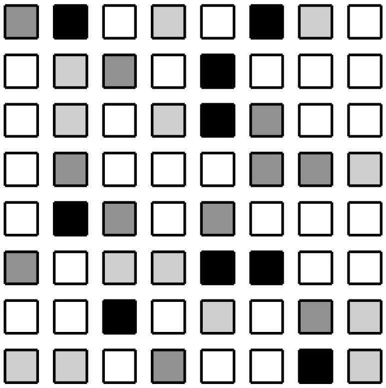
- **So the range of measurable signals ranges from ~10^1 – 10^5 electrons**
  - » the ratio of maximum possible signal to the noise signal is called the dynamic range
- **There are many design trade-offs implied by these numbers**
- **High resolution dictates large numbers of pixels, but fabrication costs limit chip area**
  - » small pixels required
  - » will also influence power consumption
- **Small pixels have a smaller full well capacity**
  - » so the dynamic range can be smaller (although, this may be limited by the external circuits rather than the pixels)
  - » and the sensitivity will be lower
- **There are many advantages to scaling the fabrication process**
  - » smaller pixels with higher fill factor
  - » lower power consumption
- **But there are also disadvantages**
  - » QE is likely to fall
  - » dynamic range is likely to be smaller
  - » more on these later!

Array Artifacts

- **There is a wide variety of factors which affect the “quality” of the captured image**
- **An artifact can be broadly described as something that appears in the captured image that was not present in the original scene**
- **Artifacts can be classed into rough categories according to their source**
  - spatial effects
  - temporal effects
  - signal-level effects
- **We will look briefly at each in turn ...**

Spatial Artifacts

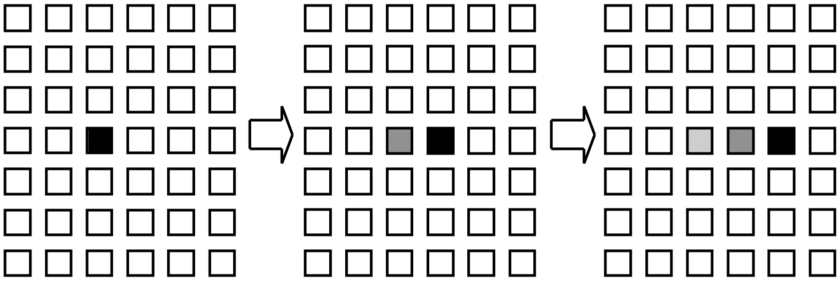
- **Spatial effects are non-uniformities across the array; e.g. differences in the signals generated by individual pixels to a uniform illumination**
  - when this noise is time and illumination invariant (i.e. always the same), it is referred to as fixed pattern noise (FPN)
  - appears as a “speckle” pattern



- **Fixed Pattern Noise often stems from non-uniformities in the characteristics of the components comprising the pixels, e.g.**
  - threshold voltage variations
  - doping variations, leading to non-uniform dark currents
- **But may also be due to the method of readout**
  - e.g. a constantly a-periodic clock

Temporal Artifacts

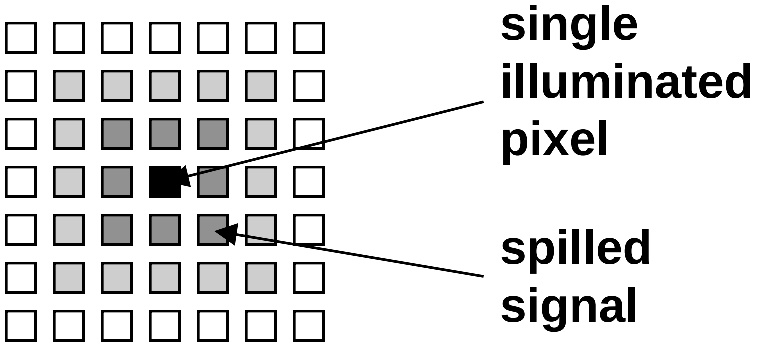
- **Temporal artifacts arise from the imperfect readout of the image from the pixels**
- **Image lag occurs when the transfer of the collected signal out of the pixel is incomplete**
    - » so some charge is left behind as an “offset” in the next frame of the image



    - » this could be seen on early colour TV pictures as a trail behind rapidly moving bright objects
- **Lag can result**
    - » if there is simply not enough time for the charges to move from the extremities of the pixel to the readout point
    - » or if charges are trapped, for example at an interface
- **It can be reduced by**
    - » using smaller pixels and careful design
    - » removing interfaces – e.g. “buried channel” devices
    - » and is not generally seen as a problem for CMOS image sensors

Signal-level Artifacts

- **Signal-level artifacts are due to the non-linear responses of individual pixels to different levels of illumination**
  - » blooming – spilling over of signal from a highly illuminated pixel to neighbouring pixels



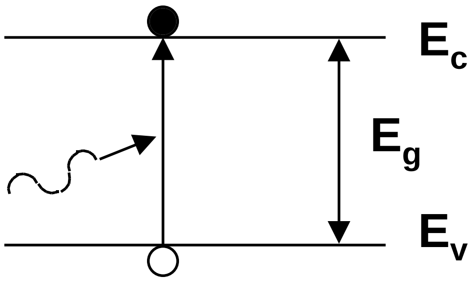
  - » photo-response non-uniformity (PRNU) – differences in the response of individual pixels to illumination
  - » e.g. pixel conversion efficiencies are not equal
- **We will consider these effects after a look at the technologies available for the fabrication of image sensors**
- **With an understanding of the structures of the sensors, we can appreciate their characteristics and limitations**
- **But first we will consider the fundamental process of optical detection using semiconductors**

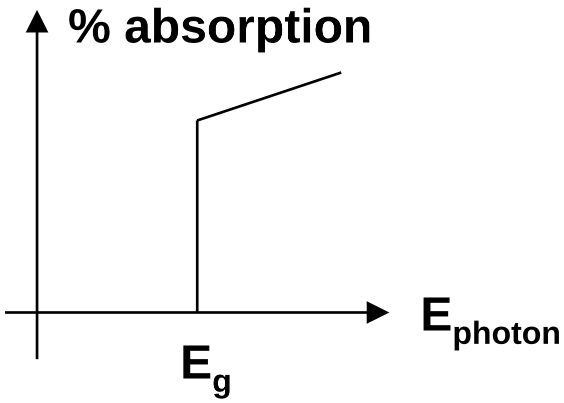
Detection of Light

- **This section will consider the transduction process by which electronic cameras detect light**
- **This will carry us**
  - » from fundamental physical concepts – the interaction of light with semiconductors
  - » to the device level – how, in general, do we detect the photo-induced charge?
- **And then to specific practical device types**
  - » photodiode
  - » MOS capacitor based devices
  - » (there are also other hybrid devices but they are outside the scope of this course)
- **Inextricably linked with the device performance is the process of fabrication, so we will consider that in the next section**

Optical Absorption

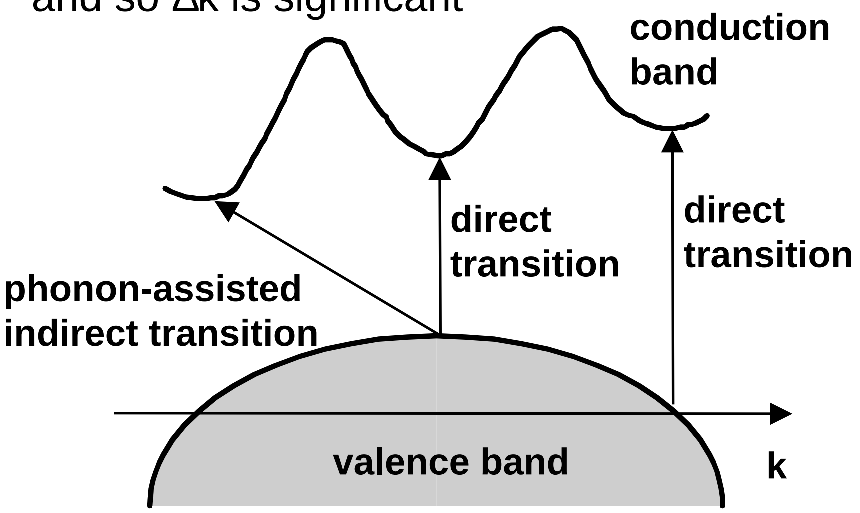
- **The concept of optical absorption in semiconductors is familiar from undergraduate courses**
- **When photons with an energy, E = hf, that is greater than the bandgap, are incident on the semiconductor**
  - » we get the generation of electron-hole (e-h) pairs
  - » and the absorption spectrum is ideally a sharp edge





- **For practical semiconductors, the situation is a little more complex**
  - » especially in materials such as Si where the bandgap is <u>indirect</u>
- **For photons, E = hc/λ, which reduces to**
  - » E(eV) = 1.24 / λ(µm)

- **An indirect bandgap means that, at the minimum energy separation between E_c and E_v, the crystal momenta, k, in the conduction and valence bands are not equal**
- **The momenta of pho<u>t</u>ons is negligibly small compared to that of the electrons**
  - » so optically induced transitions are for Δk ≈ 0
- **However, pho<u>n</u>ons have a momentum similar to that of the electrons**
  - » and so Δk is significant



- **So electrons can only make this minimum-energy transition (1.1eV for Si) if a phonon (quantised unit of lattice vibration) is also involved**
  - » this reduces the transition probability, and hence the optical absorption, as well as adding a temperature dependence

Absorption Coefficient

- **If we consider an incremental slice of material, dx, the change of intensity of light, dI, due to absorption is**

$$\mathbf{dI = \alpha I.dx}$$

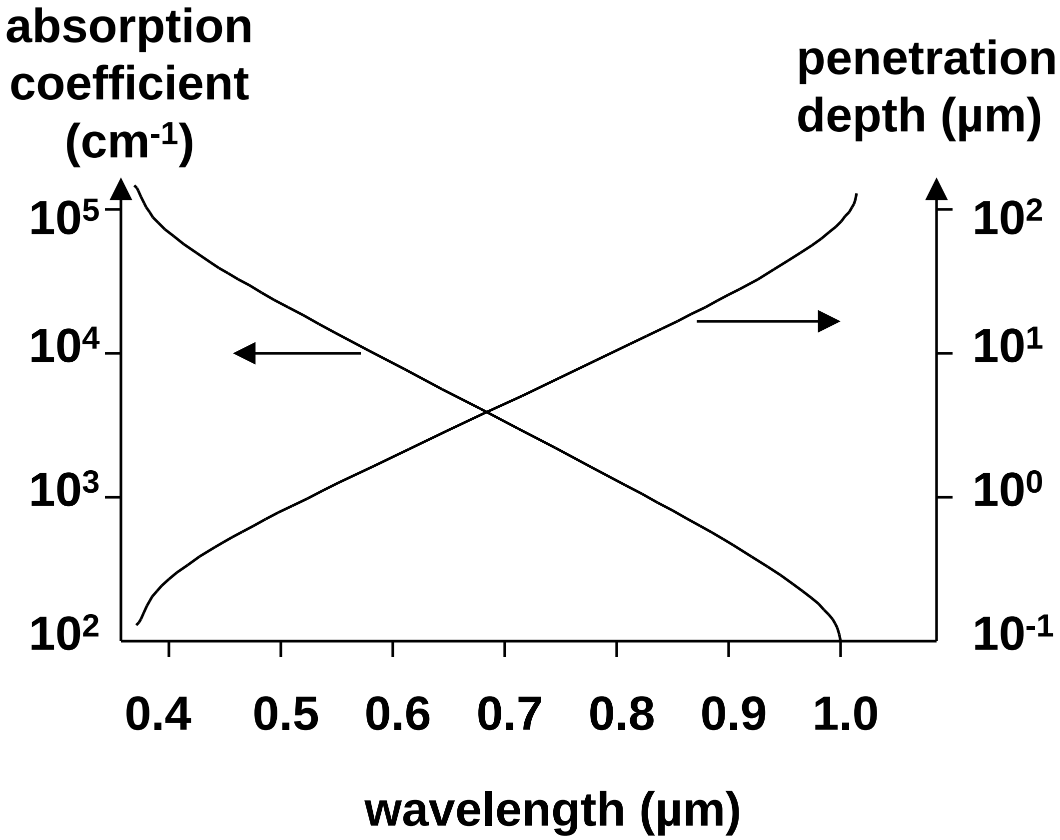
- **Solving this equation gives**

$$\mathbf{I(x) = I_0 \exp(-\alpha x)}$$

  - » where α is the absorption coefficient
  - » I is in photons/(cm^{2}s)
- **Alternatively, the penetration depth of light into the material is characterised by 1/α**
- **Now, from the previous argument, it is clear that the absorption coefficient**
  - » is wavelength-dependent
  - » because the transition probabilities depend on the energy of the photons
- **Later on, when we are interested in the quantum efficiency of a photodetector, we will have to plot a <u>spectral response</u>**
- **So what do the curves look like?**

Curves for α

- **A practical enough version for our purposes is**



  - » see Sze, Ch.1 for more detail

- **Recall that the visible wavelengths extend from about 400nm (blue) to 750nm (red)**
- **So blue light penetrates about 0.2μm, while red light penetrates more than 10μm**
  - » this can be used as the basis for colour sensors, by stacking charge collection layers

Optical Generation Rate

- **The actual number of e-h pairs generated by the absorbed photons is described by the quantum efficiency, η , of the process**
- **Now, the optical generation rate is given by**

$$\mathbf{G}(\mathbf{x}) = \eta\alpha\,\mathbf{I}(\mathbf{x}) = \eta\alpha\,\mathbf{I_0}\,\mathbf{exp}(-\alpha\mathbf{x})$$

  - » assuming that absorption coefficient is a constant, i.e. monochromatic light
  - » G is in electrons/(cm^{3}s)
  - » the generation <u>falls exponentially</u> from the surface

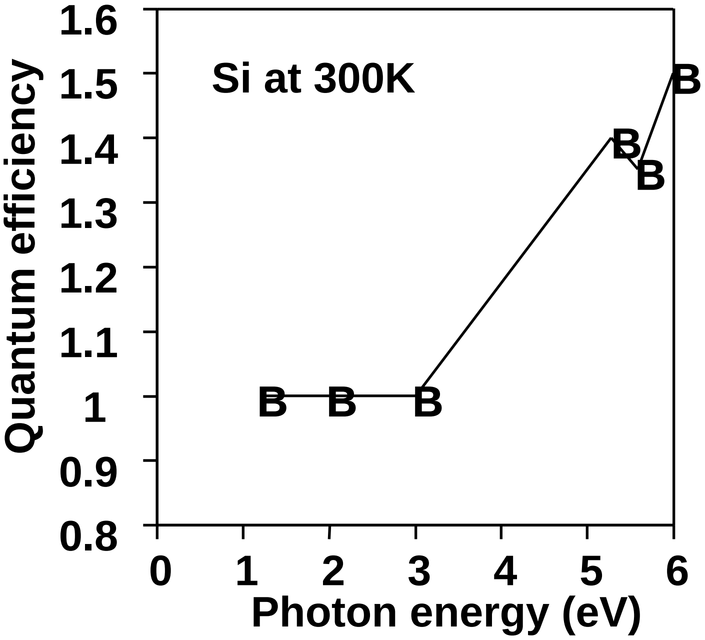
- **Of course, we know that α depends on the wavelength, so we might suspect that η does as well**
- **So to calculate the generation rate in a device, we must integrate**

$$\mathbf{G}(\mathbf{x}) = \int_{\lambda_1}^{\lambda_2} \eta(\lambda)\alpha(\lambda)\mathbf{I_0}(\lambda)\,\mathbf{exp}\left[-\alpha(\lambda)\mathbf{x}\right]\mathbf{d}\lambda$$

- **In principle, α also depends on the doping in the semiconductor**
  - » and hence could also be a function of x
  - » but this is only significant at high doping levels

Quantum Efficiency

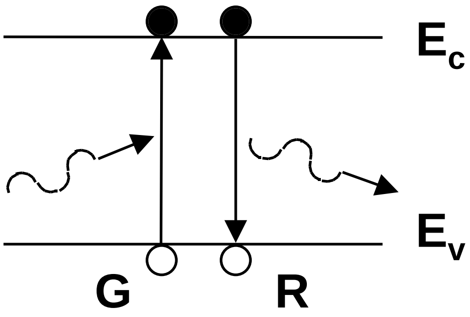
- **For cases of interest to us, the quantum efficiency is ≈1 (i.e. 1 electron for every absorbed photon**
- **At high photon energies, we get more than one e-h pair per photon**
  - » because there is enough energy to ionize more than one atom
  - » measured data are as follows



- **Remember that the overall efficiency of the sensor also depends on how well these carriers are <u>collected</u>**

Recombination

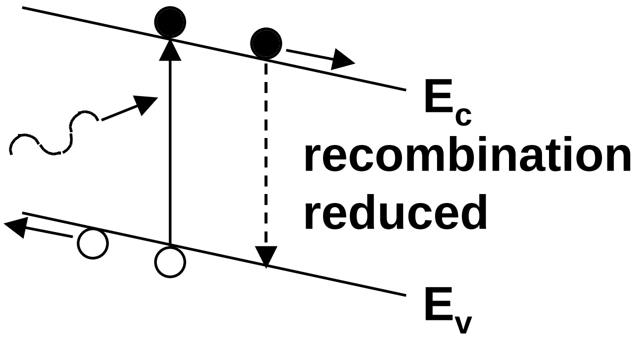
- **In an isolated piece of semiconductor, exposed to illumination, the free carrier concentrations must be in equilibrium**
- **Hence, there must be another mechanism “opposing” the generation**
  - » recombination



- **The rate of recombination is proportional to the numbers of electrons and holes**
  - » R np
- **So as the number of e-h pairs generated by the photons increases, so too does the recombination**
  - » so we can get no measurable signal simply by relying on optical generation
- **To collect a signal, we need to**
  - » separate effectively the photo-generated e-h pairs to minimise recombination
  - » and cause the carriers to reach some collection contacts

Charge Collection

- **Fortunately, we can achieve both objectives in the same way**
  - » by using an electric field



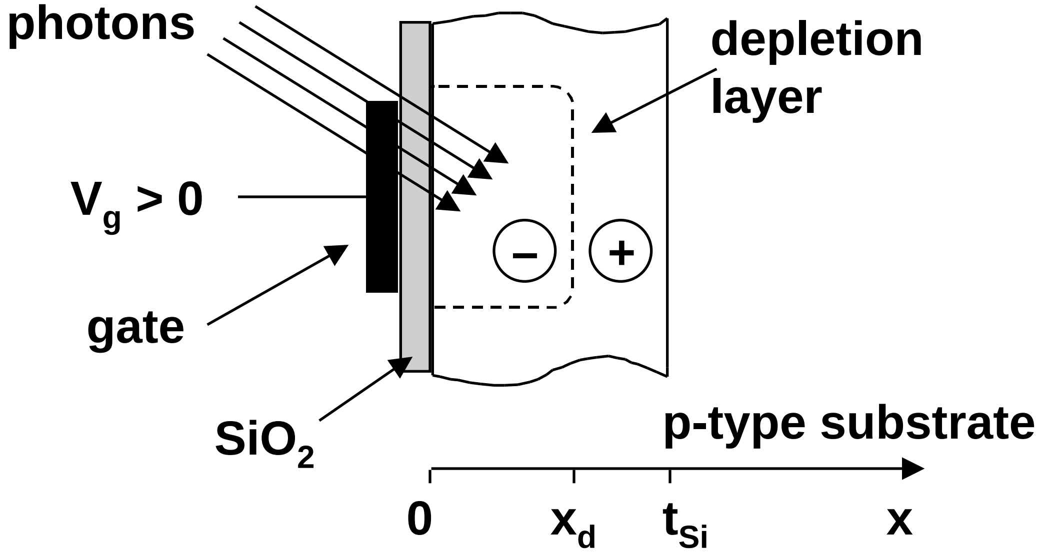
- **This electric field can be a built-in field (e.g. p-n junction), or can be applied externally (e.g. MOS capacitor)**
- **The reason for being worried <u>where</u> the e-h pair generation from optical absorption takes place is now clear**
  - » we want the generation and the field to occur at the same place!
  - » and in this lies the principle of effective sensor design
- **Now let’s look at some numbers ...**

Collected Current

- **We saw that a typical illumination level was approximately 500 lux, or about 150,000 photons/(μm^{2}s)**
- **We also take an average value for the absorption coefficient**
  - » $\alpha = 5 \times 10^3$ cm^{-1}
- **With η = 1, the total flux of generated e-h pairs**
  - » 7.5×10^{16} e-h pairs per (cm^{3}s)
- **Usually, only one type of charge carrier is collected so the above number represents the flux of, say, electrons**
- **In a 10μm x 10μm x 1μm volume, the current is**
  - » (7.5×10^6 electrons/s) x q = 1.2 pA
- **Such a small current is difficult to measure**
  - » although this value is the typical, not the minimum, it turns out that the collection volume is larger than we have estimated
- **To overcome this limitation, another function is required of our sensor**
  - » it must be able to store up charge over period of time so that a reasonable signal can be read out

MOS Capacitor

- **One of the most common way of collecting the photo-generated charge is the MOS capacitor**
  - » it is the basis of many CCD devices
  - » and one design of CMOS sensor



- **Here, the holes are expelled from the depletion layer and are lost to the substrate; the electrons are collected in the potential well**
  - » we will discuss how they are read out later
- **So, in our idea so far, collection only occurs in this depletion region**
  - » indeed, almost 100% of the photo-generated minority carriers (electrons here) will be collected in this region

Diffusion

- **However, not all the incident photons will be absorbed in the depletion width and many will go through into the substrate**
  - » can these be collected too? – yes!
- **They will not be collected so efficiently because there is no (or little) electric field here to separate the carriers**
- **However, electrons diffuse faster than holes and a reasonable number make it to the depletion width without recombining**
  - » $L_{n,p}$ is the characteristic length of the exponential distribution that arises from the combined recombination and diffusion of minority carriers
- **In fact, for a very shallow depletion width (compared with the diffusion length, L, of the electrons), a good proportion of the e-h pair generation occurs outside the depletion layer**
- **The total collection efficiency can be written**

$$\eta_{\mathbf{c}} = \eta_{\mathbf{dl}} + \eta_{\mathbf{bulk}}$$

  - » where the η's represent (collected electrons/incident photons) for the depletion length and bulk silicon
- **These two components are given by ...**

$$\eta_{\mathbf{dl}} = \mathbf{1} - \mathbf{exp}\left(-\alpha \mathbf{x_d}\right)$$

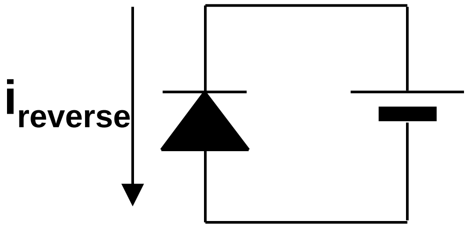
- **i.e. # collected electrons = # absorbed photons**
- **And the expression for the diffusion component is more complex:**

$$\eta_{\mathbf{bulk}} = \frac{\alpha \mathbf{L_n^2}}{\alpha \mathbf{L_n^2} - \mathbf{1}} \left\{ \alpha\, \mathbf{exp}\left(-\alpha \mathbf{x_d}\right) + \frac{\mathbf{exp}\left(-\alpha \mathbf{t_{Si}}\right) - \mathbf{exp}\left(-\alpha \mathbf{x_d}\right) \mathbf{cosh}\left[\frac{\left(\mathbf{t_{Si}} - \mathbf{x_d}\right)}{\mathbf{L_n}}\right]}{\mathbf{L_n} - \mathbf{sinh}\left[\frac{\left(\mathbf{t_{Si}} - \mathbf{x_d}\right)}{\mathbf{L_n}}\right]} \right\}$$

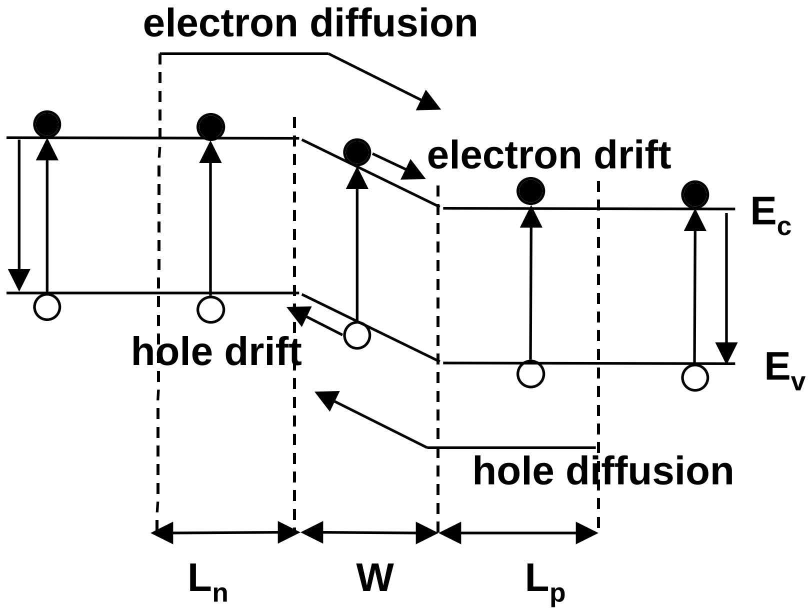
  - » where L_n is the electron (minority) diffusion length
- **For longer wavelengths:**
  - » lower absorption coefficient a larger penetration depth
  - » less absorption in depletion layer
  - » more dependence of efficiency on diffusion length
- **For shorter wavelengths:**
  - » most absorption is in the depletion layer
- **We will see later that one of the problems with using a standard CMOS process is that the junction depths are getting shallower**
  - » < ~ 0.5µm
  - » and a lot of the light goes straight through the depletion layer (see curve of α vs. λ)

Efficiency of Photodiode

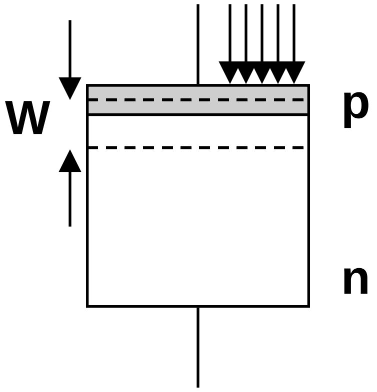
- **While the MOS capacitor is the basis of some types of imager, the most common detector is the photodiode**
- **This could be a “normal” p-n diode or a structure especially adapted for imaging (and solar cells) called a p-i-n diode**
  - » which includes an intrinsic region to increase the “depletion width” artificially



- **The band diagram of the p-n diode can show the movement of generated e-h pairs**



Vertical p-n Photodiode



- **We can write**

$$J_{tot} = J_{drift} + J_{diff}$$

- **We will assume that**
  - » the p-layer is thin enough to cause negligible absorption
  - » thermal generation (dark current) is ignored
- **From before**

$$G(x) = I_0 \alpha \exp(-\alpha x)$$

- **The drift current density is therefore**

$$J_{drift} = -q \int_0^W G(x) dx = qI_0 [1 - \exp(-\alpha W)]$$

- **For x > W in the n-type, we can write a diffusion equation**

$$D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} + G(x) = 0$$

  - » where D_p if the diffusion coefficient for holes, τ_p is the minority carrier lifetime, and p_{n0} is the equilibrium minority carrier concentration

- **The boundary conditions for this equation are**
  - » $p_n = p_{n0}$ @ $x = \infty$
  - » $p_n = 0$ @ $x = W$
- **So we can solve to get**

$$\mathbf{p_n = p_{n0} - \left[p_{n0} + C_1 \exp(-\alpha x)\right] \exp\left[(W - x)L_n\right] + C_1 \exp(-\alpha x)}$$

  - » where

$$\mathbf{L_p = \sqrt{D_p \tau_p}}$$

  - » and

$$\mathbf{C_1 \equiv \left(\frac{I_0}{D_p}\right) \frac{\alpha L_p^2}{1 - \alpha L_p^2}}$$

- **Now the current density is given by**

$$\mathbf{J_{diff} = -qD_p \left(\frac{\partial p_n}{\partial x}\right)_{x=W}}$$

$$\mathbf{= qI_0 \frac{\alpha L_p}{1 + \alpha L_p} \exp(-\alpha W) + qp_{n0} \frac{D_p}{L_p}}$$

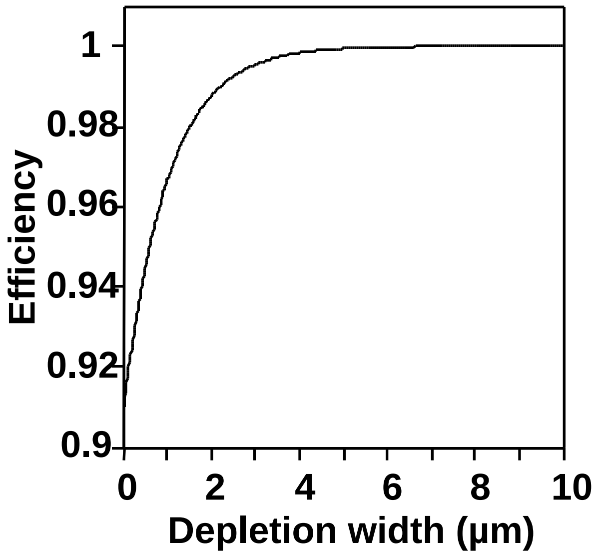
- **And so the total current density is**

$$\mathbf{J_{tot} = qI_0 \left[1 - \frac{\exp(-\alpha W)}{1 + \alpha L_p}\right] + qp_{n0} \frac{D_p}{L_p}}$$

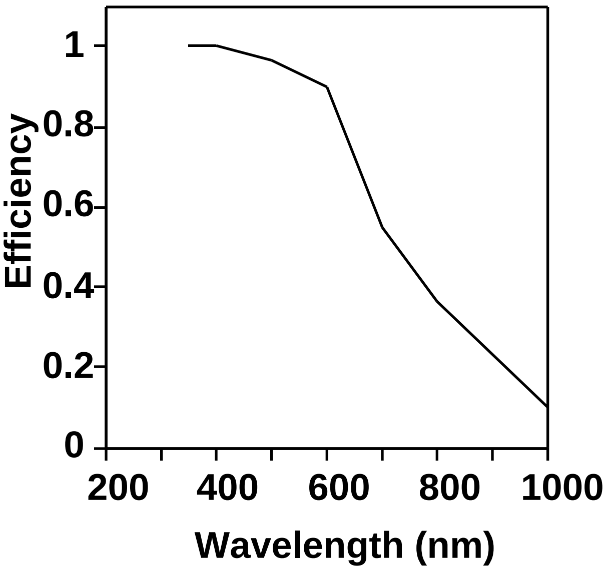
- **In most cases, the second term is less important and the photo-current density is proportional to the incident photon flux**
- **So now, the efficiency = J_{tot}/qI_0**

$$\eta = \left[1 - \frac{\exp(-\alpha W)}{1 + \alpha L_p}\right]$$

- **Thus, the efficiency is critically dependent on the magnitude of αW**
  - » it is the small α at long wavelengths that causes the efficiency to fall sharply beyond λ ≈ 500nm
  - » here α is a (given) material parameter
  - » but W is dependent on doping levels in the diode and the bias, and so W is (potentially) a design parameter

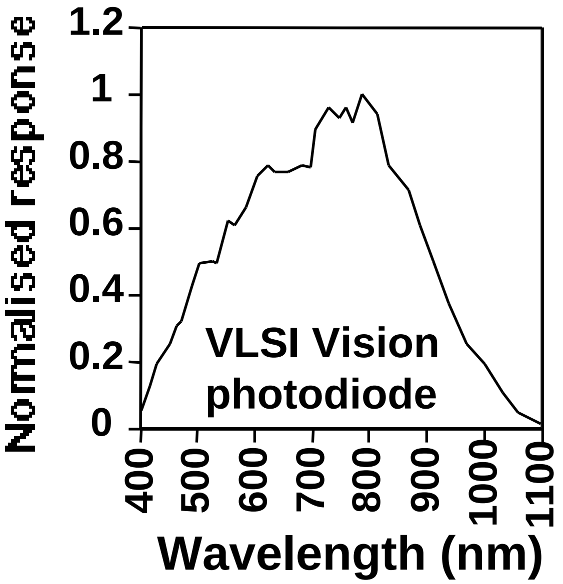


$\alpha = 10^4\ \mathrm{cm^{-1}}$, and $L_p = 10\mu m$



$L_p = 10\mu m$, $W = 1\mu m$
[assumes $\alpha(\lambda)$]

- **In deriving the previous relations, we have ignored several factors, in addition to our explicit assumptions**
  - » absorption in top doped region (p here) is negligible
  - » thermal current is negligible
  - » (neither of these is necessarily realistic)
- **But our simple derivation suggests that the efficiency is unity for short wavelengths**
  - » in reality, the efficiency drops off here too, because the penetration depth is less than the thickness of the top doped layer
- **Integrated photodiodes are often n^+-p because**
  - » fits the standard CMOS process better
  - » $L_n > L_p$

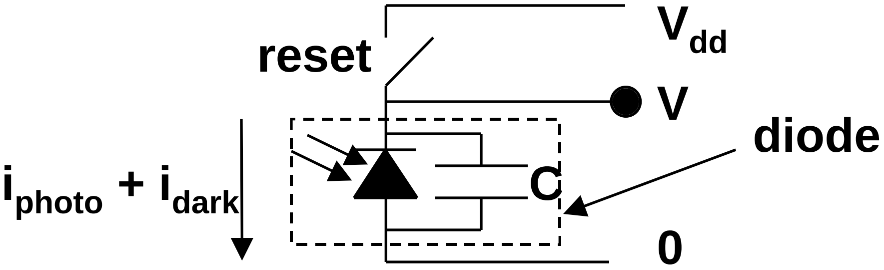


Reflectivity

- **So far, we have assumed that all the incident light is available for e-h pair generation**
- **However, in all microelectronic devices, there will be at least one layer over the top of the semiconductor**
  - » in CMOS, there will be a passivation layer of SiO_2 or SiN_x, or both
  - » in CCDs and some types of CMOS sensor, the entire light-sensitive area may be covered by a poly-Si gate and a SiO_2 dielectric
- **And even a bare Si surface will have a reflectivity, R = (reflected intensity)/(incident intensity), greater than zero**
- **So the efficiency equation must have a (1 - R) term in the front**
  - » for flat bare Si, $R \approx 0.35$
- **Moreover, the presence of thin layers causes multiple reflections and interference**
  - » so the amount of light getting into the silicon depends significantly on the wavelength
- **Practically, the peak QE ≈ 40%**

Pixel Operation

- **So how do we use a photodiode?**
- **Because of the small photo-current, we collect charge over an integration time**
  - » $Q_{coll} = i_{photo}t_{int}$
- **This then typically converted to a voltage using a capacitor**
  - » $V = Q_{coll}/C$
  - » where C is often composed of the diode's self capacitance plus that of any connected devices/layers
- **In operation, the diode is reset (charged up) to some reverse bias, and then isolated**

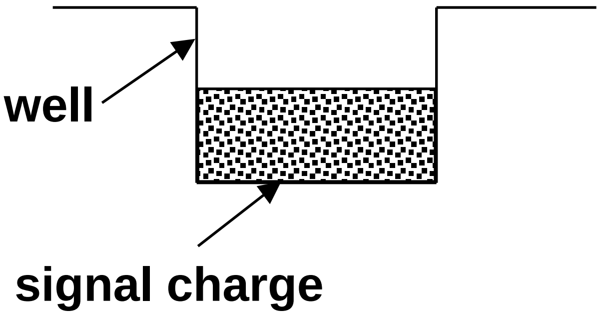


- **Over time, the reverse current through the diode (both photo- and dark-) discharges the output node, V**

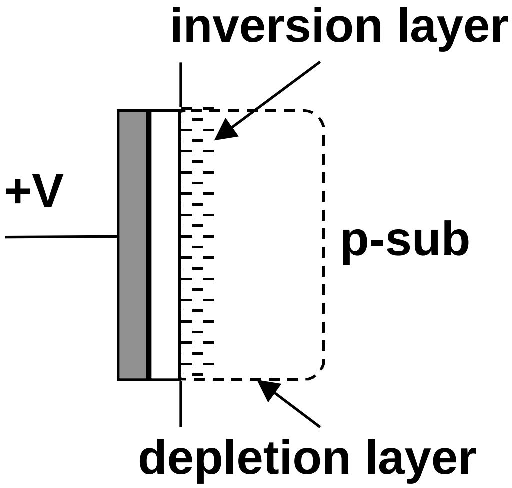
- **From before, we know that i_{photo} I_0 so the variation of V with t_{int} and I_0 are both linear**
    - » assuming that C is constant
    - » which is not strictly true because the bias on the p-n junction is changing
- **A 30 x 30μm photodiode at a reverse bias of 5V has a capacitance of approximately 1.5 x 10^{-13} F**
- **The charge stored at this voltage corresponds to ~5 x 10^6 electrons, and represents the maximum collectable charge**
    - » this will be an overestimate because the voltage does not typically reach the extremes of 5V and 0V.
    - » in practice, the saturation is usually determined by the voltage swing of the output amplifier.
    - » a practical full well capacity of 3.7 x 10^5 electrons for a 20μm square pixel at a V_{DD} of 5V is typical
- **Typical dark current densities are of the order of 500 – 1000 pA/cm^2**
    - » which is about 5 x 10^9 electrons/(s.cm^2)
    - » or 2 x 10^4 electrons/s for the 20μm pixel
    - » Hence, the well should fill up in about 20s
- **In practice, however, the maximum integration time is typically 100ms**
    - » before the dark charge is significant in comparison to the signal charge

MOS in Deep Depletion

- **The main alternative to photodiode detectors are those based on MOS capacitors in deep depletion**
- **In sensors, MOS capacitors are usually thought of a buckets which can be filled with charge**



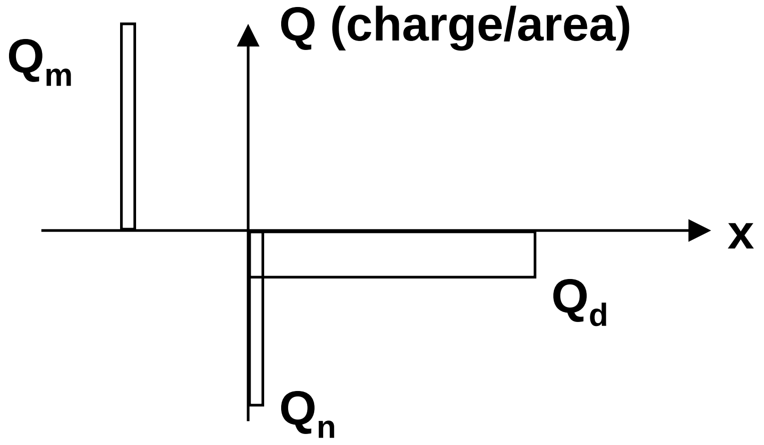
Bucket analogy



MOS capacitor in inversion mode

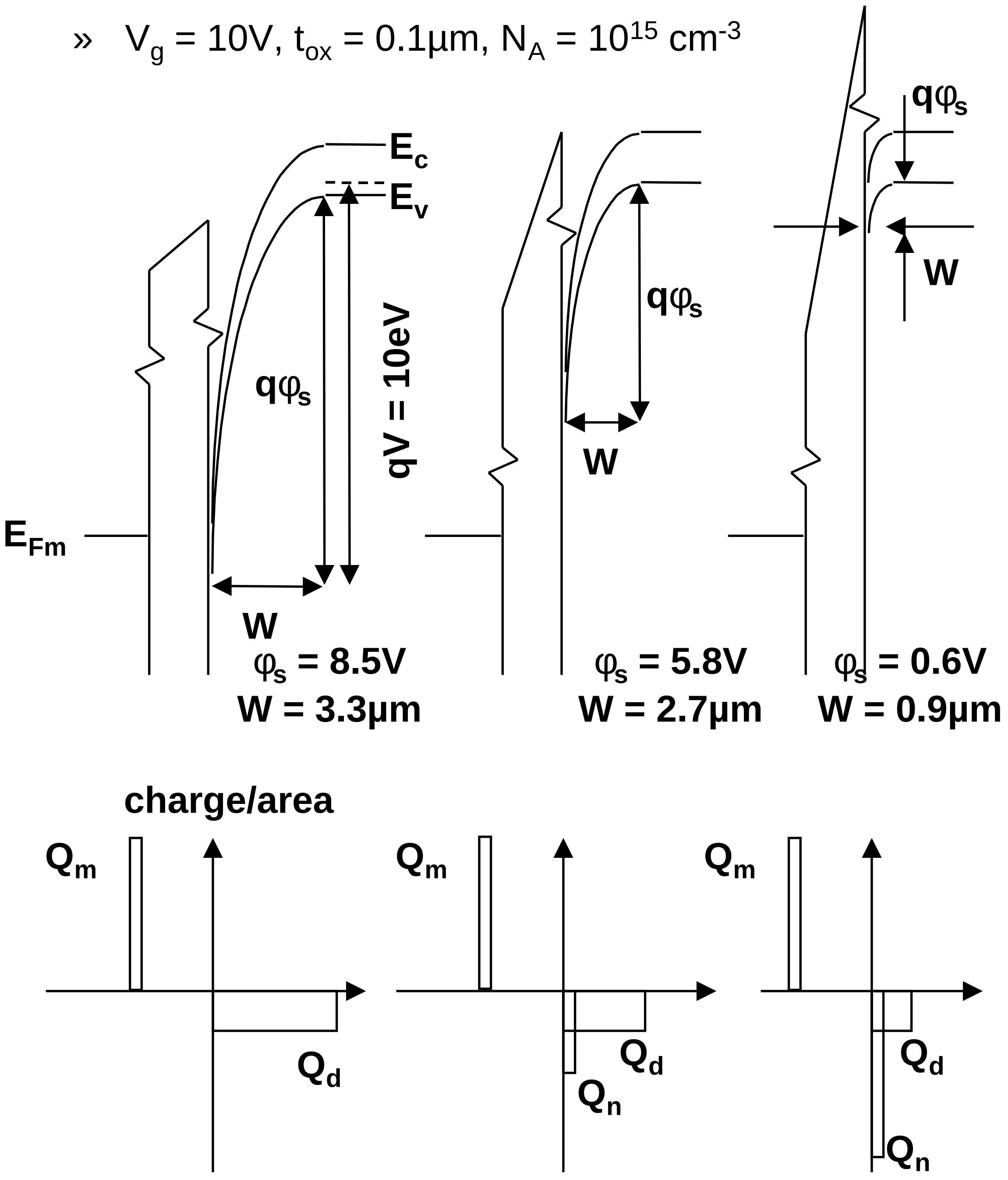
- **However, the familiar picture of the MOS in inversion (above right) is for <u>equilibrium</u>**
  - » so there is no empty potential well available for filling with charge
  - » and illumination will just change the equilibrium conditions slightly

- **Here, the positive charge on the gate is equal to the negative charge due to the inversion (n) and depletion (d) layers**



- **But it takes time to reach this equilibrium:**
  - » when the gate voltage is first applied, mobile holes are depleted from the semiconductor underneath
  - » so that the +ve charge on the metal is equalled by the "exposed" negatively charged acceptor ions in the substrate
  - » the concentration of these is low, so the depletion width is large
  - » the minority carrier (electron) concentration is very low, so the only way of achieving inversion is to collect electrons that are generated thermally within the depletion region (= dark current)
  - » this process may take several seconds, even at room temperature
  - » during this time the potential well is available to be filled by signal charge

- **The sequence could be as follows**
  - » $V_g = 10V$, $t_{ox} = 0.1\mu m$, $N_A = 10^{15}$ cm^{-3}



deep depletion (empty well)

intermediate

equilibrium (full well)

MOS Capacitor Relations

- **The width of the depletion width is given by the same expression as a one-sided p-n junction**

$$W = \sqrt{\frac{2\varepsilon_{Si}\varphi_s}{qN_A}}$$

- **In the depletion region, the charge p.u. area is**

$$Q_d = qN_A W = \sqrt{2\varepsilon_{Si}qN_A\varphi_s}$$

- **The voltage across the oxide, of thickness t_{ox}, is**

$$\varphi_{ox} = \frac{Q_d}{C_{ox}} = \frac{t_{ox}}{\varepsilon_{ox}} Q_d$$

  » where C_{ox} is the oxide capacitance per unit area

- **We know that $V_g = \varphi_{ox} + \varphi_s$, so we find the gate voltage to be**

$$V_g = \frac{1}{C_{ox}}\sqrt{2\varepsilon_{Si}qN_A\varphi_s} + \varphi_s$$

- **In all these cases, φ_s represents the “depth” of the empty well**

  » it is changed by altering the oxide thickness, substrate doping, and gate voltage

  » however the practical choices are usually limited by other factors

A Real MOS Capacitor

- **The foregoing analysis was for an ideal MOS device**
- **In real cases, at least two factors will alter the situation**
  - » charge trapped in the oxide, Q_{ox}
  - » a difference in work function between gate and semiconductor (≈ 0.1V for n-poly on p-Si)
- **These are included in the “flatband” voltage**
  - » the additional gate voltage required to get back to the ideal starting condition
  - » $V_{fb} = \varphi_{ms} - Q_{ox}/C_{ox}$
  - » where φ_{ms} is the work function difference between the gate and substrate
- **The partially-filled well can be included by a Q_n/C_{ox} term**
- **To give the remaining (un-filled) well depth as**

$$\varphi_s = V_g - V_{fb} + \frac{Q_n}{C_{ox}} - \frac{\varepsilon_{Si} q N_A}{C_{ox}^2}\left[1 - \sqrt{1 - \frac{2C_{ox}^2\left(V_g - V_{fb} + \frac{Q_n}{C_{ox}}\right)}{\varepsilon_{Si} q N_A}}\right]$$

References – Part I

- » VLSI Vision data sheets (www.vvl.co.uk)
- » B. Streetman (1995), “Solid State Electronic Devices” 4th Edn., Prentice Hall
- » J. Beynon & D. Lamb (1980), “Charge-Coupled Devices and Their Applications”, McGraw-Hill
- » A. Theuwissen (1995), “Solid State Imaging With Charge-Coupled Devices”, Kluwer
- » S. Sze (1981), “Physics of Semiconductor Devices”, 2nd edn, Wiley
- » A. Moini (1997), “Vision Chips”, University of Adelaide, Australia, revision 3.5 1997

  (http://www.eleceng.adelaide.edu.au/Personal/moini/)