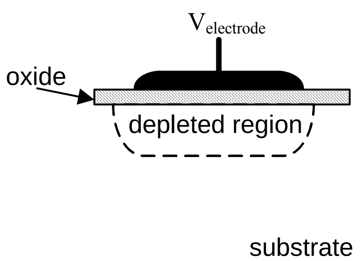
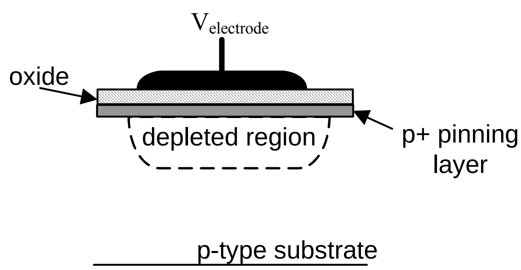
Digital Camera Sensors

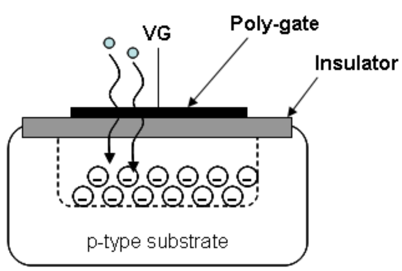
- Problem with simple photodiode is low current
- Rapidly reach the noise limits for low light
- But film integrates the photon signal
- With film can do integrations of hours of signal
- (Film though is ~1% efficient in light conversion)
- Want a sensor which integrates the photodiode
- Charge Couple Devices (CCD) were the first to do that
- CCD is related to photogate detector (one cell of it)
- Create a gate over a silicon region
- Apply voltage to gate to create a depleted region
- Ie voltage creates the Space Charge Layer as in photodiode
- Now this traps photoelectrons



(a) Standard Photogate.



(b) Buried Photogate.



Standard Photogate.

Pixel performance metrics

- Performance measured: Quantum Efficiency (QE) and responsivity
- Light comes to photodiode/photogate
- Some is reflected
- Different wavelengths have different penetration depths
- Electron hole pairs may be lost through recombination/traps

$$QE = \eta = \frac{\#Generated, Collected\_Electron - Hole - Pair}{\#incident\_photons}.$$

- Photocollection is a function of wavelength
- Hence express as function of λ

$$\eta = \frac{I_{ph} / e}{P_o / h\upsilon},$$

I_{ph} is the photogenerated current
P_o is the incident light power.
h is planck's constant

- Express responsivity in output current

$$R = \frac{I_{ph}(A)}{P_o(W)} = \eta \frac{e\lambda}{hc}.$$

- A good photodetector QE ~90-95% over visible spectrum

Charge Coupled Devices

- CCD's developed in 1970
- Linear array of MOS Capacitor like structures
- Originally looked at for memor storage (Bit Buckets)
- Now primary application in imaging devices

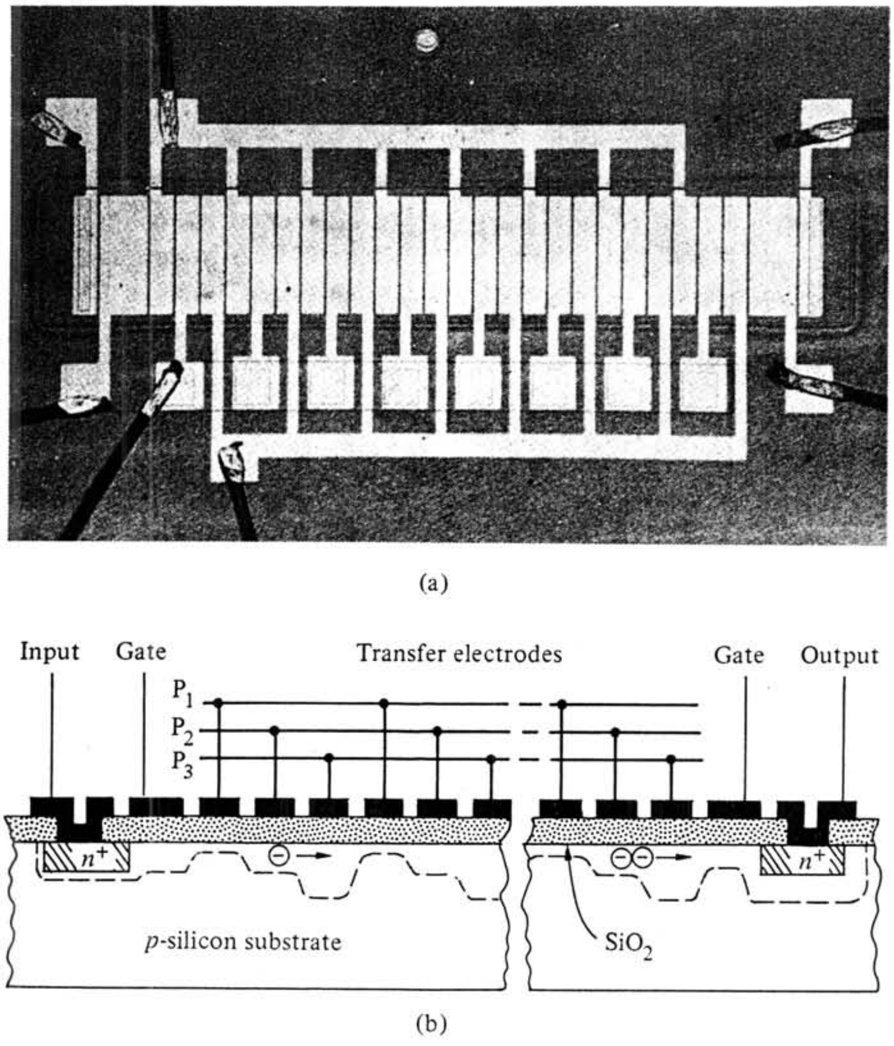


Fig. 5 First charge-coupled device comprising eight three-phase elements and input-output gates and diodes, shown (a) in plan view and (b) schematically in its cross-sectional view. (From Tompsett et al., [9].)

Charge Sortage and CCD

- Series of gate lines over oxide on p substrate
- let $V_2 > V_1$ then create deep depleation well
  (both V_1 and V_3 at V_1 value
- Surface potential well under the 2nd line
- Charges from say light e-h pairs become trapped
- At time t_0 increase V_3 so > V_2
- now well deeper for 3rd line
- Electrons flow into lower well
- Now have coupled and tranfered the charge

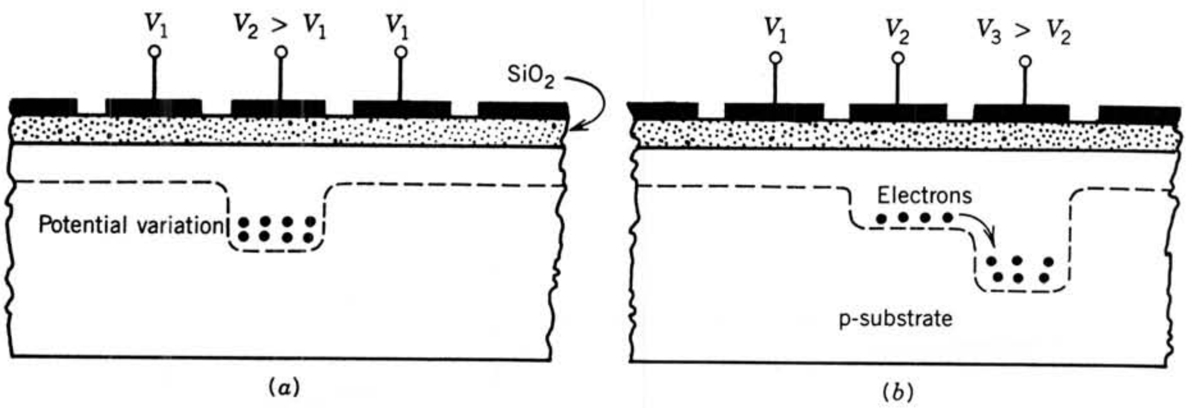


FIGURE 16.26 Cutaway view of a CCD illustrating the processes of (*a*) charge storage and (*b*) charge transfer.

Charge Trapping

- Charge trapped in both demensions
- array of gate lines in x direction
- In y have gate oxide thickness small only in trapped region

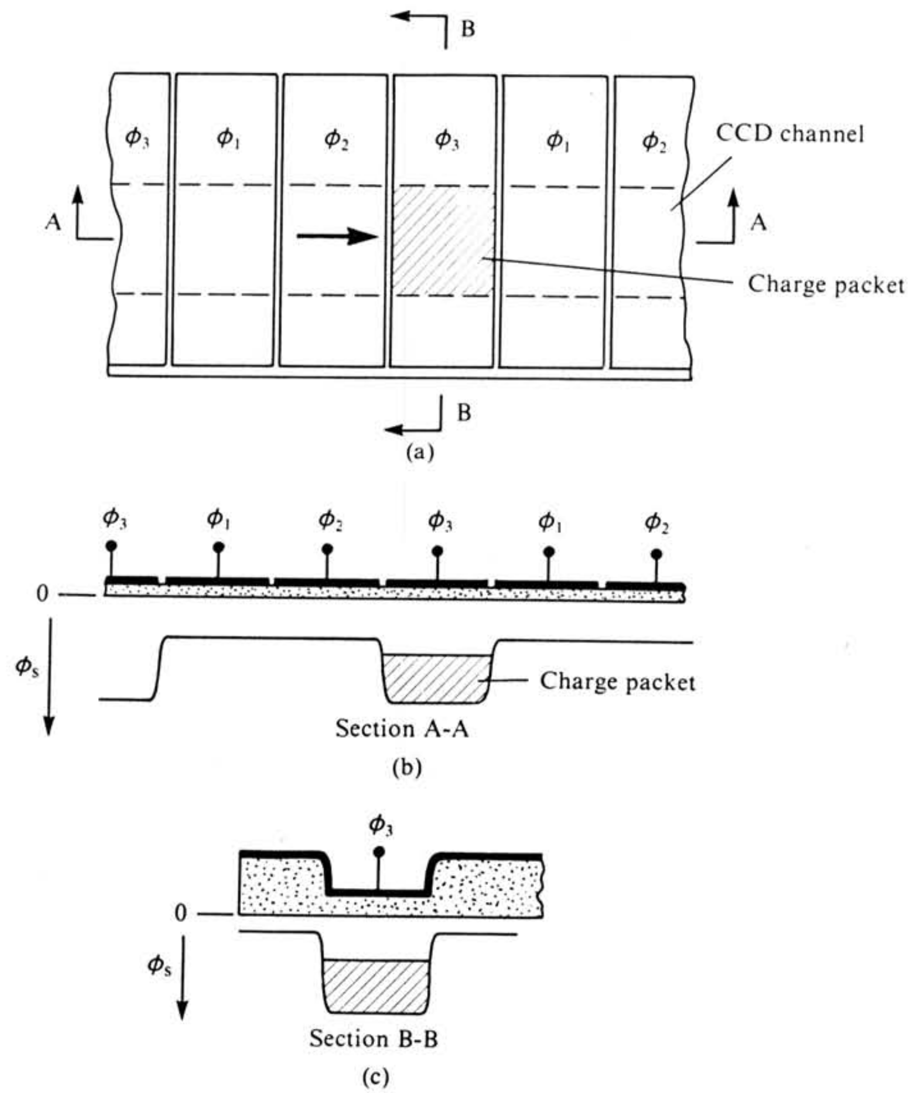


Fig. 3.10 Charge confinement in a CCD. The charge is the shaded region in (a). It is confined along A-A by the gate potentials, with $V_{G3} > V_{G1} = V_{G2}$, in (b), and along B-B by the two different oxide thicknesses in (c).

Three Phase CCD Operation

- Use a 3 phase clock in repeating 3 line sets
- Move charge to adjacent well
- Then isolate that well

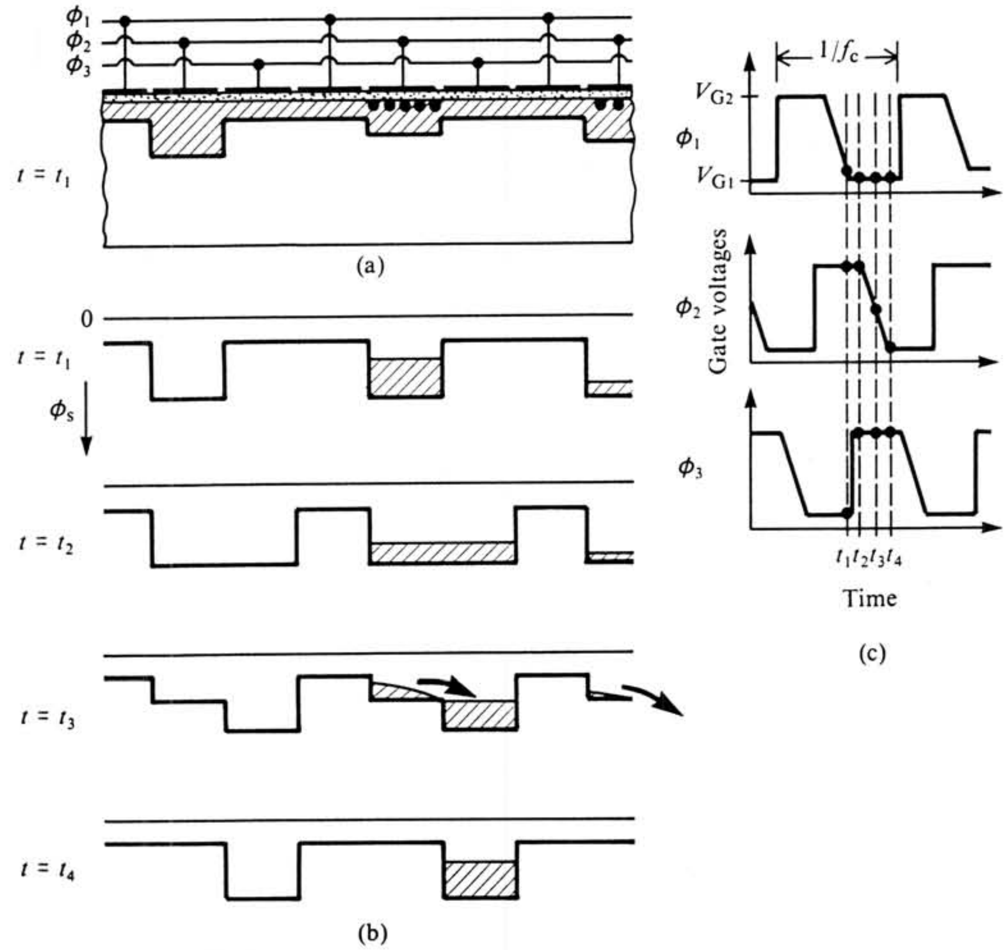


Fig. 3.11 (a) Device cross section, and (b) surface potential diagrams for times t_1, t_2, t_3, and t_4 shown on the clock-voltage waveform diagram in (c).

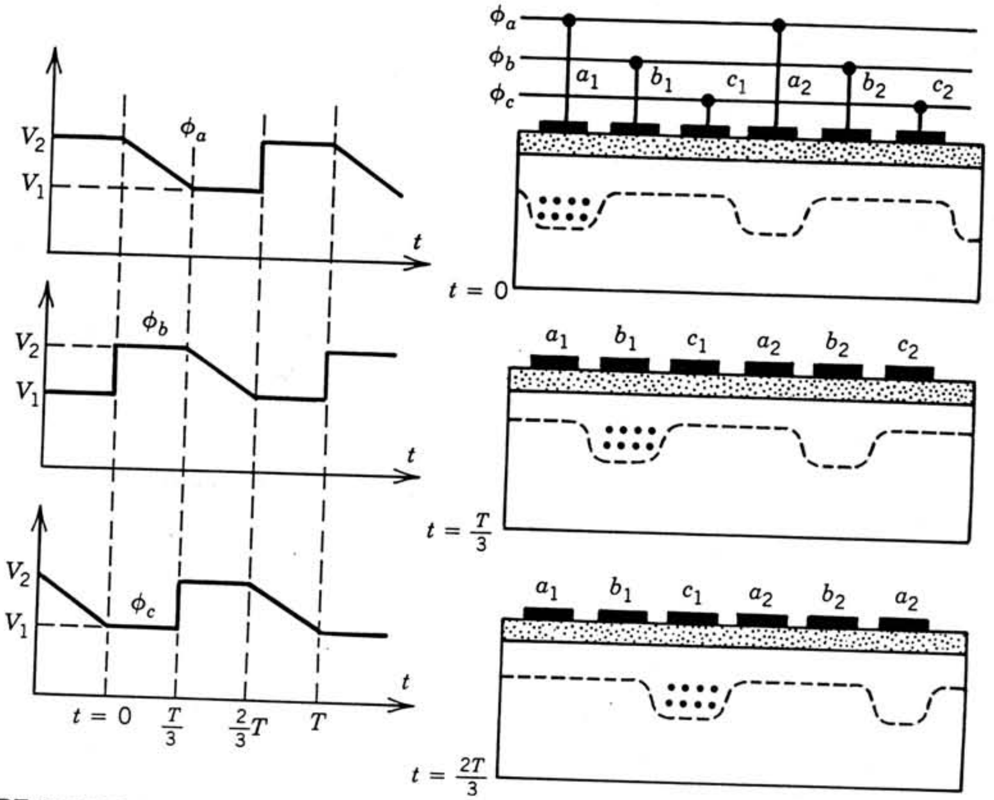


FIGURE 16.27 Schematic diagrams illustrating the operation of a three-phase CCD. (After W. S. Boyle and G. E. Smith, Charge coupled semiconductor devices, *Bell Syst. Tech. J.,* vol. 49, p. 589. Copyright © 1970 AT&T. Reprinted by special permission.)

CCD and Deep Depletion

- Important operation for CCD is Deep Depletion
- Recall that was when Voltage change faster than recombination could supply carriers
- Then go into deep depletion instead of inversion
- Time taken for carriers to move in Thermal Relaxation Time several seconds to many minutes depending on CCD
- Cool CCD to reduce that time (Dark Current noise)
- If charge of carriers minority carrier introduced Q_{sig} eg by e-h pairs from light
- Collects under gate and cause reduciton in surface potential

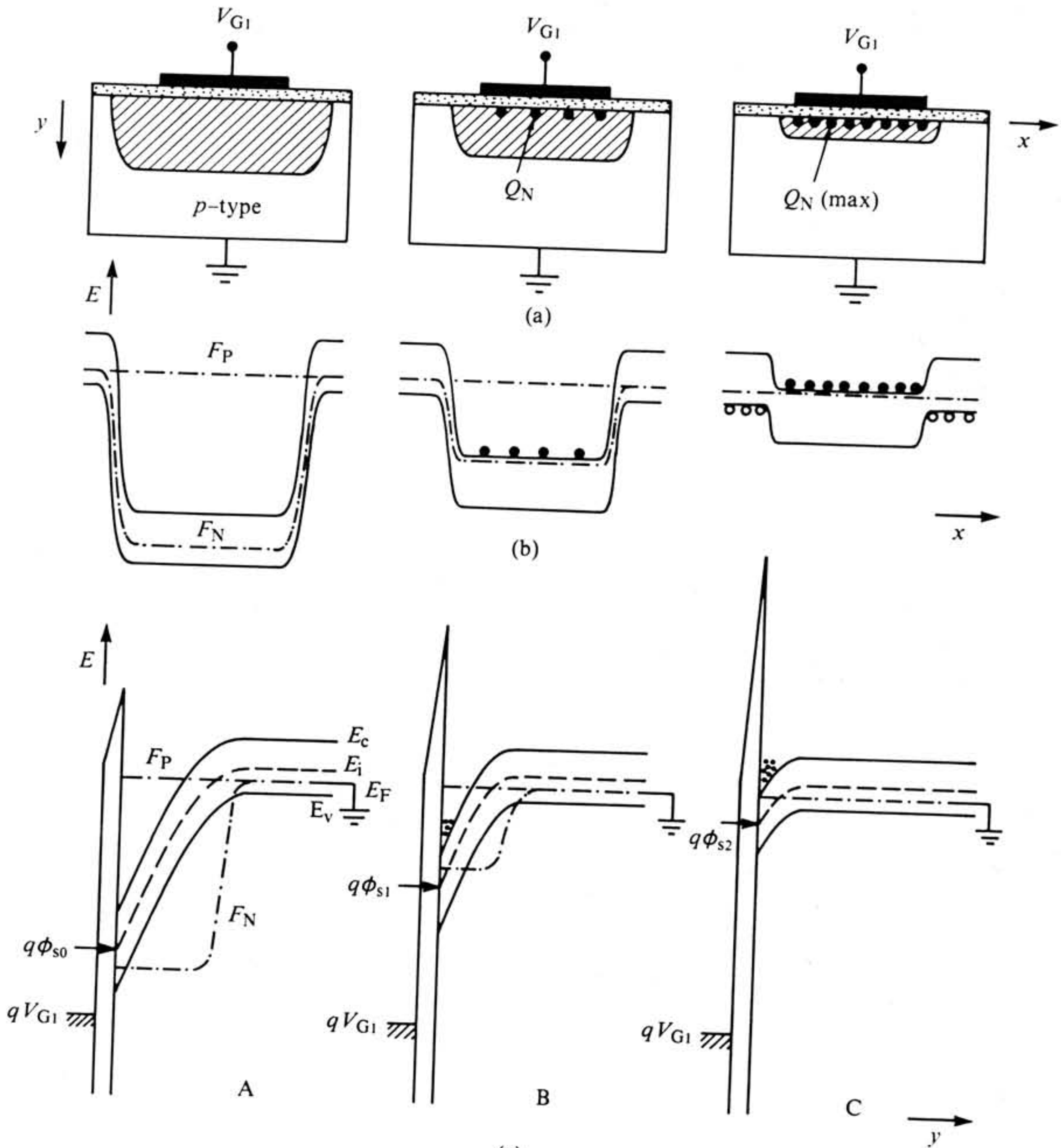


Fig. 3.6 MOS-C of Fig. 3.5 for points A, B, and C. (a) shows the space-charge regions, (b) shows the potential diagrams along x for $y = 0$, and (c) shows the potential diagrams along y into the semiconductor. The inversion charge is indicated by the solid circles.

Pontentials in CCD

- Recall that charges modify the surface potential
- Relation to gate bias is

$$V_G - V_{FB} = -\frac{Q_s}{C_o} + \varphi_s$$

- where

$$\varphi_s = \frac{qN_A W^2}{2\varepsilon_s \varepsilon_0}$$

- If a signal charge is present then surface charge becomes

$$Q_s = -qN_A W - Q_{sig}$$

- Thus the gate and potential relationship now becomes

$$V_G - V_{FB} = \frac{qN_A W}{C_o} + \frac{Q_{sig}}{C_o} + \varphi_s$$

- Eliminating W and solving for the potential yields

$$\varphi_s = V'G + V_o - (2V'_G V_o + V_o^2)^{1/2}$$

- where

$$V'_G = V_G - V_{FB} - \frac{Q_{sig}}{C_o}$$

$$V_o = \frac{qN_A 2\varepsilon_s \varepsilon_0}{C_o^2}$$

- Thus surface potential decreases almost linearly
  with signal charge

CCD output

- at output goes to floating diode and a transistor source
- charges collected when gate of transistor
- Lowers potential and charge flows in
- Acts as a source follower amplifier

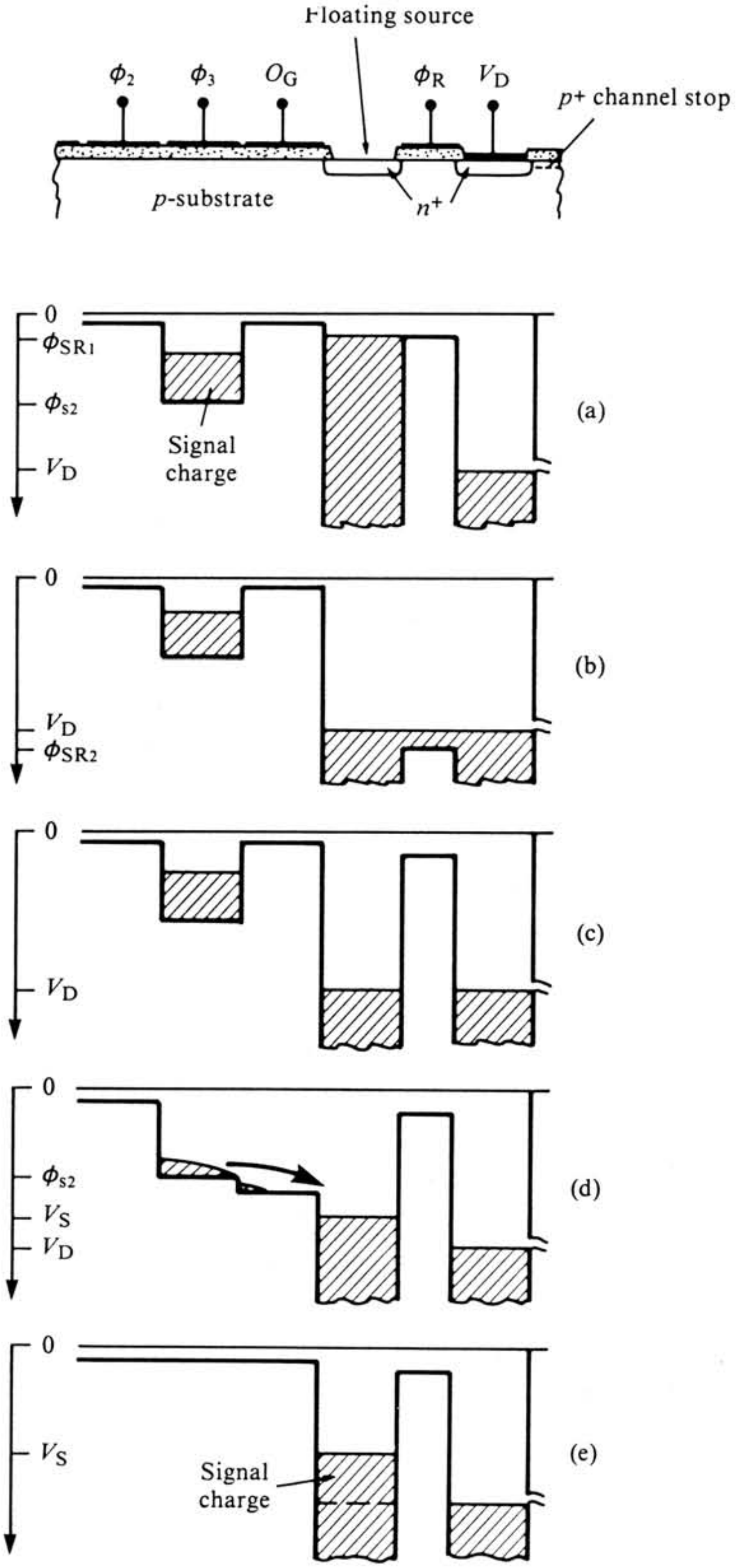


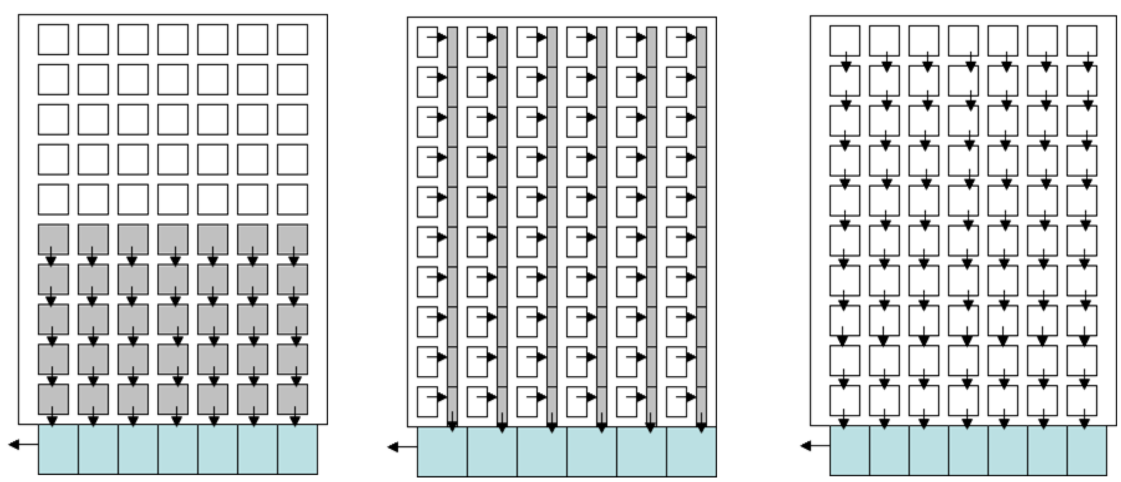
Fig. 3.13 The floating diffusion output, showing the main output circuit and the potentials at various stages, as discussed in the text.

CCD in a full Device

- CCDs were first successful digital cameras
- In the sensor array had several formats depending on output
- Imagers is an x by y array of CCDs

- Frame Transfer: move whole sensor array into another array
- Reason: fast transfer (output array is shielded from light)
- Then read out the array at needed speed
- Suffers from a smear problem

- Interline Transfer: photodiode collects e-n pairs
- Transfers to masked vertical CCD pixels
- transfer into the horizontal shift register one row at a time
- read by the output circuit
- Full-Frame CCD: most popular
- Entire array is photosensitive
- Shift data to output where it flows out
- Needs an external mechanical shutter



(a) Frame Transfer (FTCCD) **(b) Interline Transfer (ITCCD)** **(c) Full Frame (FFCCD)**

Common CCD structures (a) Frame Transfer, (b) Interline Transfer, (c) Full **Frame.**

Why Did CCDs go away

- CCDs have high QE
- Still used for most sensitive scientific work
- Especially when cooled to reduce noise
- However big problem is must be powered during exposure
- Also during readout
- Hence high power consumption
- Also requires specialized fabrication process
- Most early cameras were CCDs (Kodak, Nikon)
- CMOS APS began to replace them about 2008