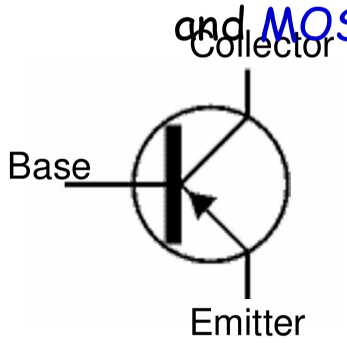
Detection of Light

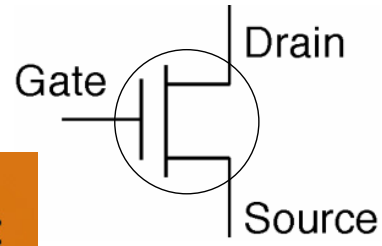
See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

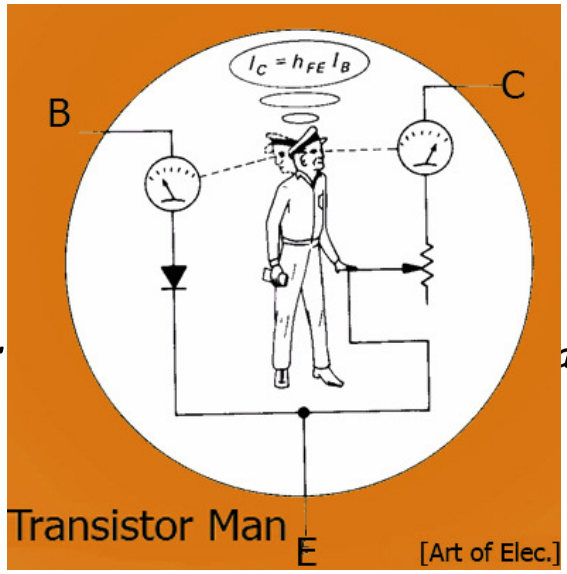
Multiplexers (MUX)

Side note: Transistors

Classical transistors and MOSFETs







Note: transistors *amplifiers*

Multiplexers

"Pixel signals → Sequential output lines" is called multiplexing.

A multiplexer (MUX) has the following functions:

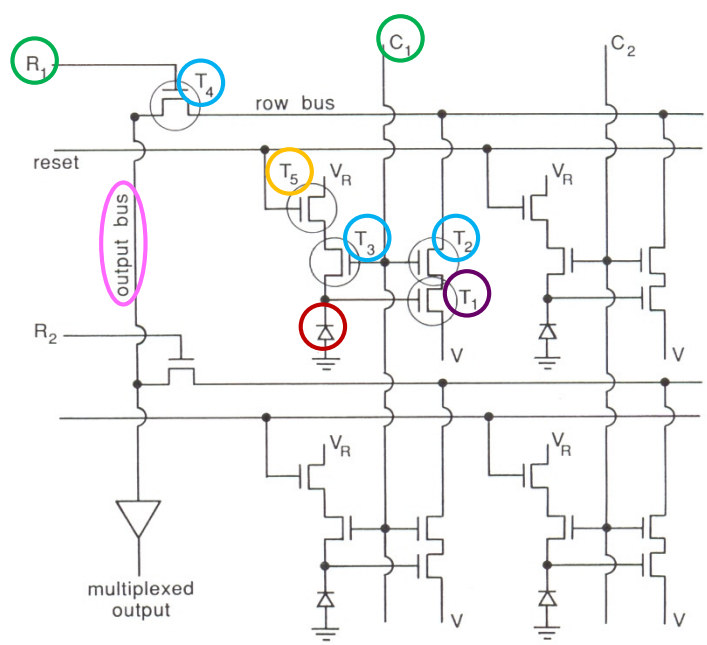
- address a column of pixels by turning on their amplifiers
- pixels in other columns with power off will not contribute a signal

Signal at photodiode → gate T_1

Readout uses row driver R_1 and column driver C_1 to close the switching transistors T_2, T_3, T_4.

→ Power to T_1 → signal to the output bus

Reset: connect V_R via T_5 and T_3.

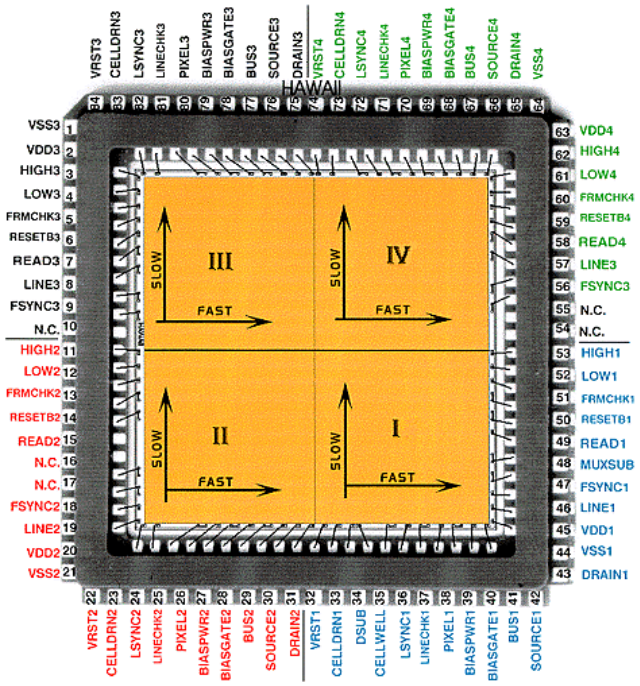


Multiplexers (2)

Advantage: all pixels can be addressed as desired ("random access")

- allows for sophisticated readout schemes
- allows (faster) subarray reading
- does not require moving charges on the array (→ CCD)

Typical wiring diagram for the Rockwell near-IR HAWAII array:



Array Readout Schemes

Detector Readouts

Two general approaches:
1. CCDs: shutter determines exposure time – destructive reads

2. IR arrays: readouts determine integration time (continuously exposed) – non-destructive reads.

"non-destructive" ≡ charge is not altered by sampling its current value

Example:

Assume a 1k × 1k array → 1024^2 pixels

Four channels → 262,144 pixels per channel

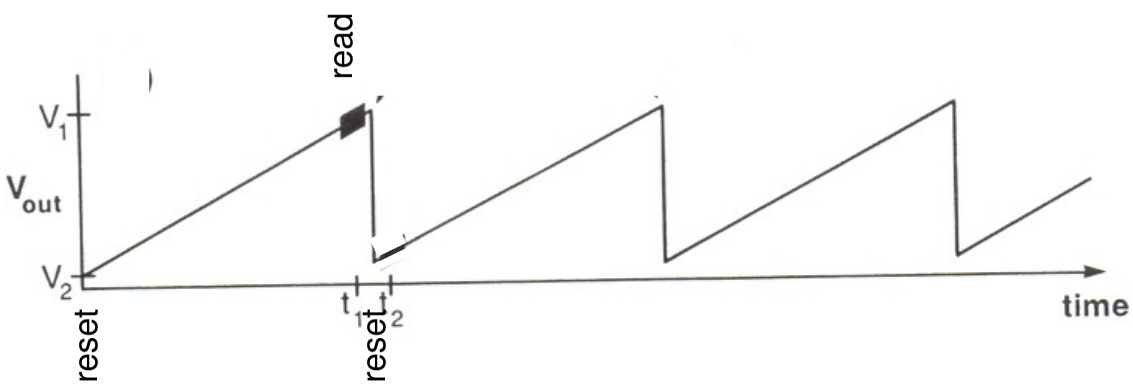
Readout time per pixel ~ 4μs → t_F = 1.0486s "frame time"

(maximum) frame rate = $1/t_F$ = 0.95 Hz

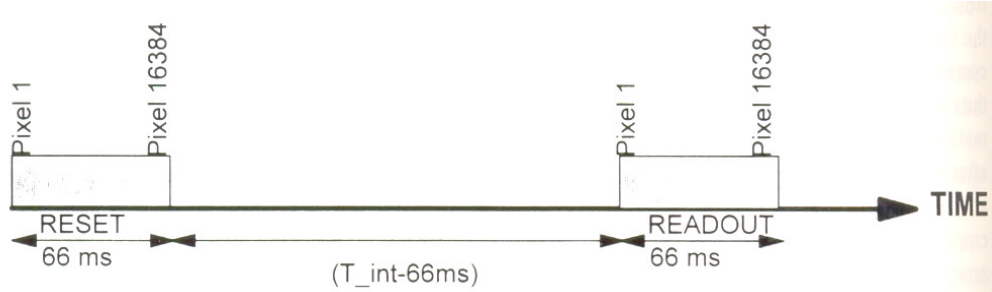
0.95 Hz is rather slow! – what can we do?

→ shorter read out times → more noise
→ better: more readout channels

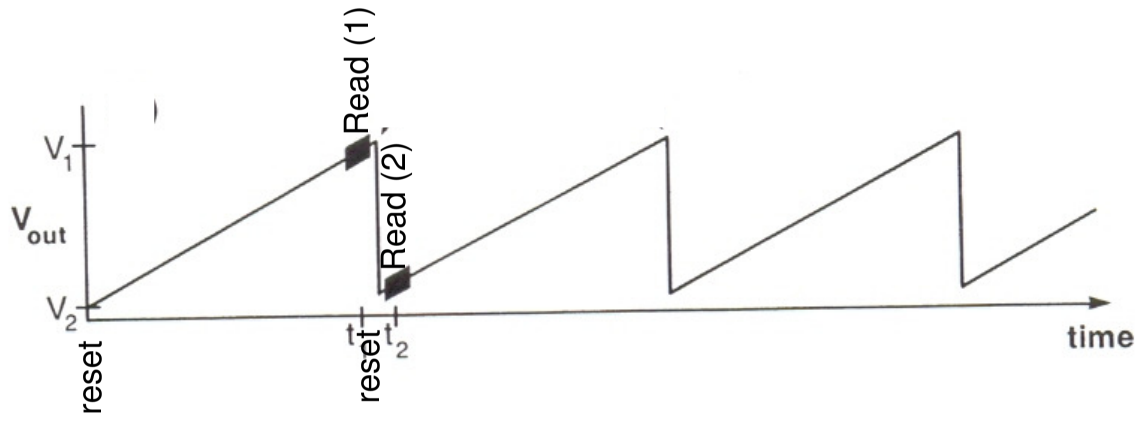
Single Sampling



- This is the most simple approach
- It does not remove kTC noise and voltage drifts
- It measures directly the signal level (important e.g., to detect saturation)

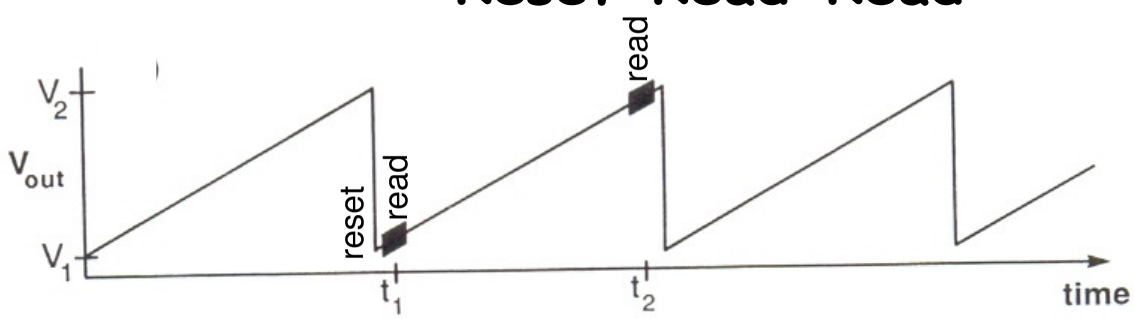


Double-correlated Sampling

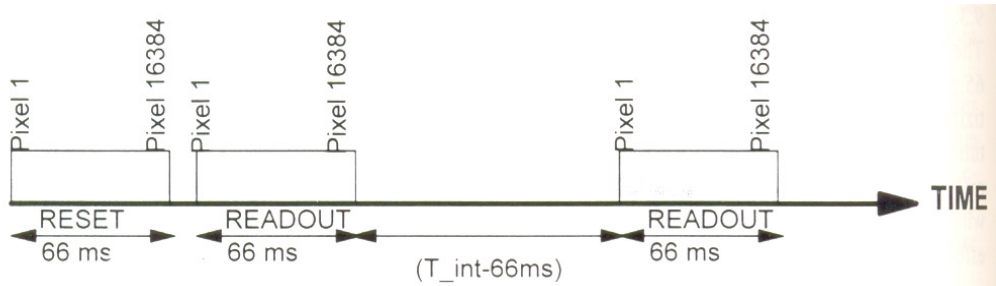


- Reads pixel twice (before and after the reset) before "moving" to the next pixel
- Signal = Read(1) – Read(2)
- Takes care of voltage drifts
- Advantage: operates on pixel-by-pixel basis
- Disadvantage: long reset settling times introduce noise

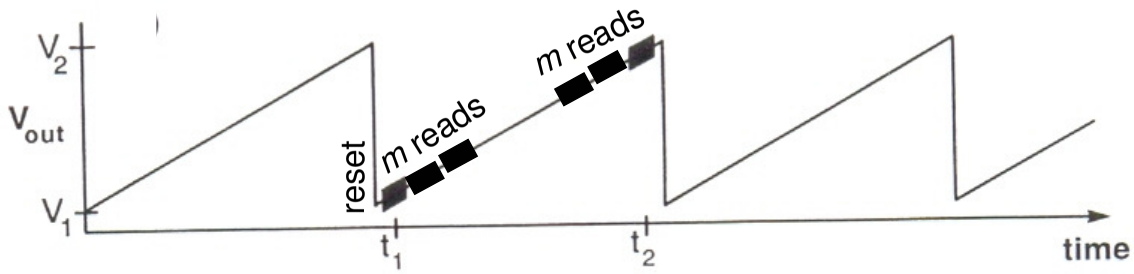
Reset-Read-Read



- Resets the array pixel-by-pixel (or column-wise)
- Reads the array pixel-by-pixel (at start of integration)
- Reads the array pixel-by-pixel (at end of integration)
- Signal = Read(2) – Read(1)
- Advantage: best correlation, no reset noise
- Disadvantages: requires frame storage, has reduced dynamical range, and will not reveal saturation.

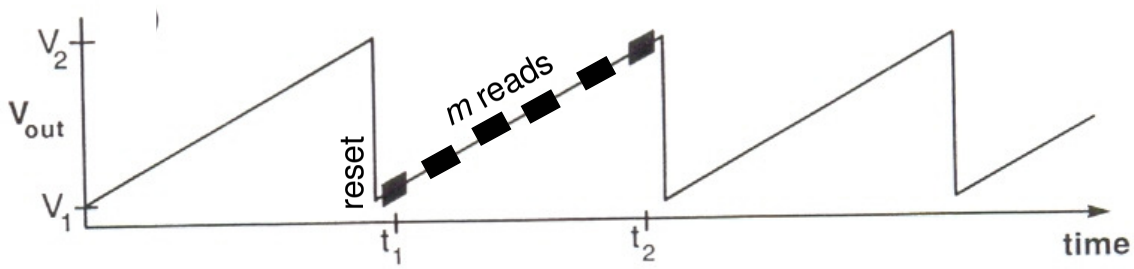


(Multiple) Fowler Sampling



- Named after Al Fowler (NOAO)
- Similar to reset-read-read but each read is now done *m* times
- Signal = mean(read2) – mean(read1)
- Reduces the readout noise by √m over reset-read-read

Sample-up-the-ramp Fitting



- *m* equidistant reads during the integration
- Linear fit → "slope"
- Reduces the readout noise by √m (until 1/f noise dominates)
- Particularly useful when particle hits are likely during t_{int}.

General problem for any BLIP non-destructive reads: successive signal measurements are correlated in their noise.

Further Reading

E.g.,

- *Fowler & Gatley (1990, ApJ, 353, L33)*
- *Garnett & Forrest (1993, SPIE Vol. 1946, 395-404)*
- *or "Uniform Data Sampling: Noise Reduction & Cosmic Rays" by Offenberg, J. D., Fixsen, D. J., Nieto-Santisteban, M. A., Sengupta, R., Mather, J. C., & Stockman, H. S. 2001, in ASP Conf. Ser., Vol. 238, Astronomical Data Analysis Software and Systems X, eds. F. R. Harnden, Jr., F. A. Primini, & H. E. Payne (San Francisco: ASP), 396*

Charge Coupled Devices (CCDs)

CCDs = *array of integrating capacitors that store electric charges until they are read out by transferring them sequentially to an output amplifier.*

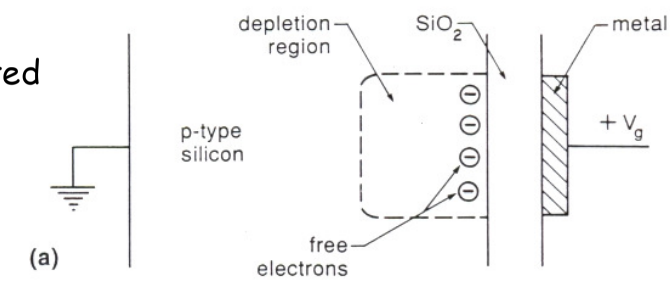
CCDs

A. Photon Detection

Basic Functionality

Pixel structure: metal "gate" evaporated onto SiO_2 (isolator) on silicon = MOS

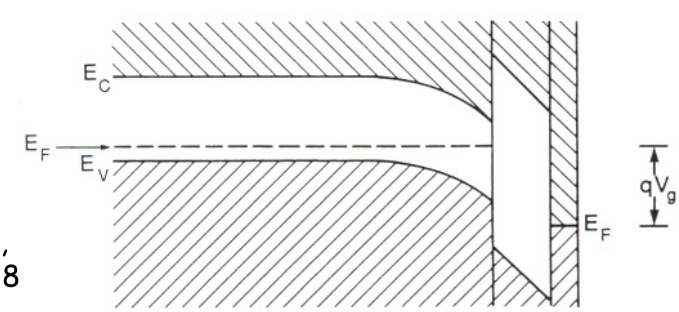
Applying a voltage V_g → bias for the intrinsic semiconductor. Charge current only due to absorbed photons.



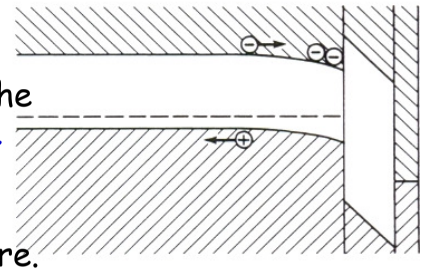
p-type doping → width of depletion zone:

$$w = \left(\frac{2\kappa_0 \varepsilon_0}{qN_D} \left| V_g \right| + t_I^2 \right)^{1/2} - t_I$$

where t_I is the thickness of the insulator, N_D the density of ionized donors, $\kappa_0 = 11.8$ the dielectric constant of silicon.

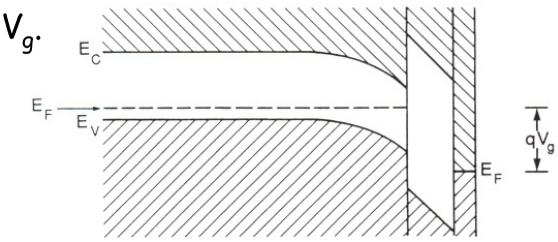


Basic Functionality (2)



1. photons create free electrons in the photoconductor
2. e^- drift toward the electrode but cannot penetrate the SiO_2 layer → e^- accumulate at the Si—SiO_2 interface
3. the total number of e^- collected at the interface is a measure of the number of photons during the exposure.

Well depth:
Charges will collect until their charge balances V_g.



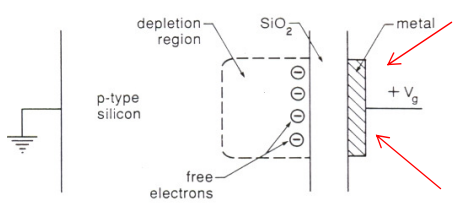
The maximum number of electrons the MOS capacitor can hold is the well capacity:

$$Q_W = C_0 (V_g - V_T)$$

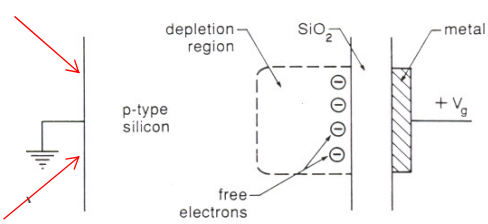
where V_T is the threshold voltage for the formation of a storage well, and C_0 is the pixel capacitance:

$$C_0 = \frac{A \kappa_0 \varepsilon_0}{d}$$

Front and Back Illumination



Front illuminated CCDs:
The metal electrode would block the incoming photons → make electrode transparent by using heavily doped silicon instead → problems at blue/UV wavelengths (transparency of Si)



Back illuminated CCDs:
Blue/UV photons will be efficiently absorbed behind surface → long distance to depletion region → low QE.

Solution: thinning the detector (→ efficient diffusion into depletion zone)

Thinned CCDs

Considerations for thinning the CCD:

- Thickness must be ≥ one photon absorption length 1/a (if not, photons will be lost)
- $a = a(\lambda)$, hence the thickness depends on design wavelength [$1/(a_{1\mu m}) = 80\ \mu m$; $1/(a_{0.4\mu m}) = 0.3\ \mu m$!]
- Luckily, the electron diffusion length in low-level doped Si is 10–50 µm [at 150K].
- Good compromise for visible CCDs: thinning to 15–20 µm [at the cost of QE in the red]

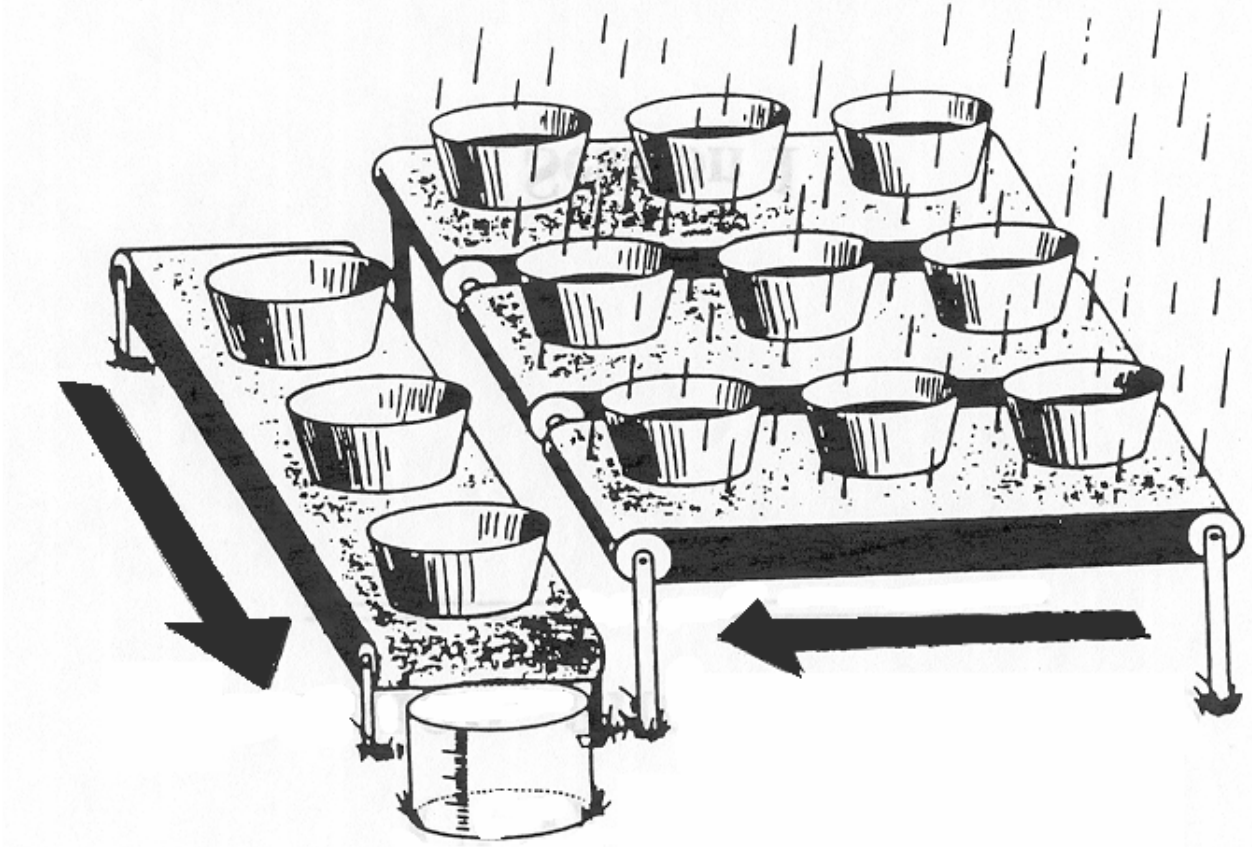
Making CCDs too thin results in:
- low QE
- back reflection from the opposite site → fringing (see below)

Making CCDs too thick results in:
- wandering into neighbouring depletion zones → loss in resolution

CCDs

B. Charge Transfer and Readout

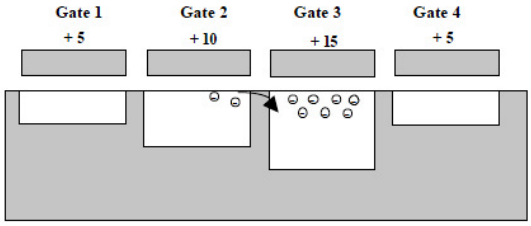
And this is how the CCD readout works …



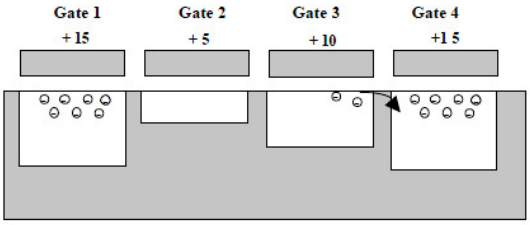
http://solar.physics.montana.edu/nuggets/2000/001201/ccd.png

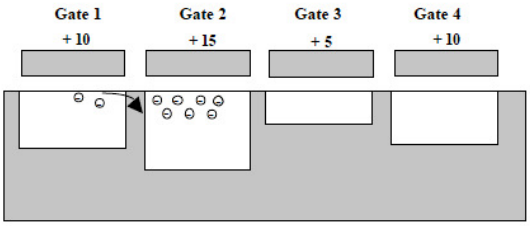
Charge Transfer "in a Nutshell"

If a potential well is moved together with the surrounding barrier, most of the electric charge will move with it.



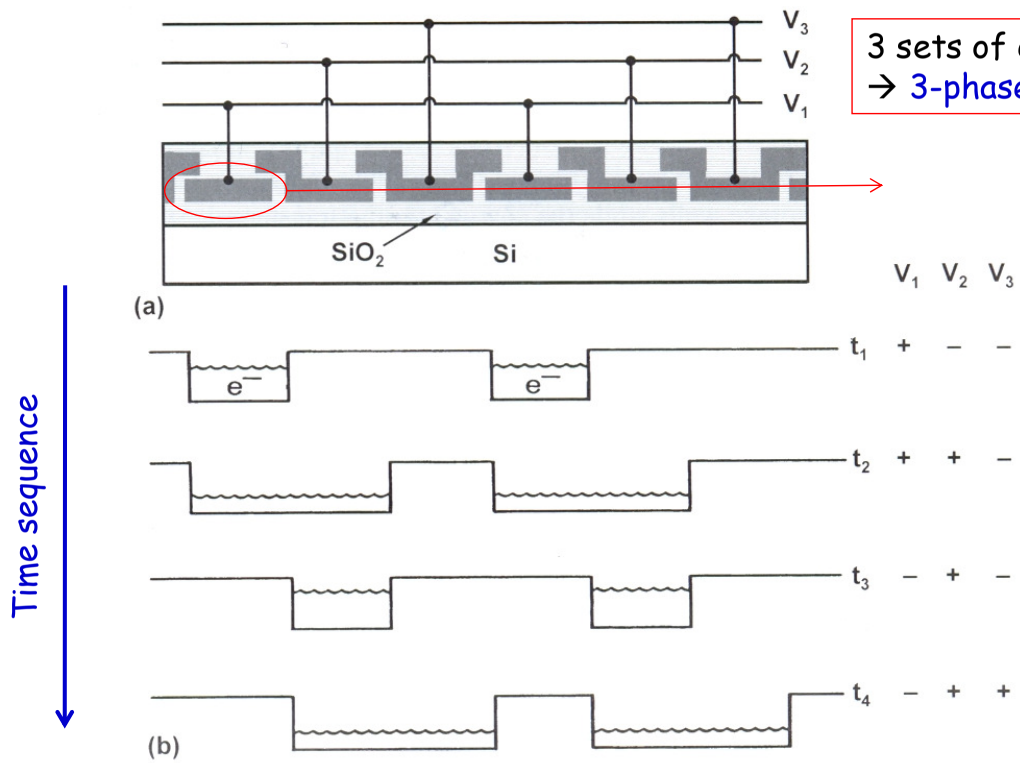
The collected charges are passed along the columns to the edge of the array to the output amplifier.





Taken from a lecture by Dr. L. Fuller, given at RIT – see http://people.rit.edu/lffeee/lec_CCD.pdf

Charge Transfer in a 3-Phase CCD



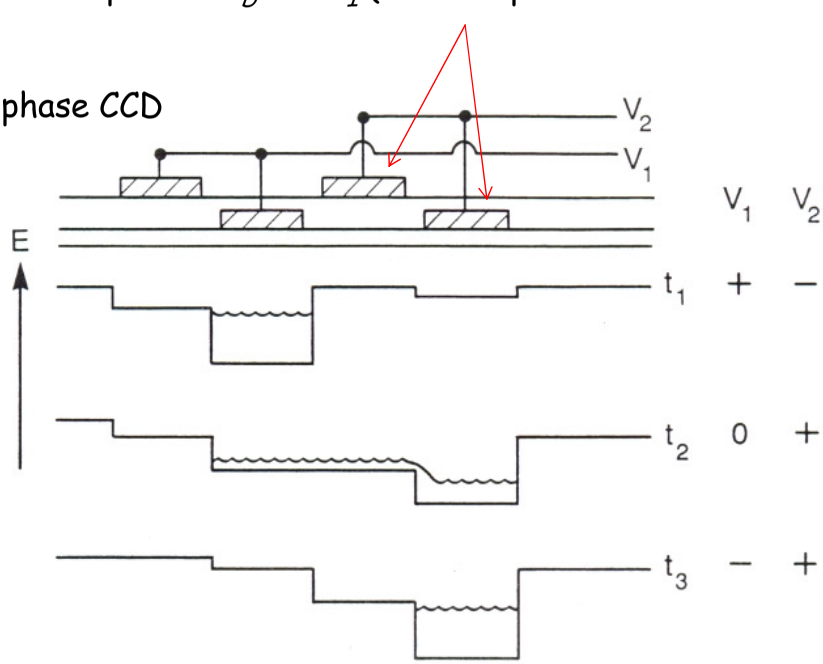
3 sets of electrodes
→ 3-phase CCD

4- and 2-Phase Clocking Schemes

Remember: width of depletion zone = $w = \left(\frac{2\kappa_0 \varepsilon_0}{qN_D} \left| V_g \right| + t_I^2 \right)^{1/2} - t_I$

One can use dependency of well depth on N_D and t_I (relative placement in the SiO_2 layer)

→ Operate 4 phases as a 2-phase CCD

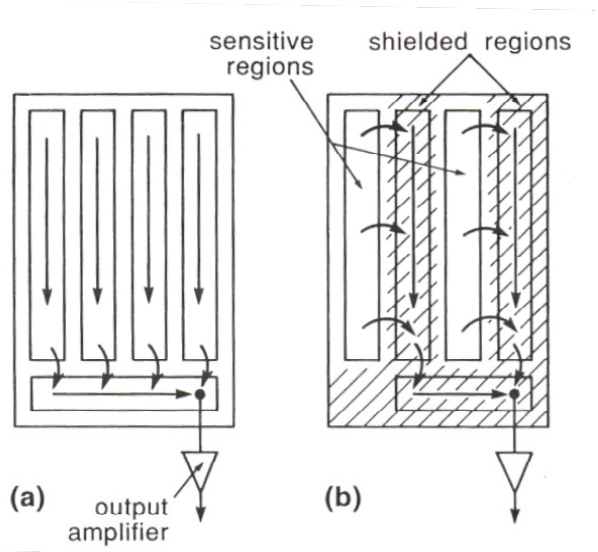


Charge Transfer Architectures (1)

1. Line address architecture (a) – shifts contents of columns to output register (row) which transfers the charge packages to amplifier. The array is illuminated while transfers occur → $t_{int} \gg t_{read}$ (o.k. for astronomy) <u>or</u> a shutter will be closed during the readout.

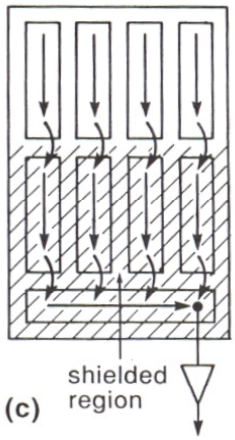
2. Interline transfer (b) – charges are shifted into columns which are protected from light (masked).

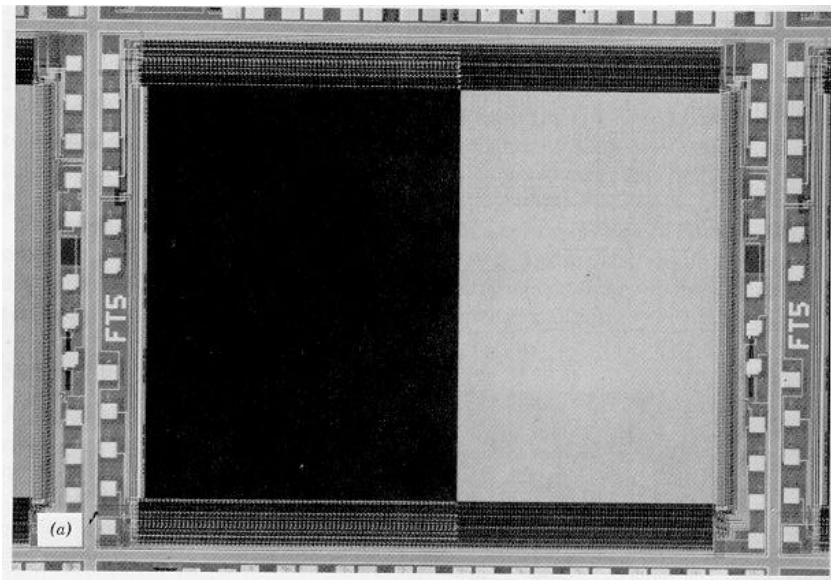
Scheme (a) can also be operated in time-delay-integration (TDI) mode → image moves along the columns at transfer speed.
(see side note on GAIA)



Charge Transfer Architectures (2)

3. Frame field transfer (c) – charges are shifted to an adjacent CCD section which is protected from light.

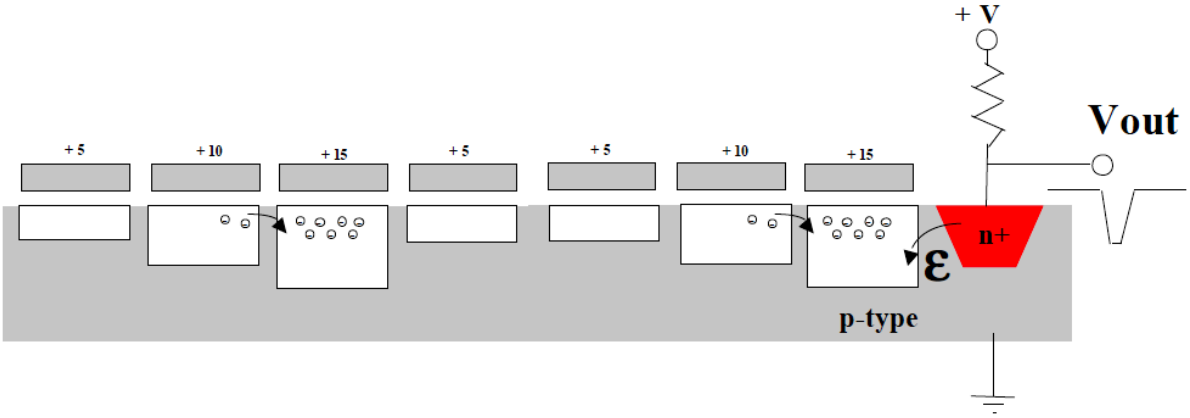




588 lines of 604 pixels, sensor area on left and light shielded storage area on right
Taken from a lecture by Dr. L. Fuller, given at RIT – see http://people.rit.edu/lffeee/lec_CCD.pdf

Charge Readout

When electrons are emptied from the last gate the electric field associated with the p-n junction collects electrons that move to +V, and V_{out} will drop to a level proportional to the number of electrons in that packet.



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