Astronomical Observational Techniques and Instrumentation

RIT Course Number 1060-771

Professor Don Figer

PN junction, diodes, transistors, circuits, single-element detectors

Aims for this lecture

- describe the physics of the PN junction
- describe the principles behind important electrical components for detectors
- provide working knowledge of these components
- give examples of the components used in detector applications

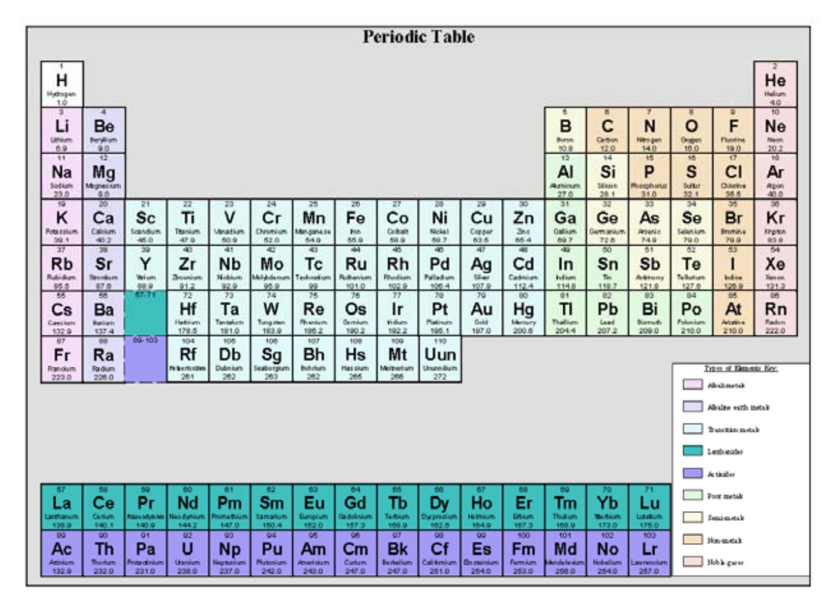
Lecture Outline

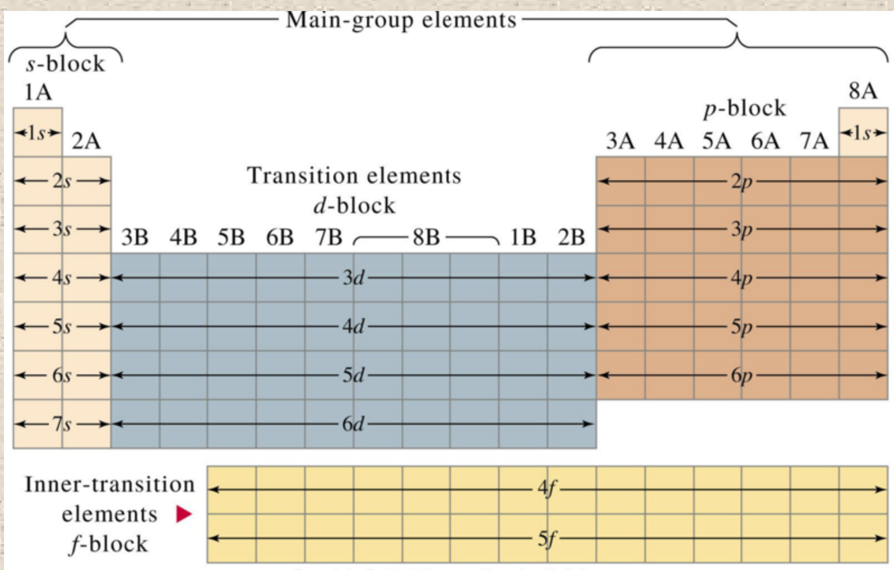
- Theory and operation of electrical components
  - semiconductors
  - pn junction
  - diode
  - photodiode
  - light emitting diode (LED)
  - transistor
  - field-effect transistor (FET)
  - junction field-effect transistor (JFET)
  - metal-oxide field-effect transistor (MOSFET)
- Detector applications
  - pixel photodiode
  - source follower
  - amplifier

Semiconductors

Periodic Table and Groups

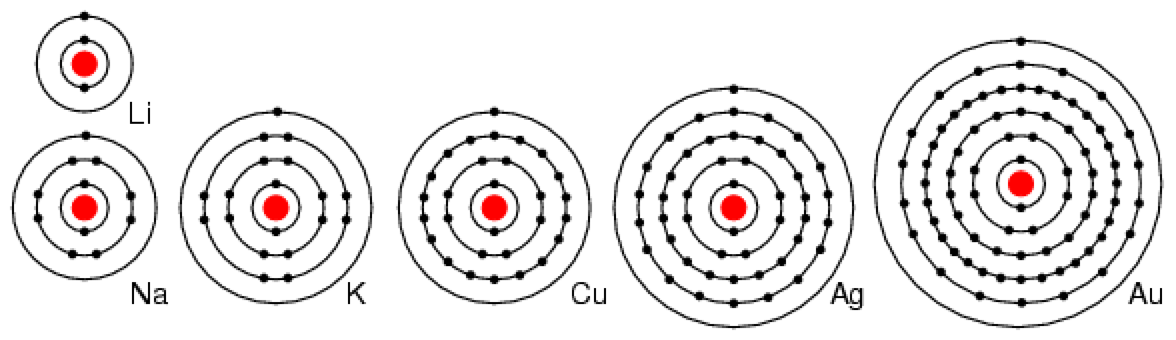
- Material properties depend on outer electron shell.
- Format of periodic table associates population of outer shell with columns (groups).





Conductors

- Li, Na, K, Cu, Ag, and Au have a single valence electron. These elements all have similar chemical properties. These atoms readily give away one electron to react with other elements. The ability to easily give away an electron makes these elements excellent conductors.

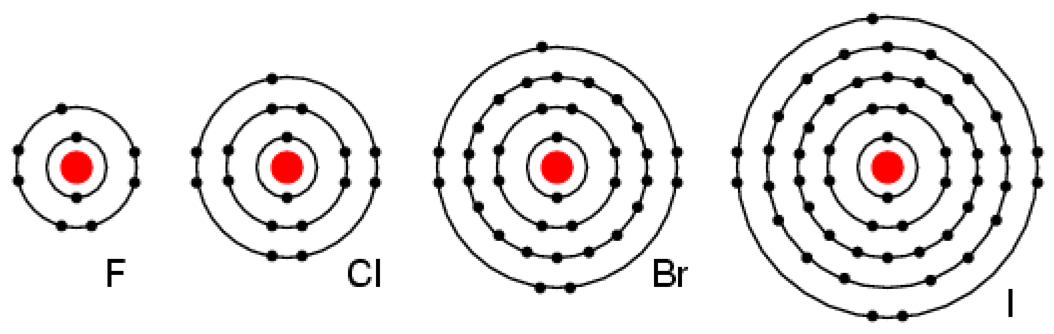


- *Periodic table group IA elements: Li, Na, and K, and group IB elements: Cu, Ag, and Au have one electron in the outer, or valence, shell, which is readily donated. Inner shell electrons: For n= 1, 2, 3, 4; $2n^2$ = 2, 8, 18, 32.*

http://www.allaboutcircuits.com/vol_3/chpt_2/3.html

Insulators

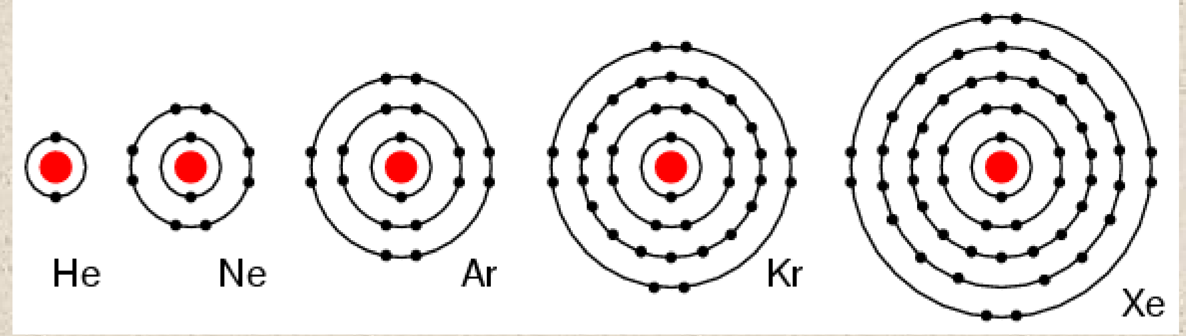
- Group VIIA elements: Fl, Cl, Br, and I all have 7 electrons in the outer shell. These elements readily accept an electron to fill up the outer shell with a full 8 electrons. (Figure below) If these elements do accept an electron, a negative ion is formed from the neutral atom. These elements which do not give up electrons are insulators.



- *Periodic table group VIIA elements: F, Cl, Br, and I with 7 valence electrons readily accept an electron in reactions with other elements.*

Noble (Inert) Gases

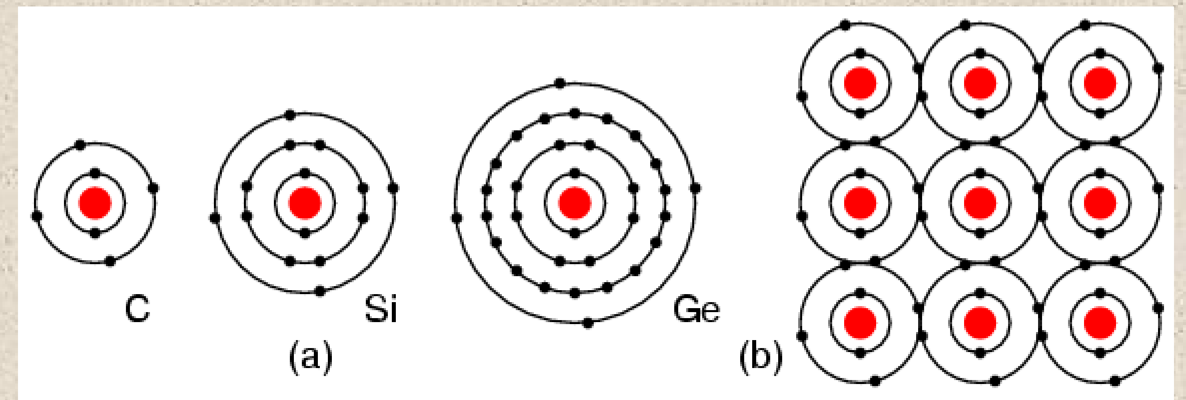
- Group VIIIA elements: He, Ne, Ar, Kr, Xe all have 8 electrons in the valence shell. (Figure below) That is, the valence shell is complete meaning these elements neither donate nor accept electrons. Nor do they readily participate in chemical reactions since group VIIIA elements do not easily combine with other elements. These elements are good electrical insulators and are gases at room temperature.



- *Group VIIIA elements: He, Ne, Ar, Kr, Xe are largely unreactive since the valence shell is complete.*

Semiconductors

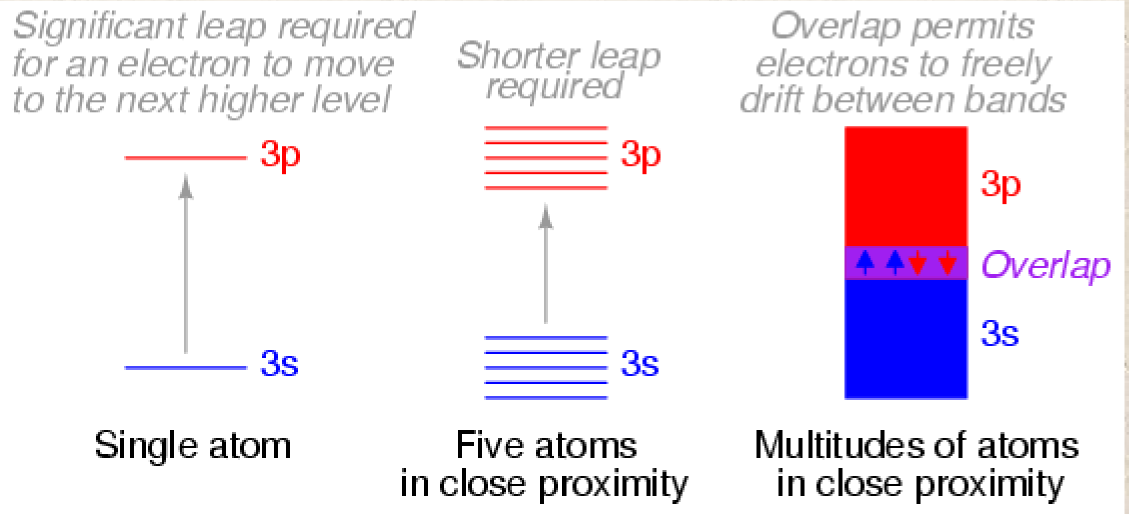
- Group IVA elements: C, Si, Ge, having 4 electrons in the valence shell, form compounds by sharing electrons with other elements without forming ions. This shared electron bonding is known as *covalent bonding*. Note that the center atom (and the others by extension) has completed its valence shell by sharing electrons. Note that the figure is a 2-d representation of bonding, which is actually 3-d. It is this group, IVA, that we are interested in for its semiconducting properties.



- *(a) Group IVA elements: C, Si, Ge having 4 electrons in the valence shell, (b) complete the valence shell by sharing electrons with other elements.*

Energy Bands in Conductors

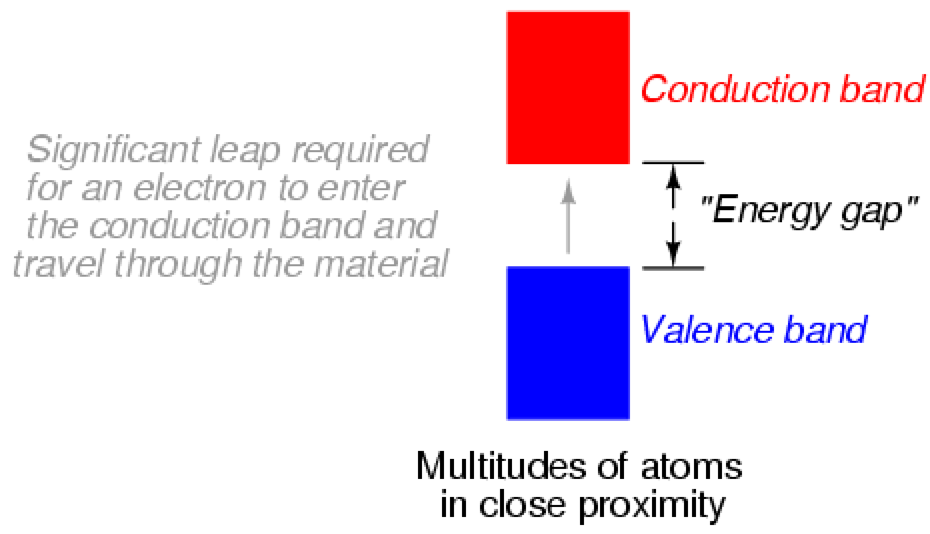
- When atoms combine to form substances, the outermost shells, subshells, and orbitals merge, providing a greater number of available energy levels for electrons to assume. When large numbers of atoms are close to each other, these available energy levels form a nearly continuous band wherein electrons may move as illustrated in Figure.



Electron band overlap in metallic elements.

Energy Bands in Insulators

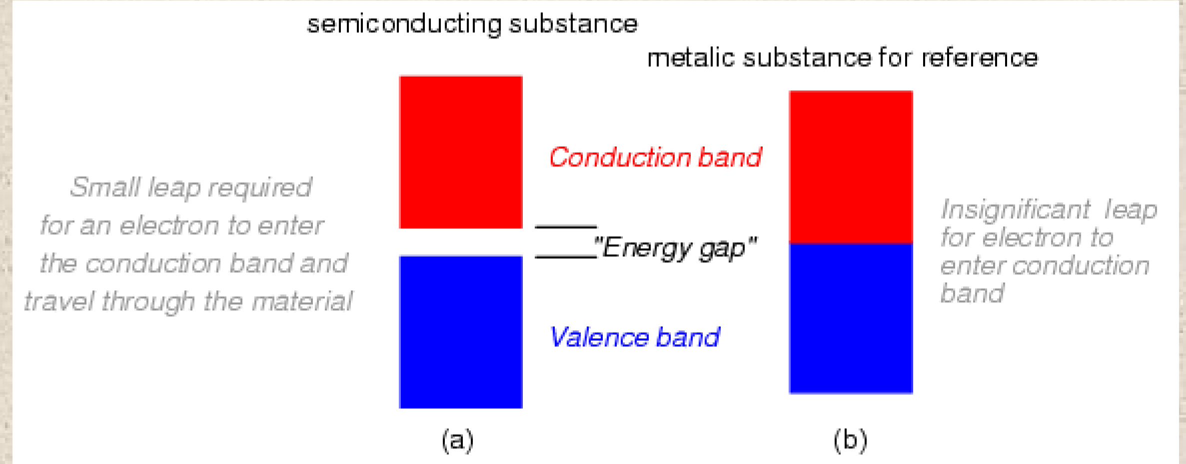
- In some substances, a substantial gap remains between the highest band containing electrons (the valence band) and the next band, which is empty (the conduction band). As a result, valence electrons are “bound” to their constituent atoms and cannot become mobile within the substance without a significant amount of imparted energy. These substances are electrical insulators.



Electron band separation in insulating substances.

Energy Bands in Semiconductors

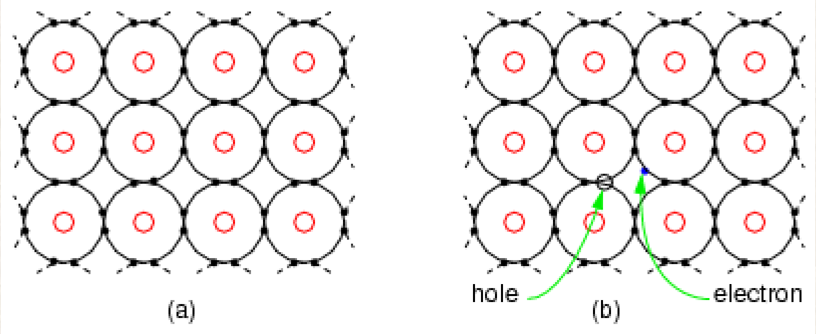
- Materials that fall within the category of semiconductors have a narrow gap between the valence and conduction bands. Thus, the amount of energy required to motivate a valence electron into the conduction band where it becomes mobile is quite modest.



Electron band separation in semiconducting substances, (a) multitudes of semiconducting close atoms still results in a significant band gap, (b) multitudes of close metal atoms for reference.

Intrinsic Semiconductors

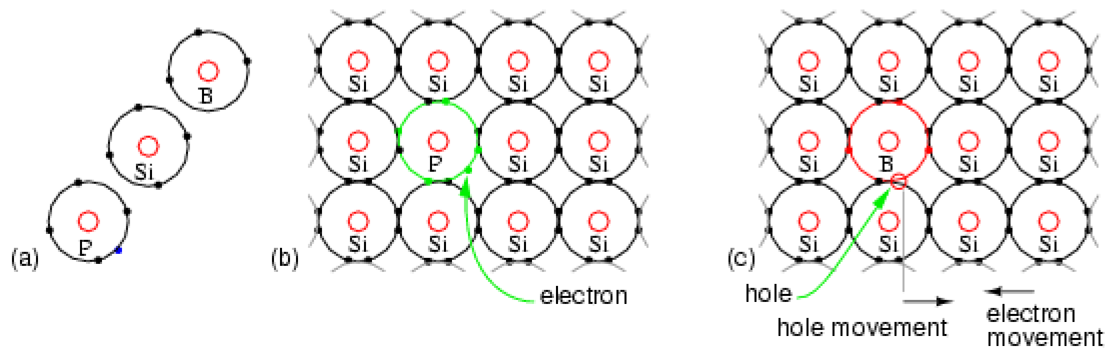
- Four electrons in the valence shell of a semiconductor form covalent bonds to four other atoms. All electrons of an atom are tied up in four covalent bonds, pairs of shared electrons. Electrons are not free to move about the crystal lattice. Thus, intrinsic, pure, semiconductors are relatively good insulators as compared to metals.



- *(a) Intrinsic semiconductor is an insulator having a complete electron shell. (b) However, thermal energy can create few electron hole pairs resulting in weak conduction.*

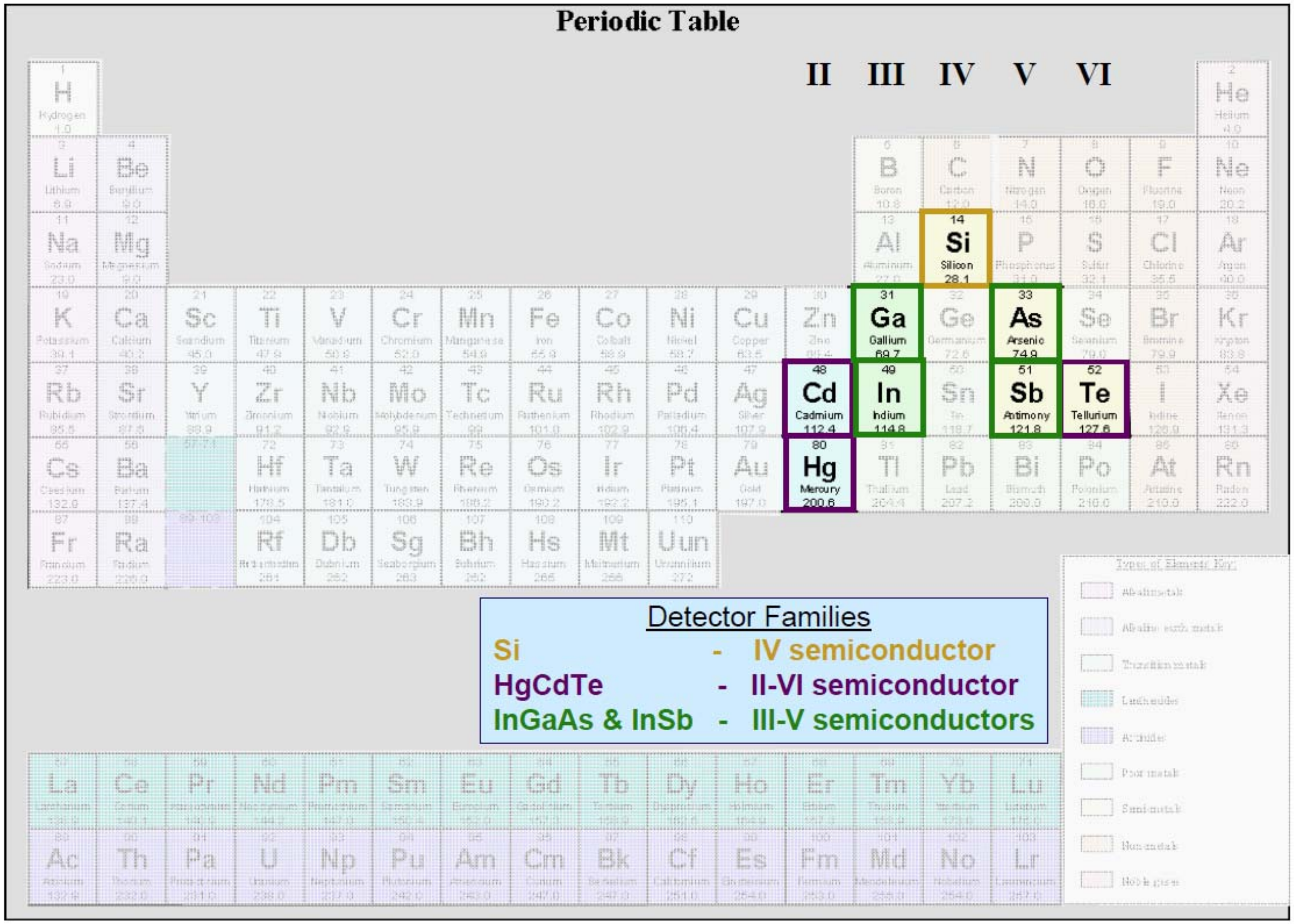
Dopants in Semiconductors

- The crystal lattice contains atoms having four electrons in the outer shell, forming four covalent bonds to adjacent atoms.
- The addition of a phosphorus atom with five electrons in the outer shell introduces an extra electron into the lattice as compared with the silicon atom.
- The impurity forms four covalent bonds to four silicon atoms with four of the five electrons, fitting into the lattice with one electron left over.
- The spare electron is not strongly bonded to the lattice as the electrons of normal Si atoms are. It is free to move about the crystal lattice.
- Application of an external electric field produces strong conduction in the doped semiconductor in the conduction band. Heavier doping levels produce stronger conduction.
- Thus, a poorly conducting intrinsic semiconductor has been converted into a good electrical conductor.



- *(a) Outer shell electron configuration of donor N-type Phosphorus, Silicon (for reference), and acceptor P-type Boron. (b) N-type donor impurity creates free electron (c) P-type acceptor impurity creates hole, a positive charge carrier.*

Periodic Table and Detector Material



Detector Families

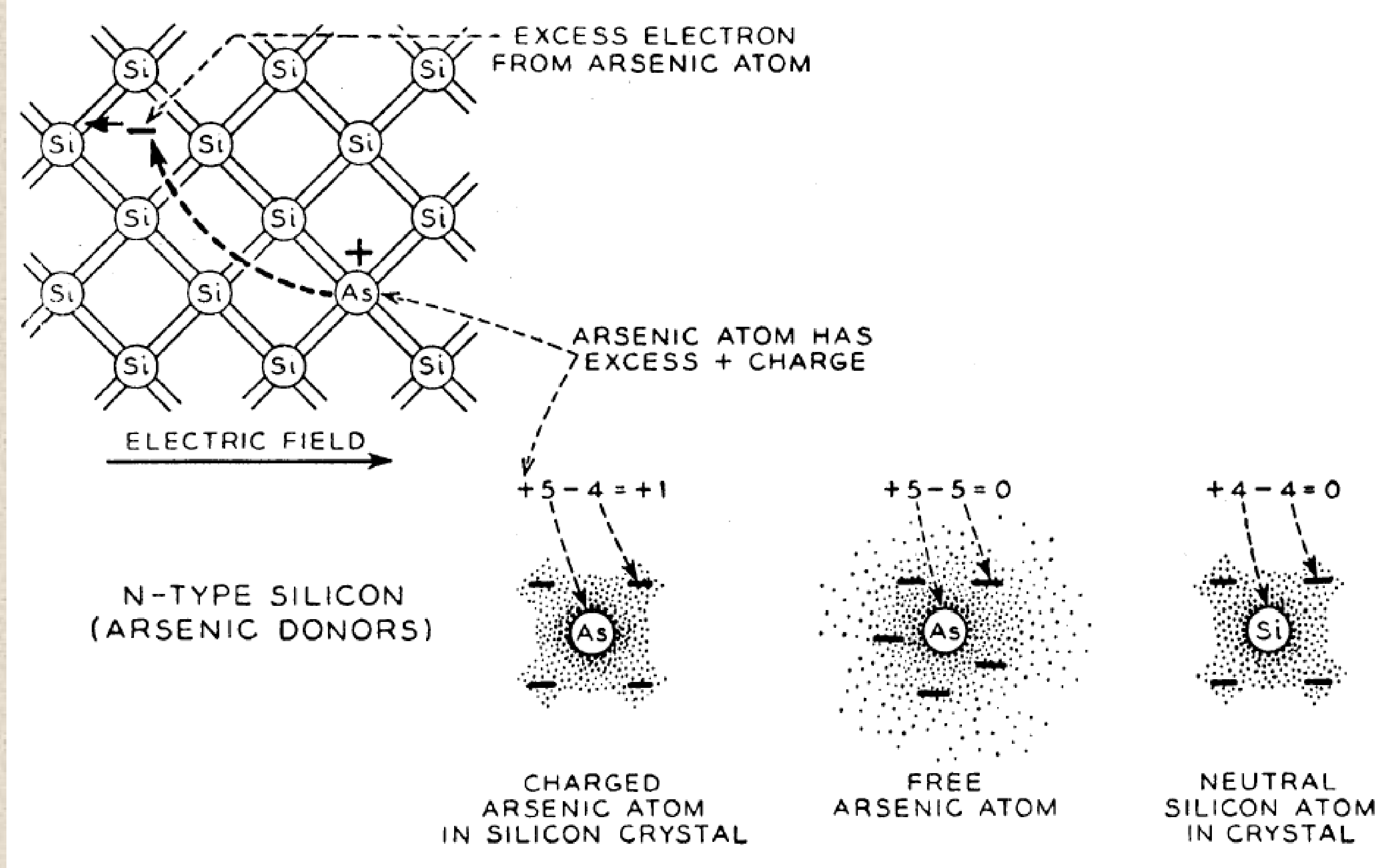
Si - IV semiconductor
HgCdTe - II-VI semiconductor
InGaAs & InSb - III-V semiconductors

PN Junction

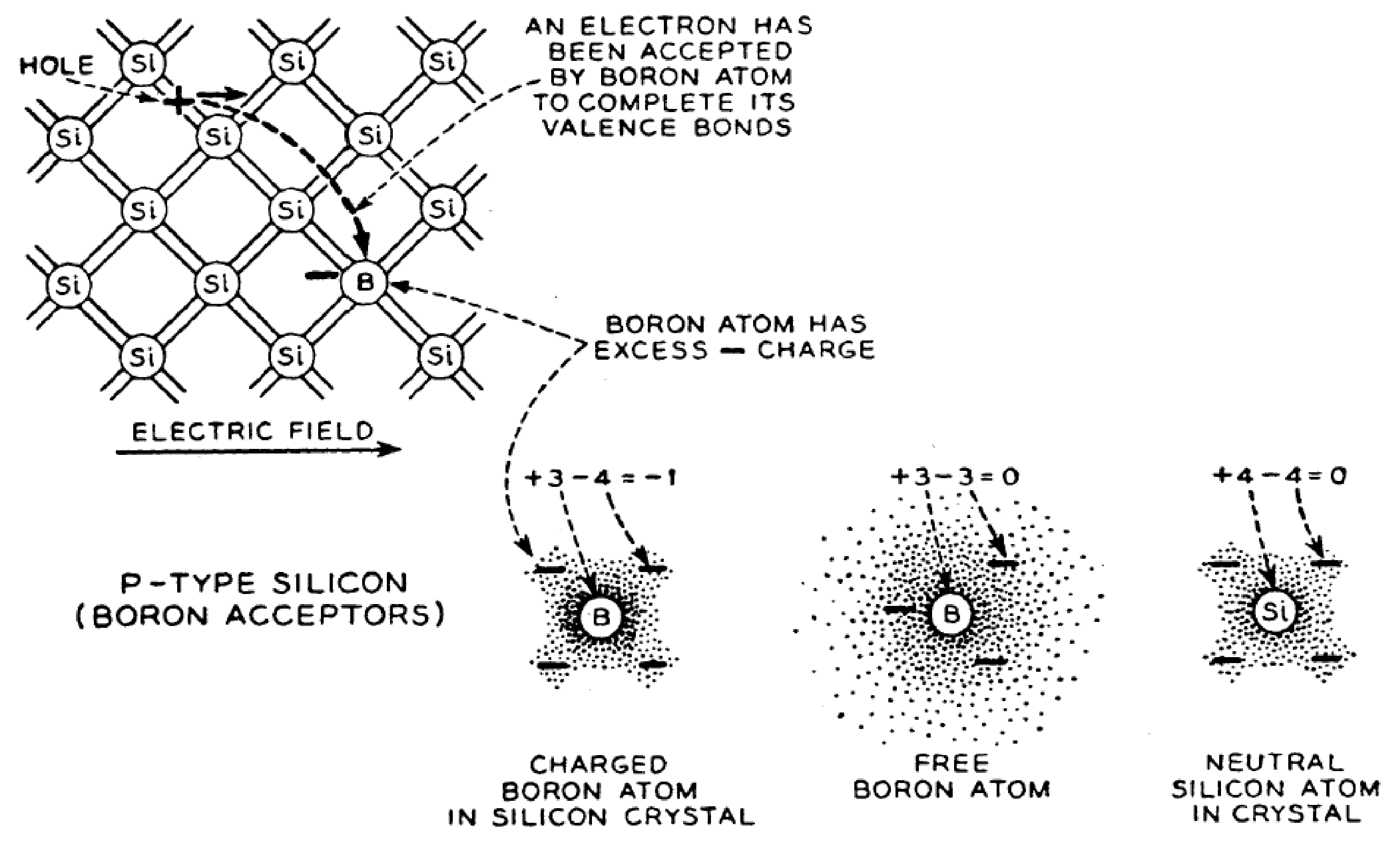
pn Junction Review

- PN junctions are fabricated from a monocrystalline piece of semiconductor with both a P-type and N-type region in proximity at a junction.
- The transfer of electrons from the N side of the junction to holes annihilated on the P side of the junction produces a barrier voltage. This is 0.6 to 0.7 V in silicon, and varies with other semiconductors.
- A forward biased PN junction conducts a current once the barrier voltage is overcome. The external applied potential forces majority carriers toward the junction where recombinetion takes place, allowing current flow.
- A reverse biased PN junction conducts almost no current. The applied reverse bias attracts majority carriers away from the junction. This increases the thickness of the nonconducting depletion region.
- Reverse biased PN junctions show a temperature dependent reverse leakage current. This is less than a µA in small silicon diodes.

N-type

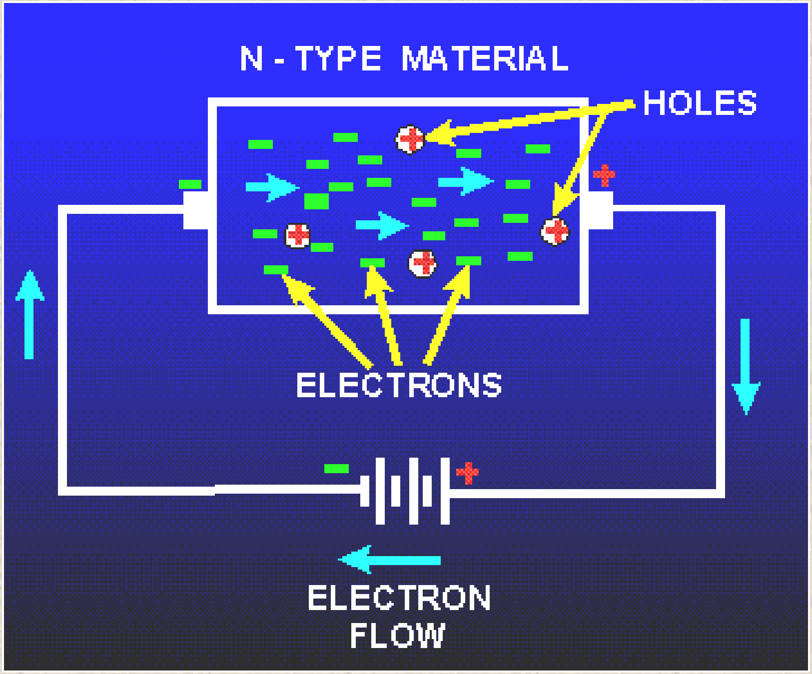

EXCESS ELECTRON FROM ARSENIC ATOM
Si
As
+
−
ARSENIC ATOM HAS EXCESS + CHARGE
ELECTRIC FIELD
N-TYPE SILICON (ARSENIC DONORS)
+5 − 4 = +1
+5 − 5 = 0
+4 − 4 = 0
CHARGED ARSENIC ATOM IN SILICON CRYSTAL
FREE ARSENIC ATOM
NEUTRAL SILICON ATOM IN CRYSTAL

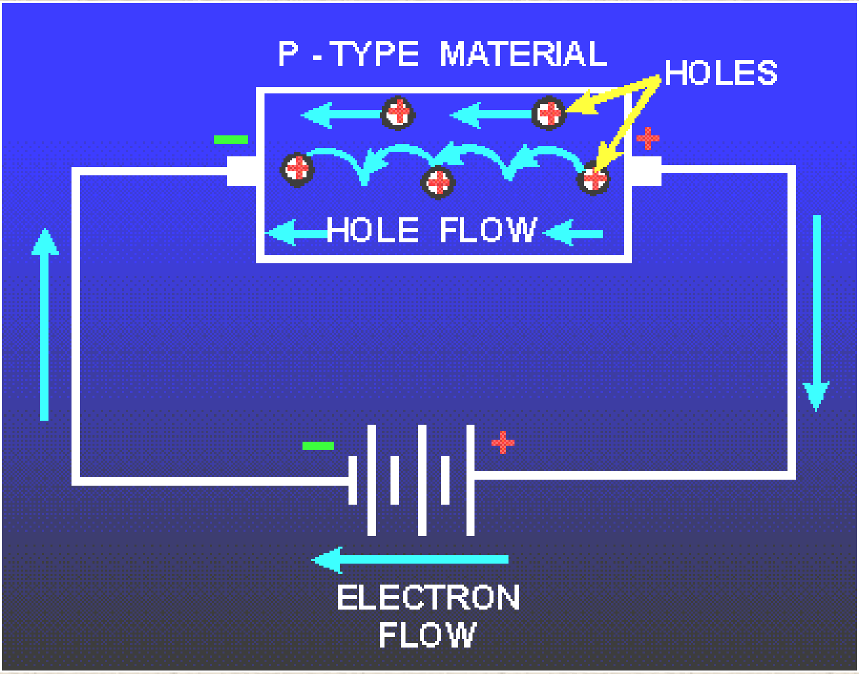
P-type


HOLE
Si
B
AN ELECTRON HAS BEEN ACCEPTED BY BORON ATOM TO COMPLETE ITS VALENCE BONDS
BORON ATOM HAS EXCESS — CHARGE
ELECTRIC FIELD
P-TYPE SILICON (BORON ACCEPTORS)
+3 − 4 = −1
+3 − 3 = 0
+4 − 4 = 0
CHARGED BORON ATOM IN SILICON CRYSTAL
FREE BORON ATOM
NEUTRAL SILICON ATOM IN CRYSTAL

Conduction in p/n-type Semiconductors

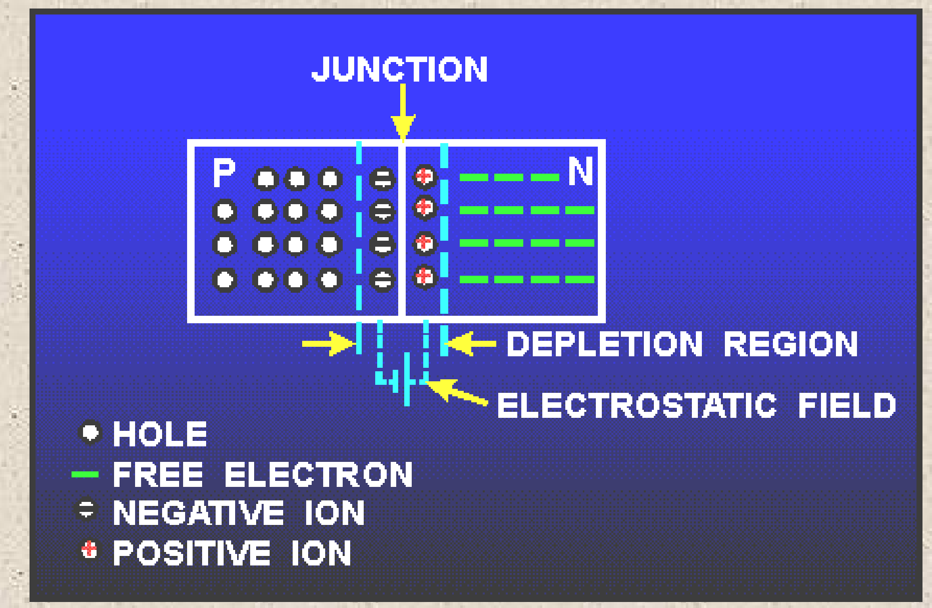
- In n-type material, excess electrons move freely in an electric field.
- In p-type material, holes migrate as electrons move in an electric field.

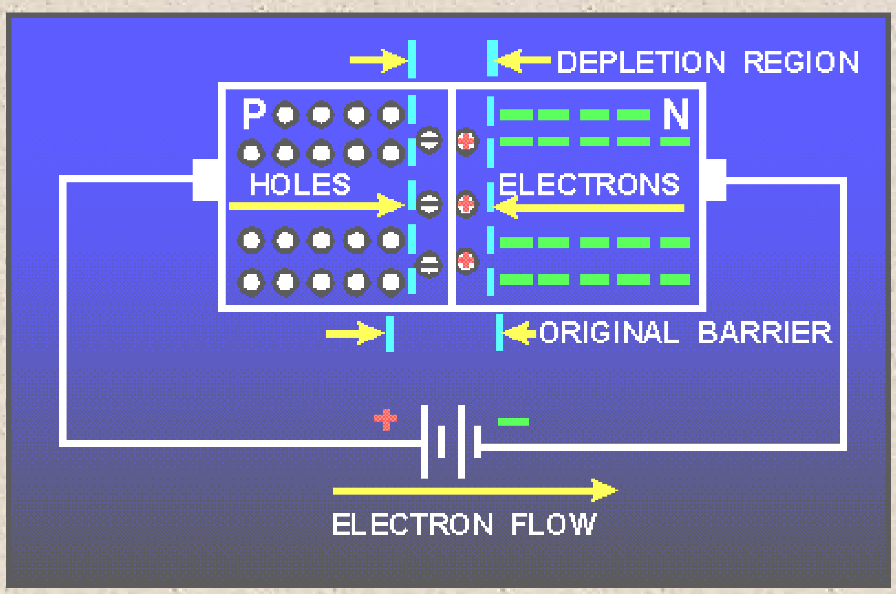


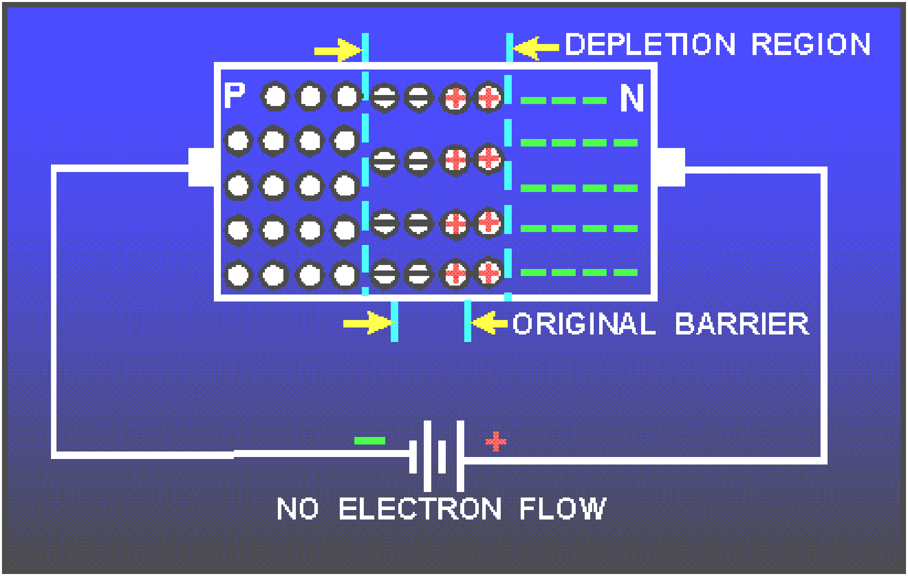


pn Junction and Biasing

- A pn junction is a sandwich of p-type and n-type material.
- A depletion region (free of excess charge) forms.
- An intrinsic electric field exists in this region.
- An external bias field can increase or decrease the width of the depletion region.







Carrier Densities

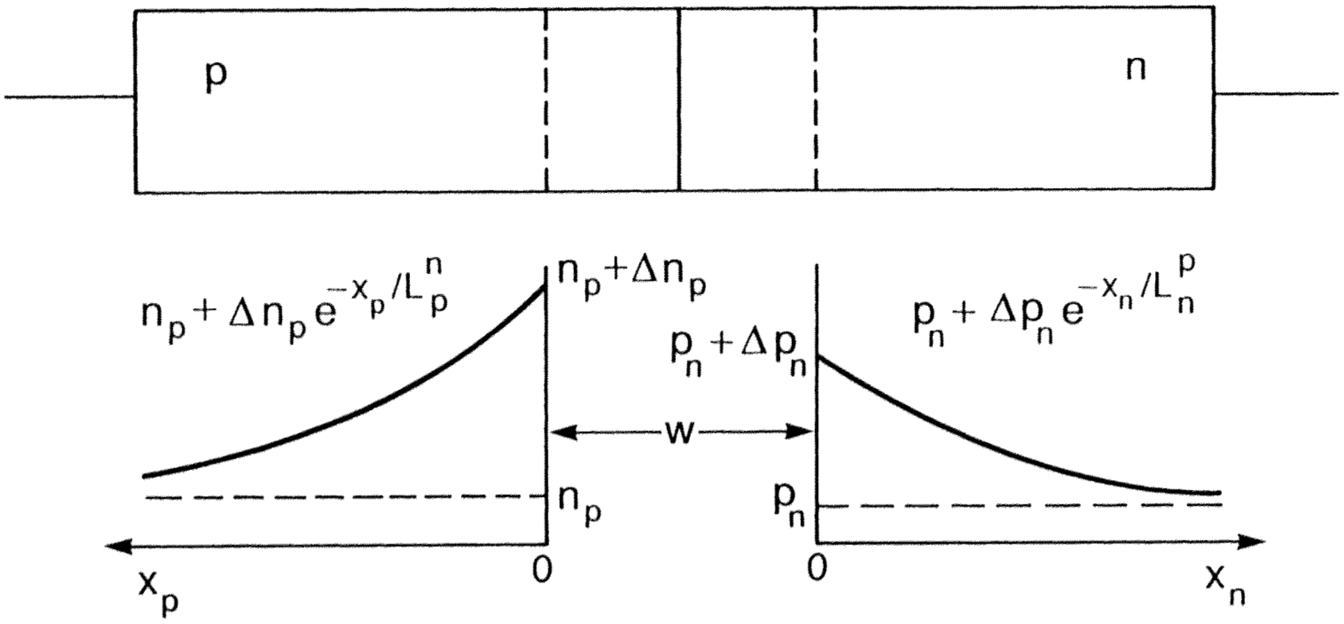


Figure 4.7. Carrier densities in a diode.

PN Junction: IV Characteristics

- Current-Voltage Relationship

$$I = I_o[e^{eV/kT} - 1]$$

- Forward Bias: current exponentially increases.
- Reverse Bias: low leakage current equal to ~I_o.
- Ability of pn junction to pass current in only one direction is known as "rectifying" behavior.

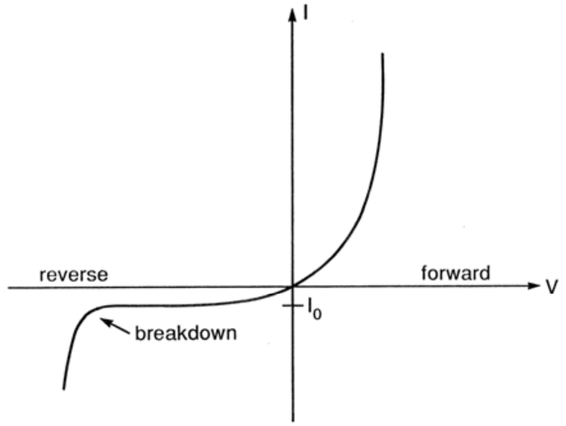
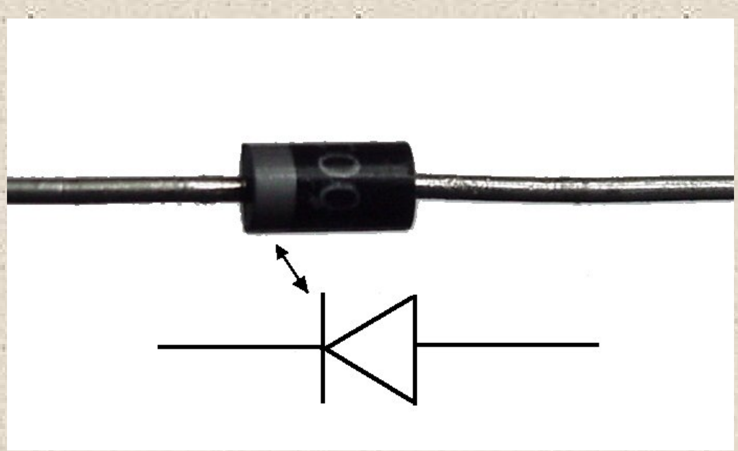


Figure 4.4. Current–voltage curve for a diode. I_0 is the saturation current.

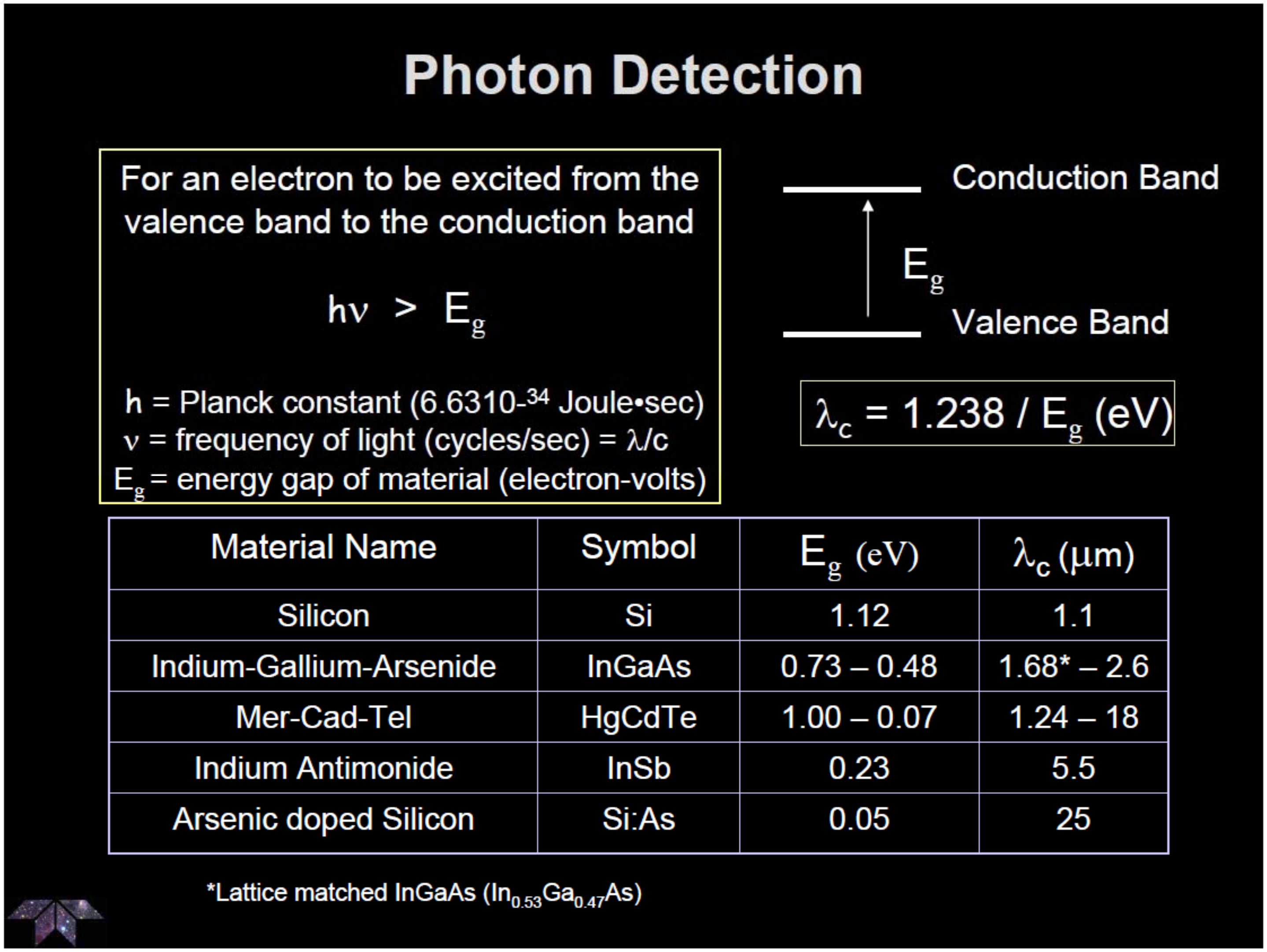
Diode

Definition of a Diode

- A diode is an electronic component that
  - has two terminals,
  - limits current to one direction, and
  - has nonlinear (non-Ohmic) behavior.
- Diodes have an anode and a cathode.
- Positive current normally flows from the anode to the cathode.
- Diodes are useful for protecting circuitry from harmful voltage or current.
- Diodes are a basic building block of the charge-collecting element in many detectors.



Band Gaps



Photon Detection

For an electron to be excited from the valence band to the conduction band

$$h\nu > E_g$$

h = Planck constant (6.6310-^{34} Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
E_g = energy gap of material (electron-volts)

$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

Material Name	Symbol	E_g (eV)	λ_c (μm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

*Lattice matched InGaAs ($In_{0.53}Ga_{0.47}As$)

Photodiode

Definition of a Photodiode

- A photodiode is a diode that converts photons into voltage or current.
- This conversion happens when photons of sufficiently high energy promote photogenerated charge into the conduction band of the semiconductor.
- The photogenerated charge migrates to the depletion region where it recombines with ions.

Photon Detection in Photodiode

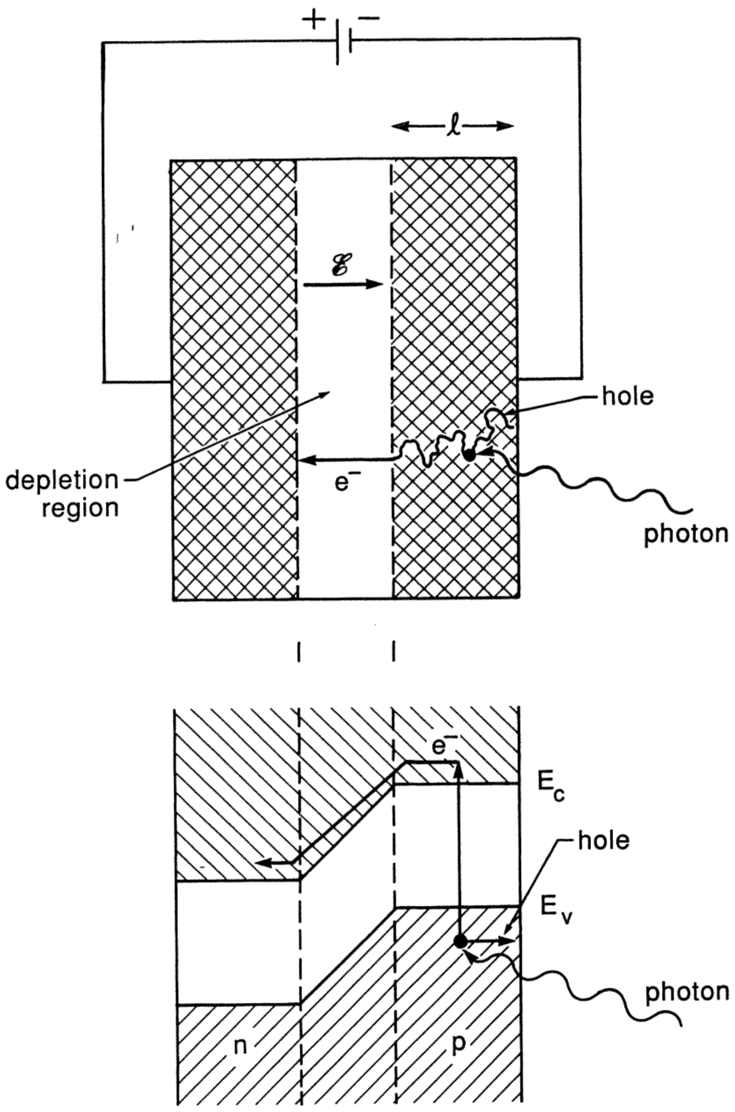
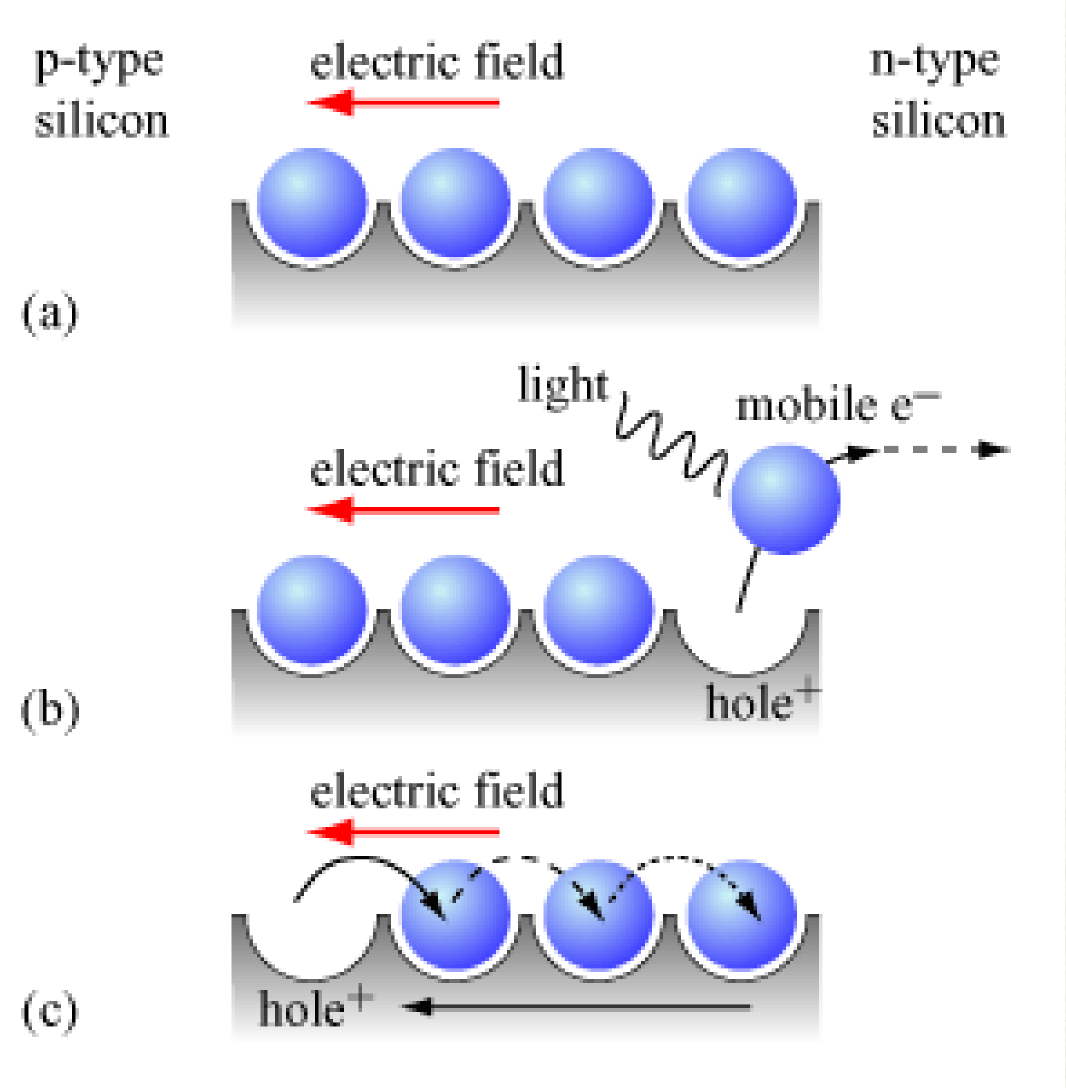


Figure 4.5. Illustration of the detection process in a photodiode. The photogenerated electron diffuses into the depletion region, where the field sweeps it across to the n-type region.

Migration of Electrons and Holes



Response of Photodiode to Light

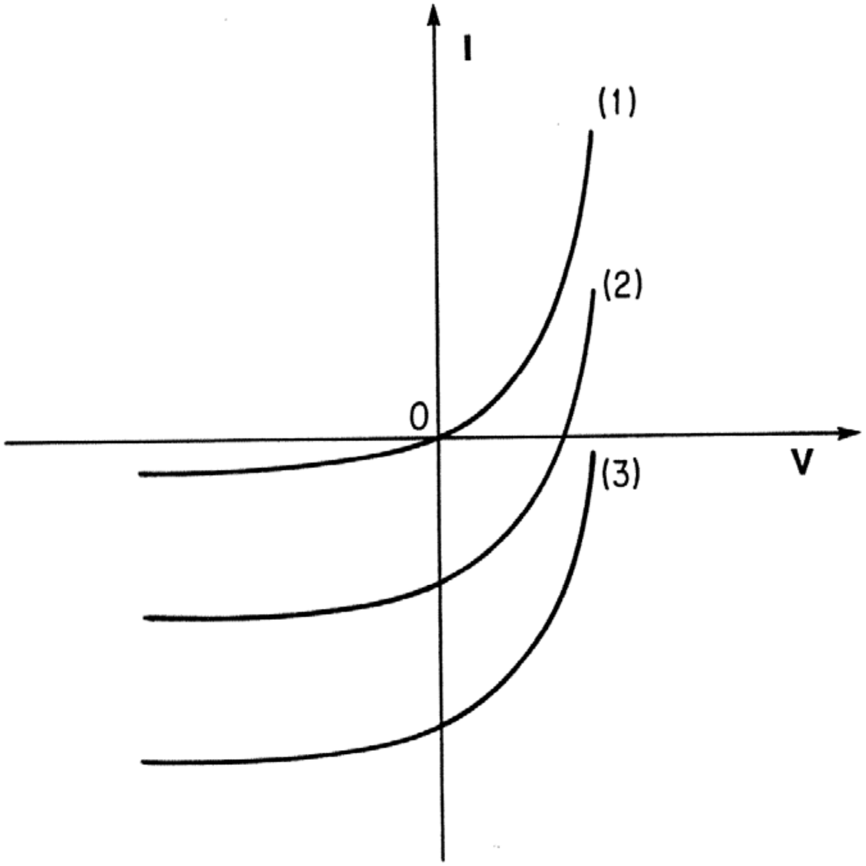


Figure 4.8. Response of a diode to illumination. The illumination increases for curves (1) to (3), starting from zero for curve (1).

Avalanche Photodiode

- Photon absorbed in intrinsic layer.
- Photogenerated electrons drift to pn+ junction where they are accelerated through high field, producing more electrons.
- Benefit: one photon gives large signal.

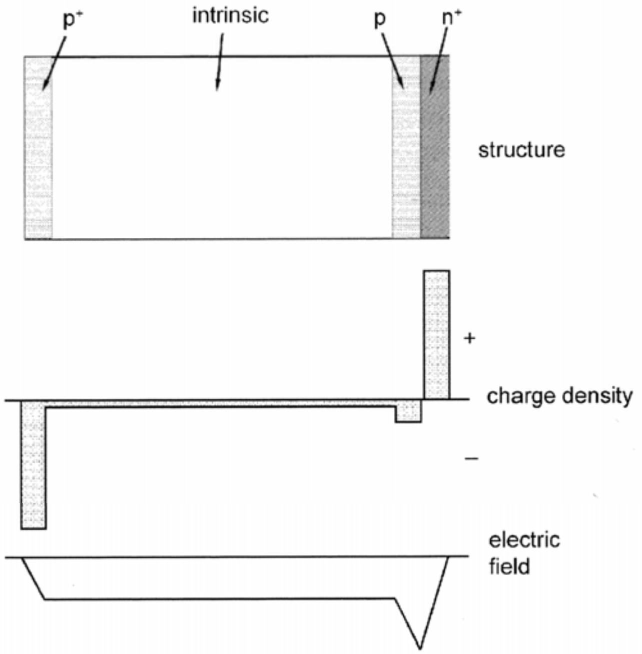
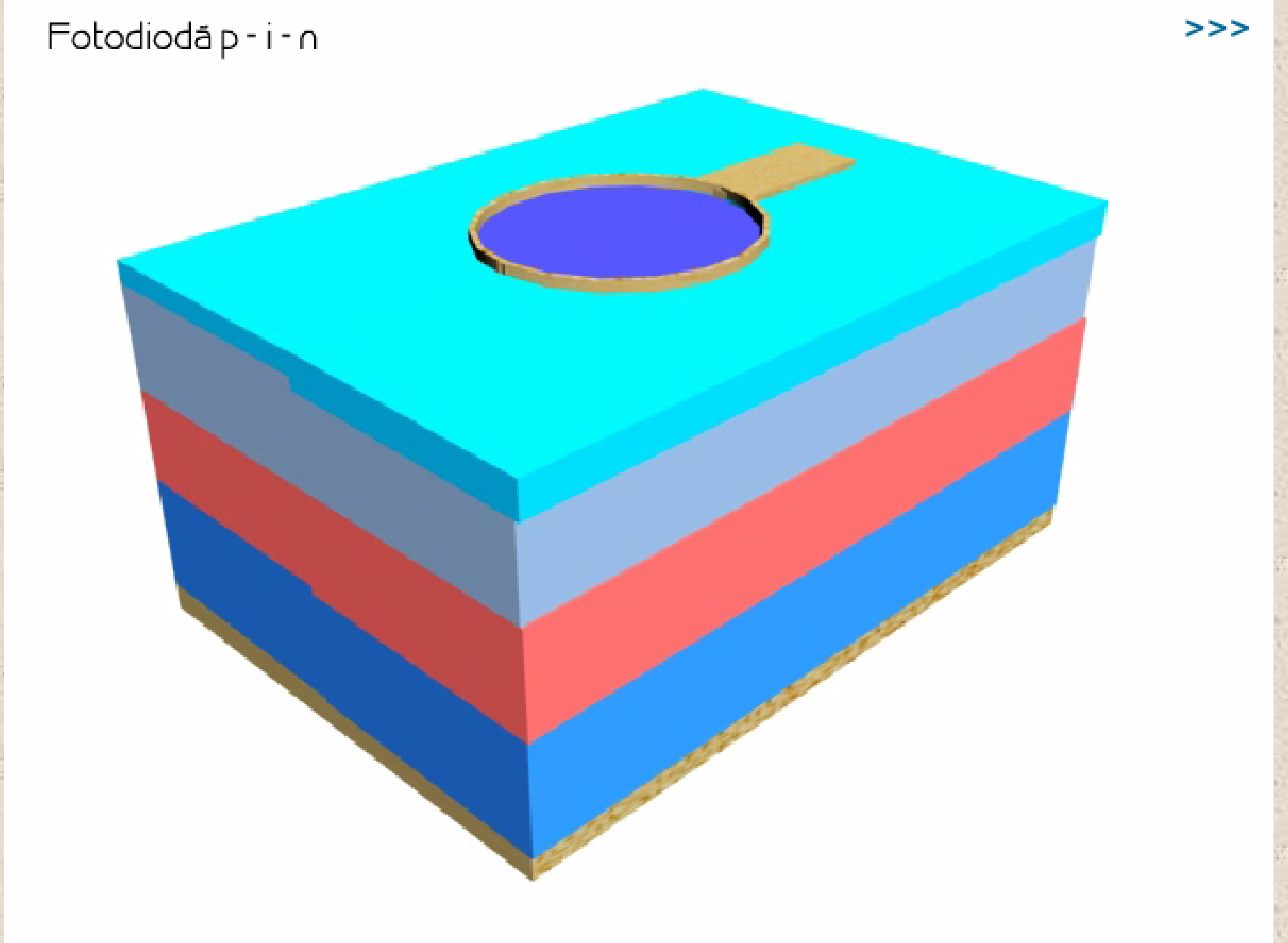


Figure 4.9. Construction of a "reach-through" avalanche photodiode.

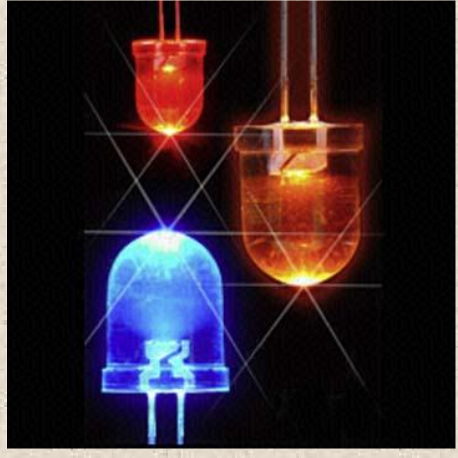
PIN Photodiode



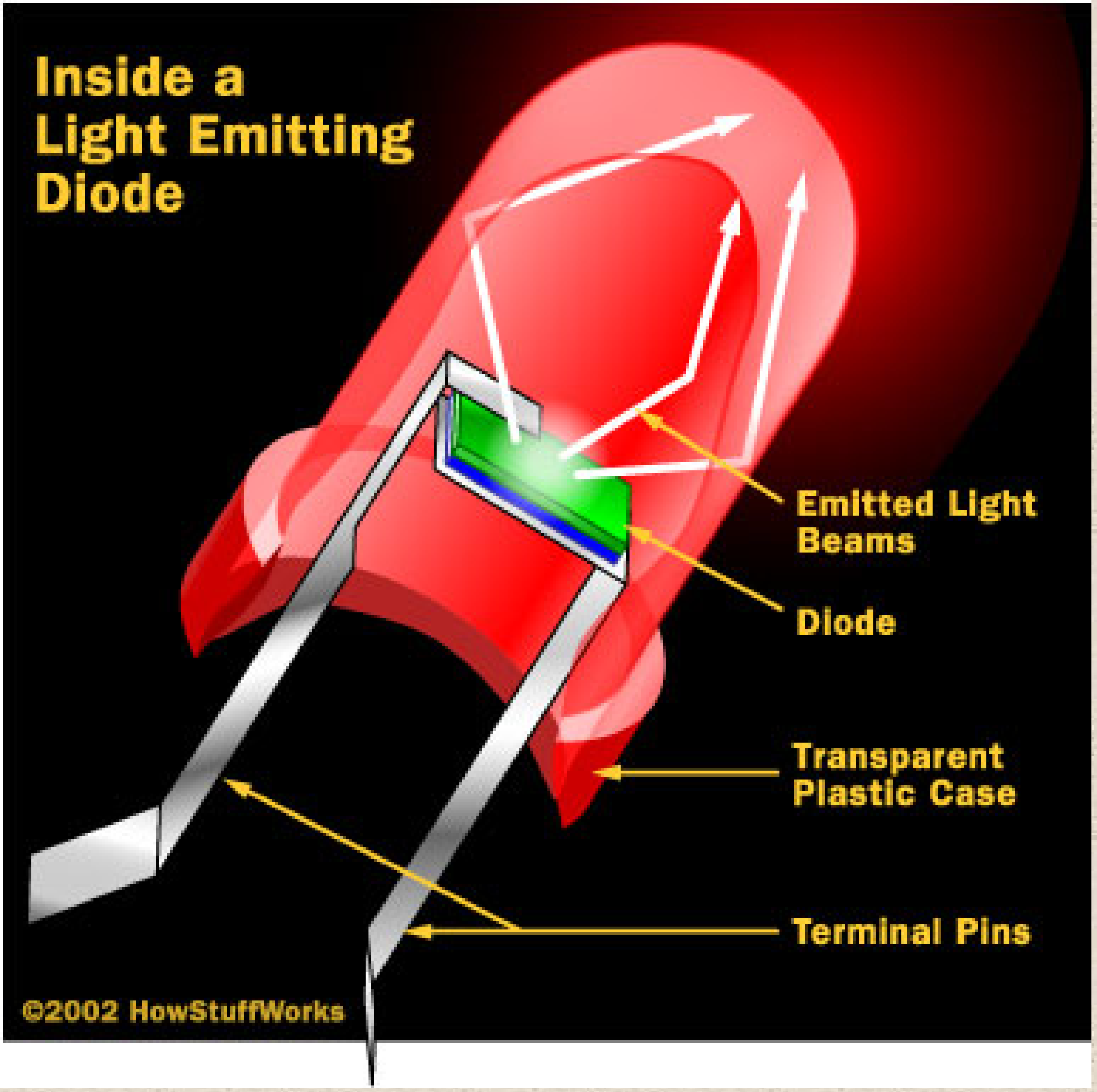
Light-Emitting Diode

Definition of a Light Emitting Diode (LED)

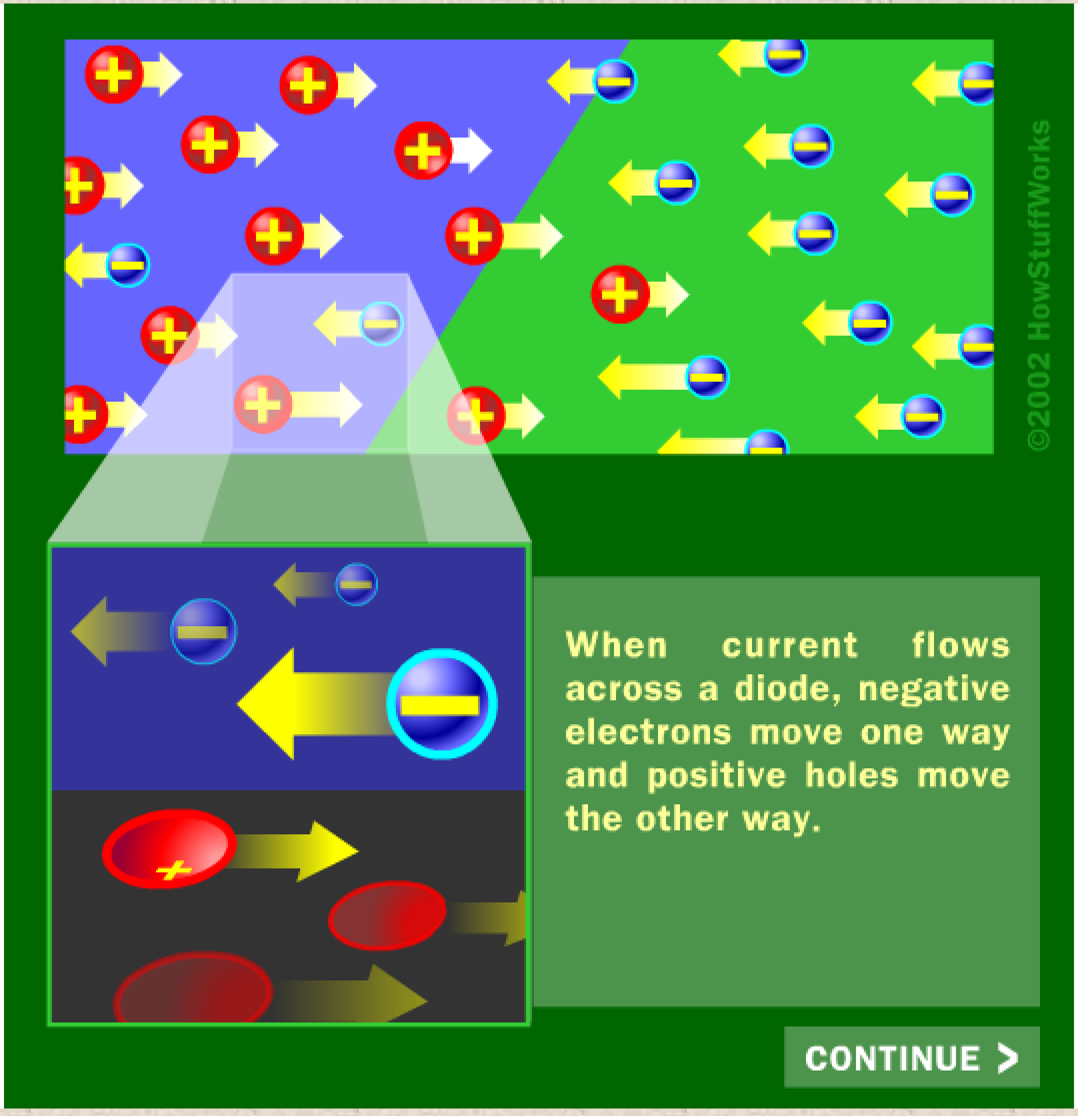
- A Light Emitting Diode converts electrical current into light.
- LEDs are based on pn junctions under forward bias.
- The wavelength of emitted light is fixed for a material and depends on the energy gap between the conduction band and the hole energy level.
- LEDs tend to be more efficient for lighting applications as compared to ordinary light bulbs that convert heat into blackbody radiation (most of which cannot be seen by the human eye).



LED Cutaway

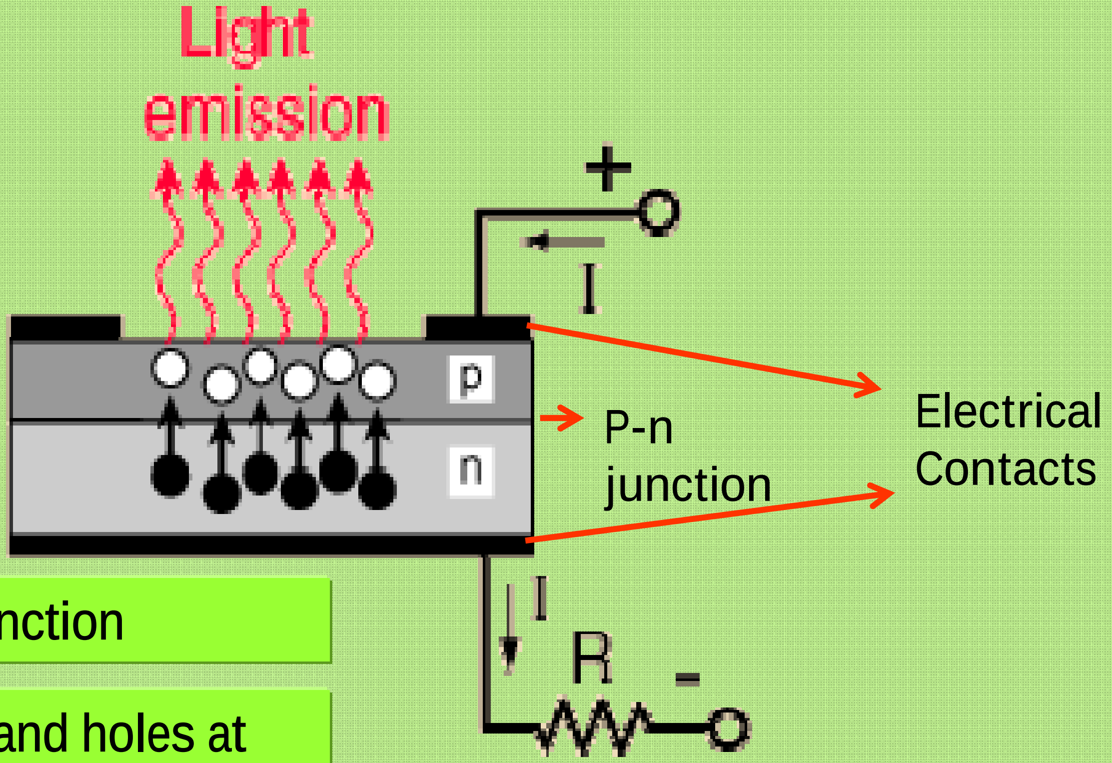

Inside a
Light Emitting
Diode
Emitted Light
Beams
Diode
Transparent
Plastic Case
Terminal Pins
©2002 HowStuffWorks

LED Animation



When current flows across a diode, negative electrons move one way and positive holes move the other way.

How does it work?



A typical LED needs a pn junction

There are a lot of electrons and holes at the junction due to excitations

Electrons from n side need to be injected to p side to promote recombination

Junction is biased to produce even more e-h and to inject electrons from n to p for recombination to happen

Recombination produces light!!

LED Construction

- Efficient light emitter is also an efficient absorber of radiation therefore, a shallow p-n junction required.
- The p-n junction will be forward biased with contacts made by metallisation to the upper and lower surfaces.
- Output material must be transparent so photon can escape.
- ‘Right coloured LED’ → $hc/\lambda = E_c - E_v = E_g$

  → so choose material with the right E_g
- Must be thin enough to prevent reabsorption of photons.

Visible LED

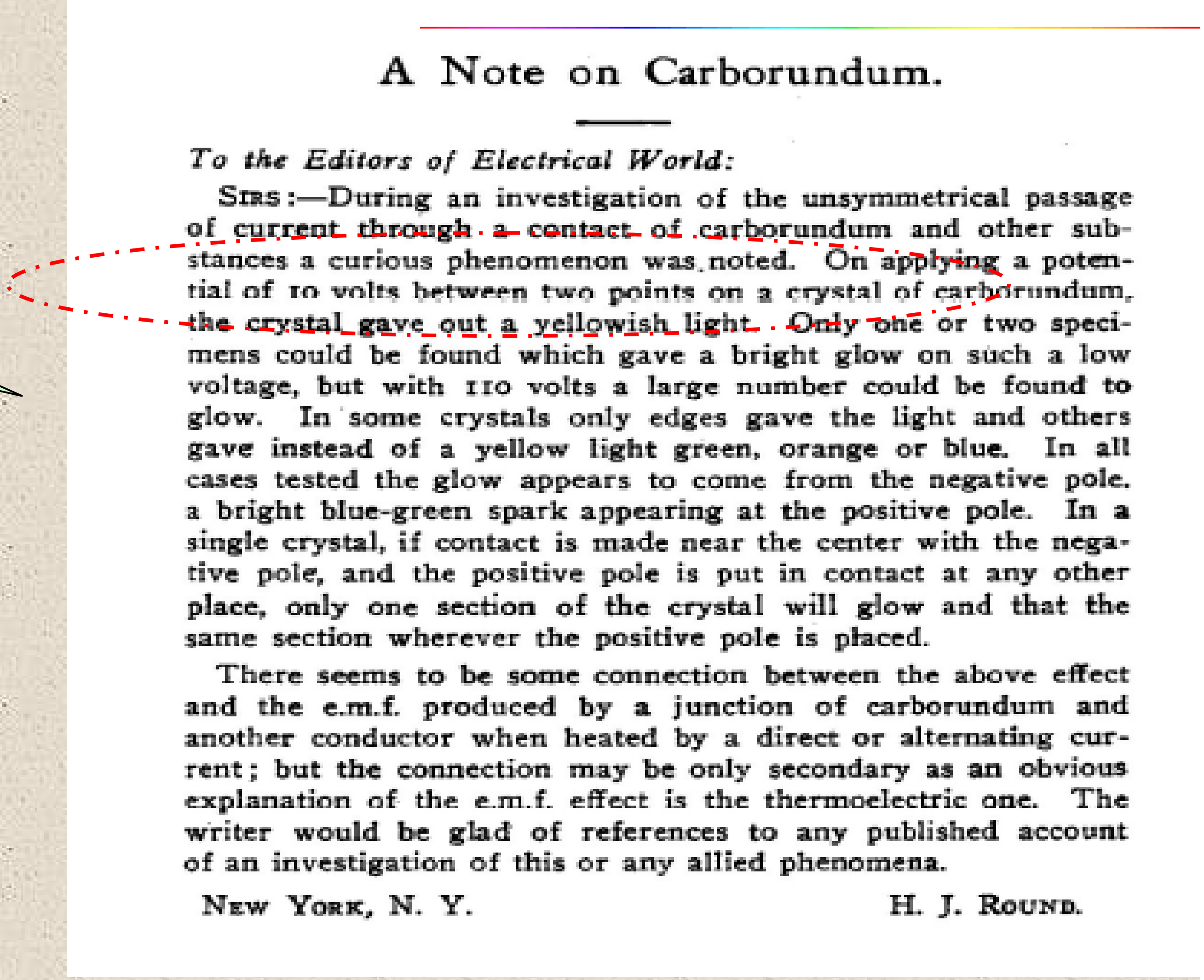
The band gap of the materials that we use must be in the region of visible wavelength = 390-770nm. This coincides with the energy value of 3.18eV- 1.61eV which corresponds to colours as stated below:

Violet	***~ 3.17eV***
Blue	***~ 2.73eV***
Green	***~ 2.52eV***
Yellow	***~ 2.15eV***
Orange	***~ 2.08eV***
Red	***~ 1.62eV***

The band gap, E_g that the semiconductor must posses to emit each light

1907 Publication report on Curious Phenomenon

On applying a potential to a crystal of carborundum (SiC), the material gave out a yellowish light



A Note on Carborundum.

To the Editors of Electrical World:

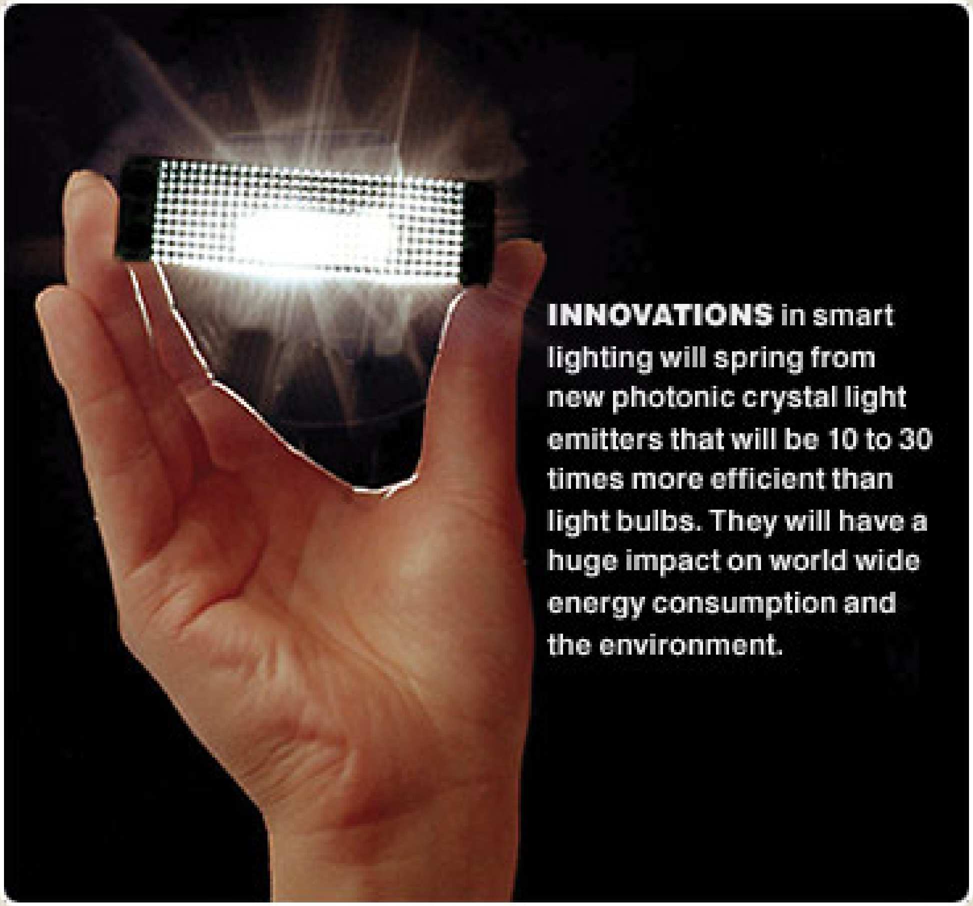
SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

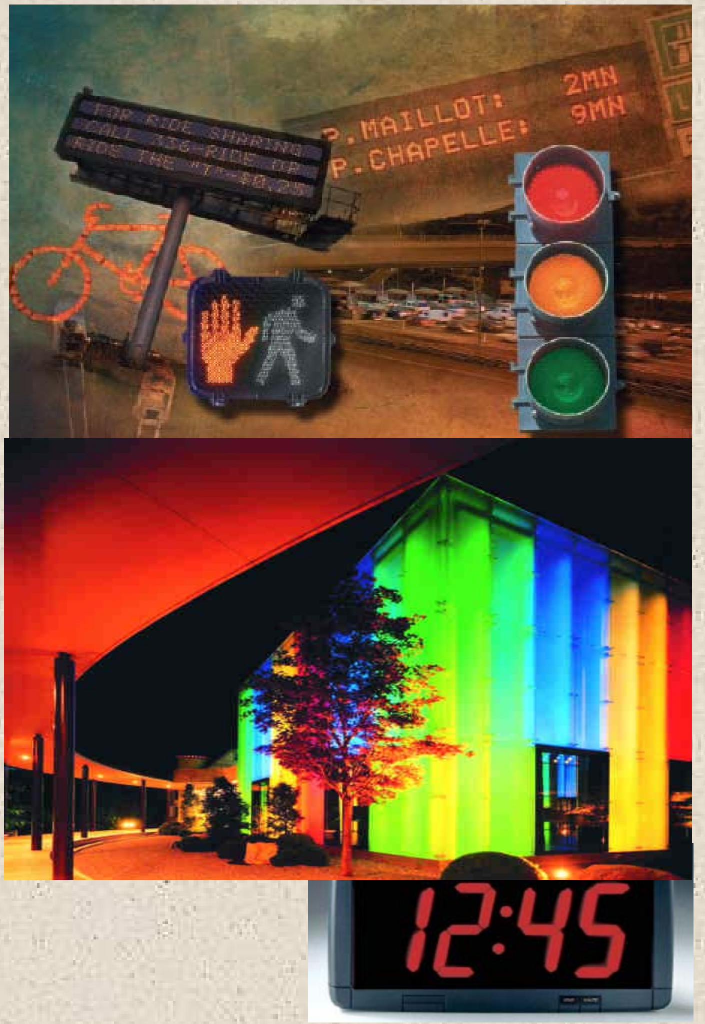
NEW YORK, N. Y. H. J. ROUND.

H.J. Round, Electrical World, 49, 309, 1907

Applications of LEDs



INNOVATIONS in smart lighting will spring from new photonic crystal light emitters that will be 10 to 30 times more efficient than light bulbs. They will have a huge impact on world wide energy consumption and the environment.

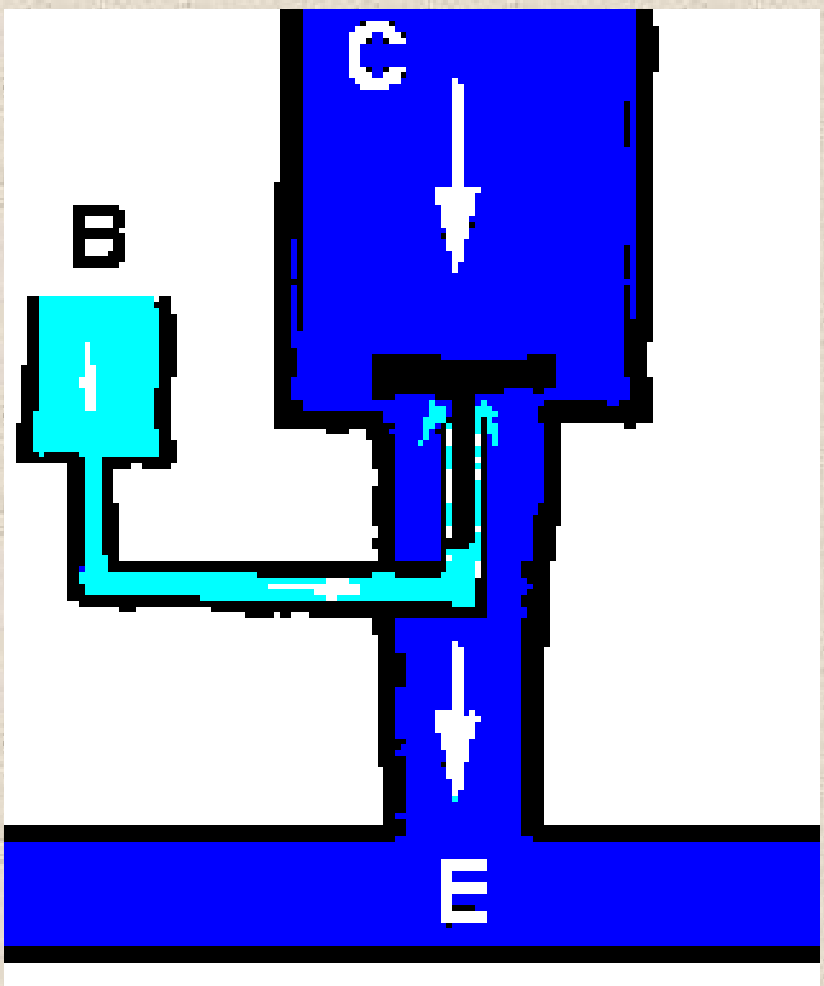


Transistor

Definition of a Transistor

- A transistor controls current through a circuit via an applied current, i.e. it behaves like a current-controlled resistor.
- A transistor has three terminals:
  - base: the control
  - collector: the source of the current
  - emitter: the destination of the current
- The transistor operation is as follows:
  - apply a voltage to the base
  - this voltage sets up an electric field in the “body” of the device
  - the electric field inhibits or supports the flow of charge from collector to emitter
- Most common (and original) form is the bipolar junction transistor (BJT), although the MOSFET has completely taken over almost all applications.

Transistor: Water Flow Model



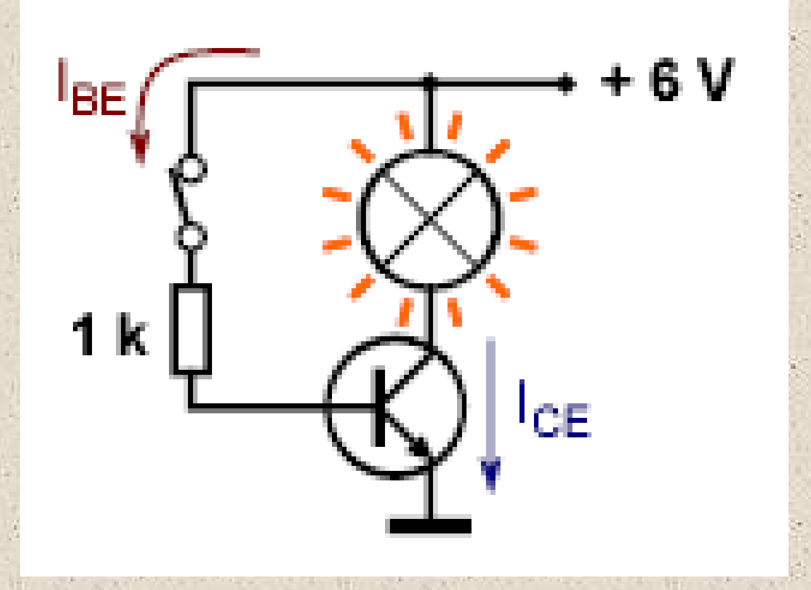
Water flow in B raises the plunger so that water can flow from C to E.

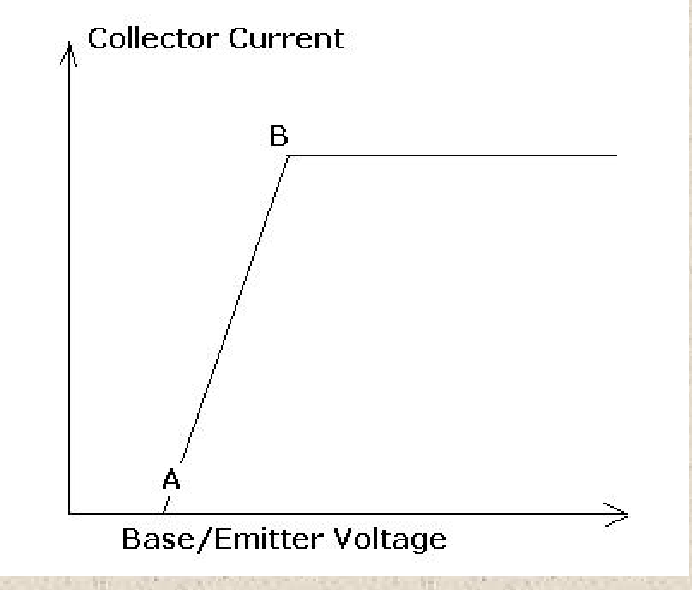
Small flow turns on and off bigger flow.

Put signal on B, transfer signal C to E.

Transistor in Operation

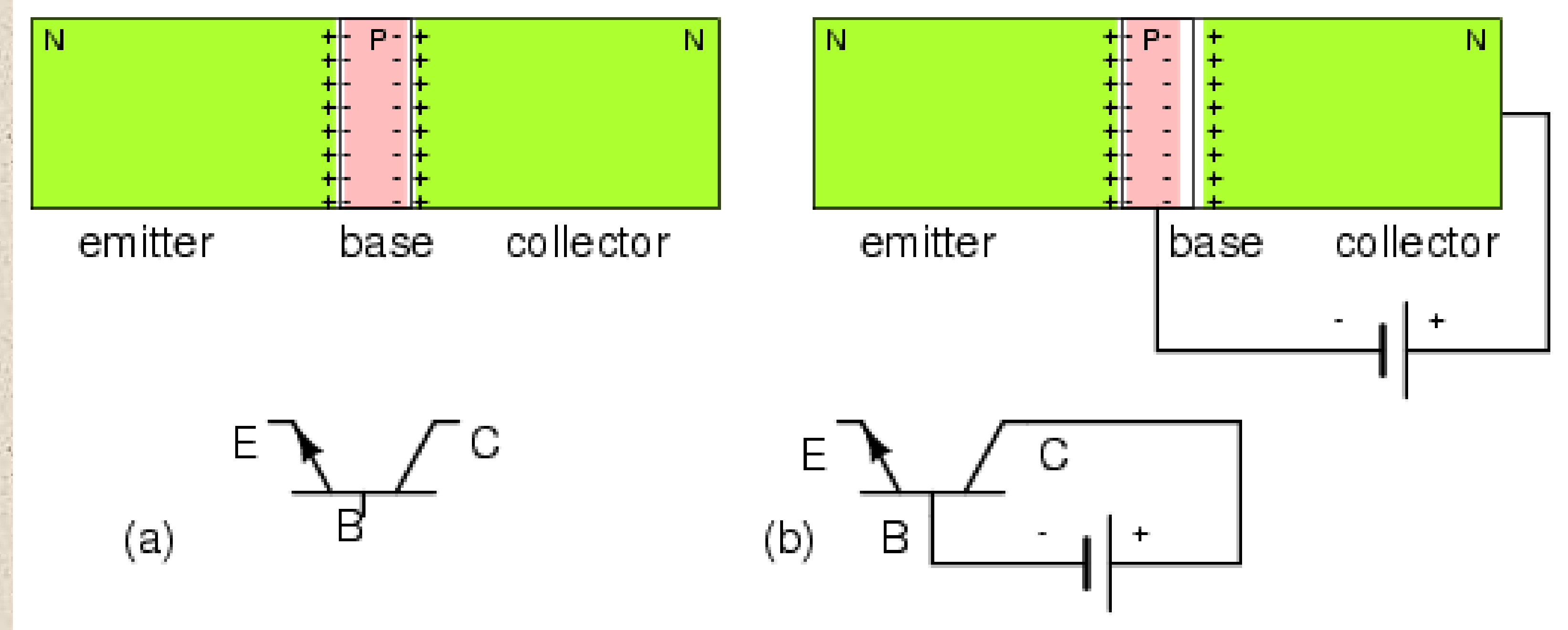
- The transistor base-emitter current controls the current from its “collector” to “emitter.”
- At a certain threshold, the transistor behaves like an “on” switch.





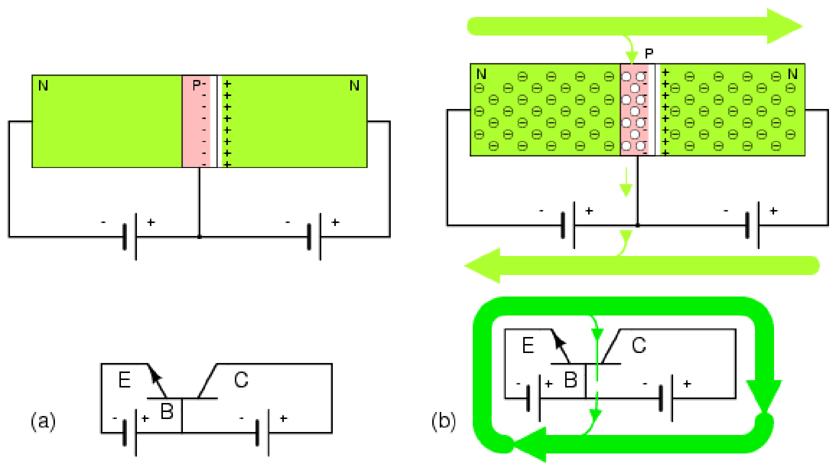
Transistor Architecture

- NPN BJT has three layers with an emitter and collector at the ends, and a very thin base in between (Figure a).
- Base-collector is reverse biased, increasing the width of the associated depletion region (Figure b).



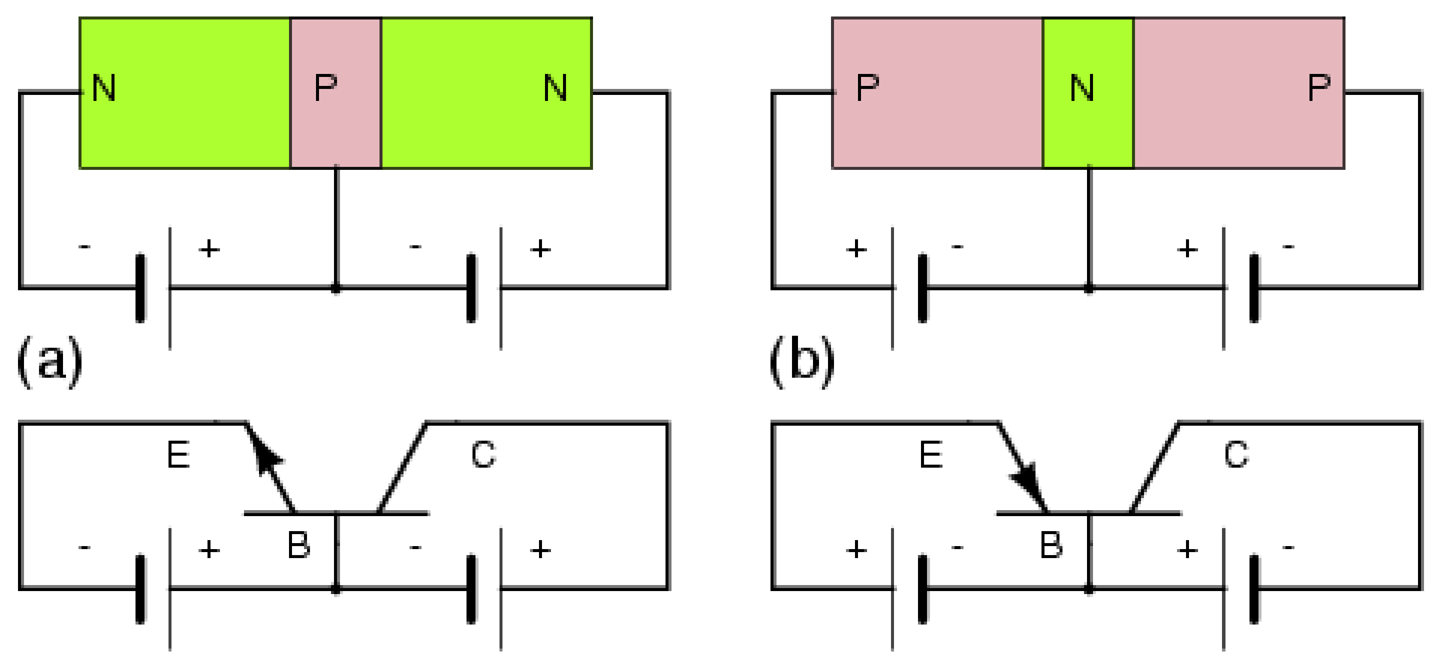
Transistor Architecture

- Base-emitter is forward biased above the threshold voltage to overcome depletion field (Figure b).
- Most of the emitter current of electrons diffuses through the thin base into the collector.
- Changing the small base current produces a larger change in collector current.
- If the base voltage falls below threshold, the large emitter-collector current ceases to flow.



Transistor Architecture (NPN vs. PNP)

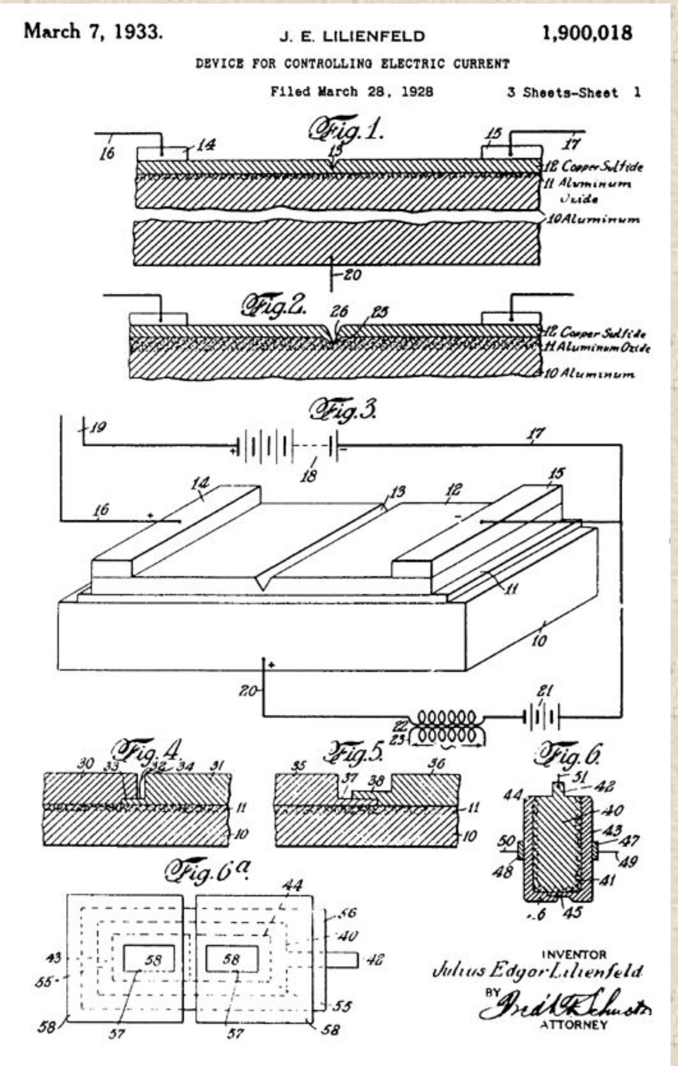
- PNP transistor uses opposite polarity.
- Note that for both types of transistors, the base-emitter junction is forward biased and the base-collector junction is reverse biased.



Common Transistor Packages

Historical Prediction of Transistor Effect

- Effect predicted as early as 1925 by Julius Lilienfeld ("Field Effect")
- Patent issued in the 1926 and 1933
- Technology at the time was not sufficiently advanced to produce doped crystals with enough precision for the effect to be seen



March 7, 1933. J. E. LILIENFELD 1,900,018

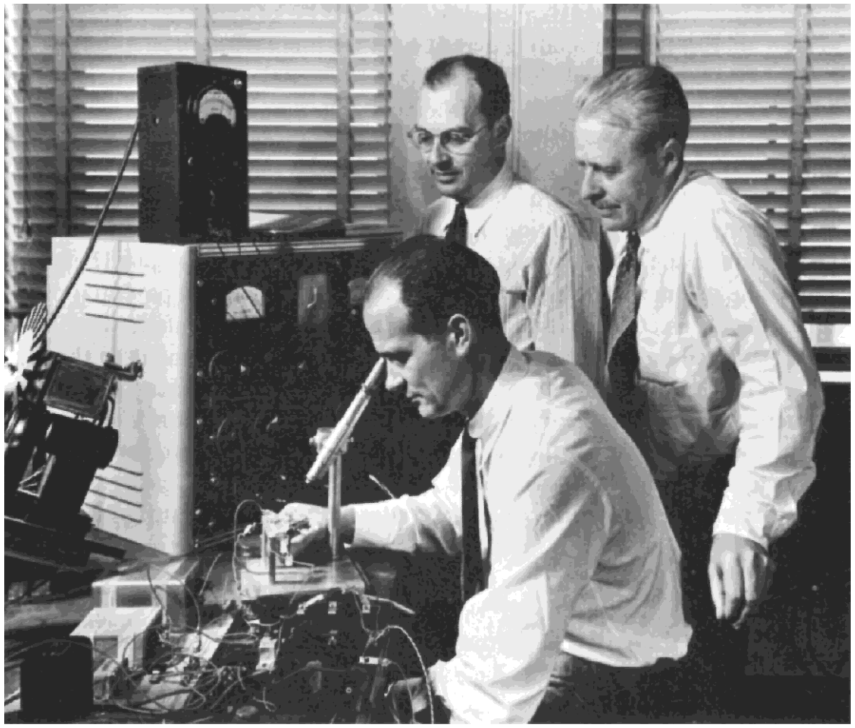
DEVICE FOR CONTROLLING ELECTRIC CURRENT

Filed March 28, 1928 3 Sheets-Sheet 1

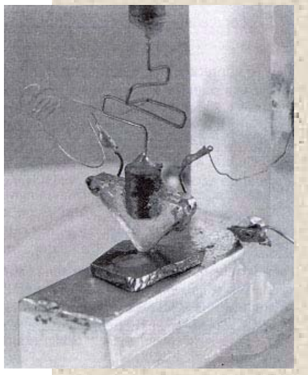
INVENTOR
Julius Edgar Lilienfeld
BY
ATTORNEY

“Invention” of Transistor

- Shockley, Brattain, and Bardeen tried making a field effect transistor in 1947, but got sidetracked into inventing the bipolar transistor instead (for which they won Nobel Prize).



William Shockley, (seated), John Bardeen (left) and Walter Brattain (right) invented the transistor at Bell Labs and thereby ushered in a new era of semiconductor devices. The three inventors shared the Nobel prize in 1956. (Courtesy of Bell Laboratories.)



Now for the rub!

- Shockley's field effect transistor theory was published in 1952. However, the materials processing technology was not mature enough until 1960 when John Atalla produced a working device.
- While re-invention of transistors some twenty years after the Lilienfeld's work earned Bell Telephone Laboratories three Nobel Prizes, they were forced to abandon most patent claims to the field-effect transistor (which dominates modern electronics) because of Lilienfeld's "prior art."

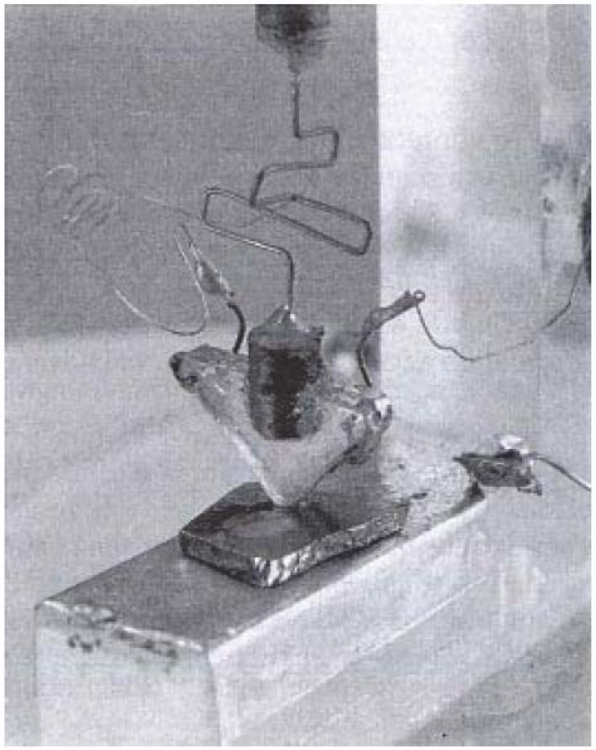
Transistor Invention History Epilogue

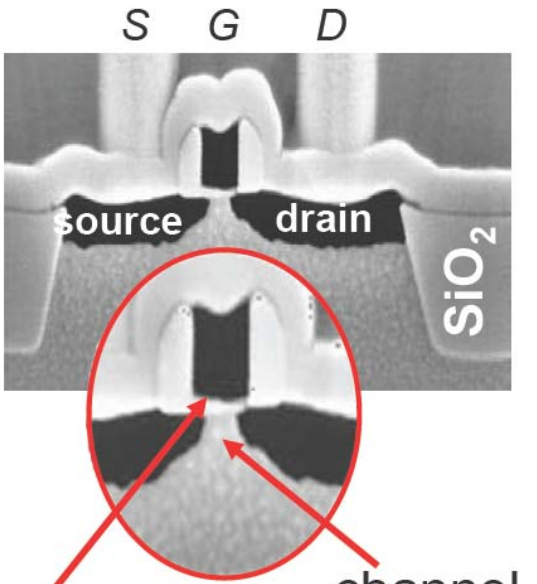
- The three argued over patents and the team split up.
- Schockley founded Silicon Valley in 1956 with money from his buddy Beckman. He eventually left physics to pursue genetics research. He was mad that everyone made money but him. (His early co-workers got fed up and started Fairchild, and then Intel).
- Bardeen went to the University of Illinois. In 1957, along with post-doctoral student Leon Cooper and graduate student Bob Schrieffer, he developed the first theory on superconductivity. To this day, this theory is known as the BCS theory (for Bardeen, Cooper, and Schrieffer)
- Brattain stayed at Bell Labs until he retired and then taught Physics at Whitman College.

Evolution of the Transistor

evolution of silicon technology

Bell Labs, 1947





gate oxide
SiO_2 (1-2nm)

channel
(~ 30nm)

Field Effect Transistor

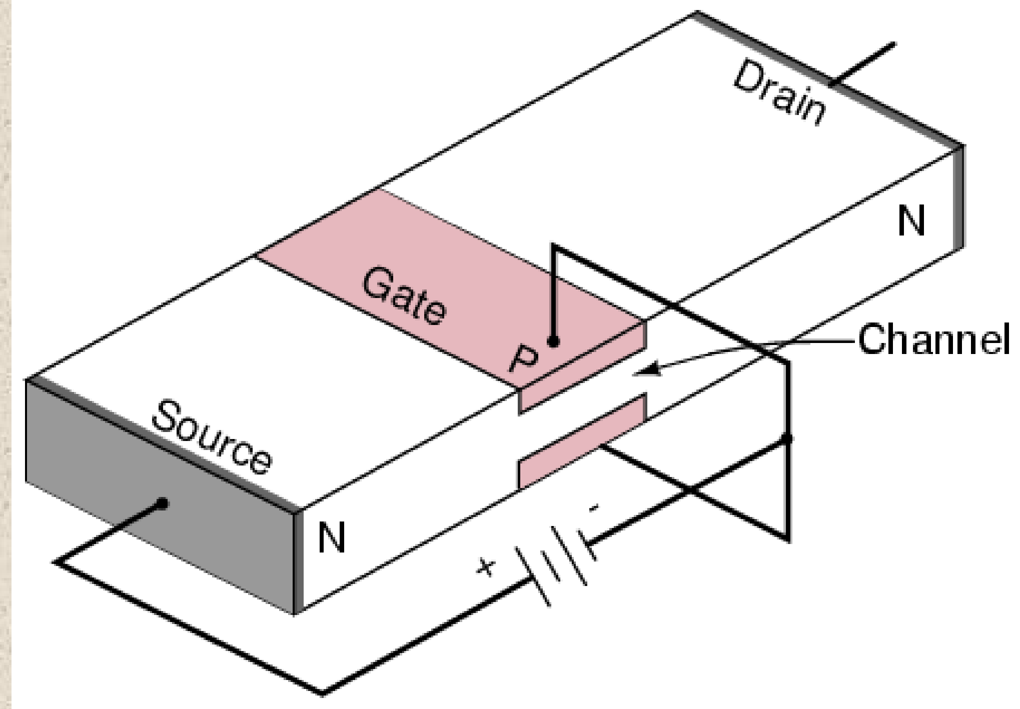
Definition of a FET

- The field-effect transistor (FET) is a generic term for a device that controls current through a circuit via an applied voltage, i.e. it behaves like a voltage-controlled resistor.
- A FET has three terminals:
  - gate: as in the “gate” keeper of the current
  - source: the source of the current
  - drain: the destination of the current
- The FET operation is as follows:
  - apply a voltage to the gate
  - this voltage sets up an electric field in the “body” of the device
  - electric field inhibits/supports the flow of charge from source to drain
- There are two main varieties of FETs:
  - junction FETs (JFETs)
  - metal-oxide FETs (MOSFETs)
- FETs can be made in NPN or PNP variety.
- FETs are “Unipolar” (conduct either electrons or holes, not both).
- Typical output transimpedance is a few hundred Ohms.

Junction Field-Effect Transistor (JFET)

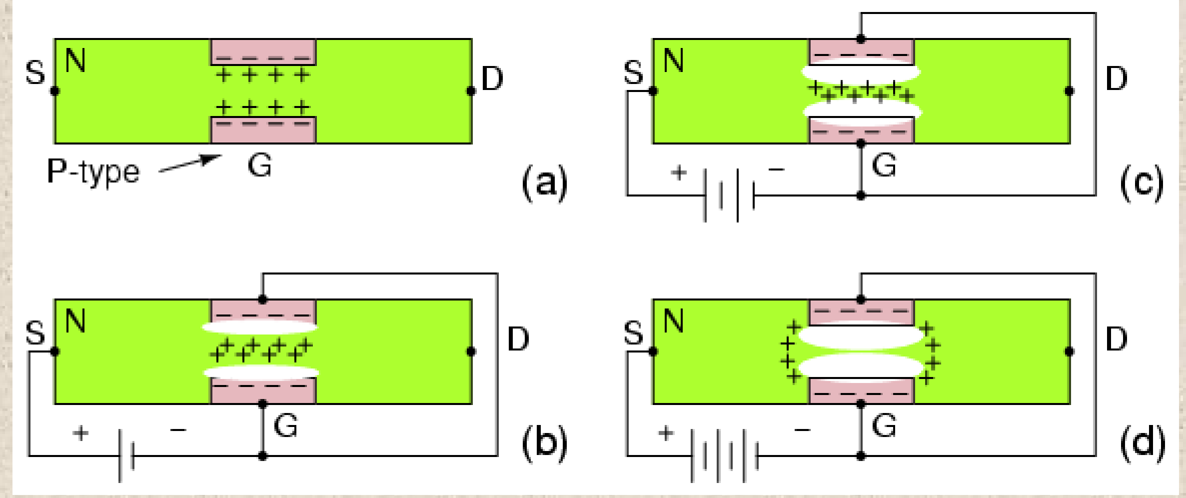
JFET Architecture

- An n channel JFET is composed of:
  - n-type body
  - p-type gate
- Gate is generally reverse biased to control current flow.
- Channel conducts regardless of polarity between source and drain.



JFET Architecture

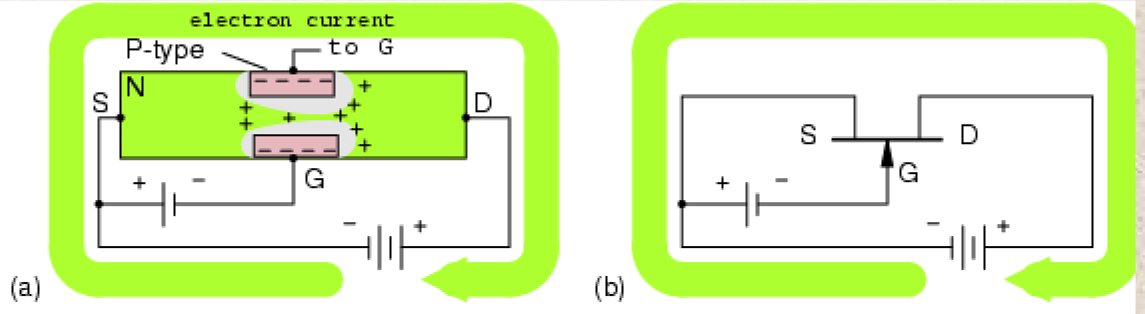
- The gate and channel form depletion regions.
- A stronger reverse bias makes the depletion regions wider and closer to each other.
- Therefore, voltage controls channel resistance.



N-channel JFET: (a) Depletion at gate diode. (b) Reverse biased gate diode increases depletion region. (c) Increasing reverse bias enlarges depletion region. (d) Increasing reverse bias pinches-off the S-D channel.

JFET Architecture

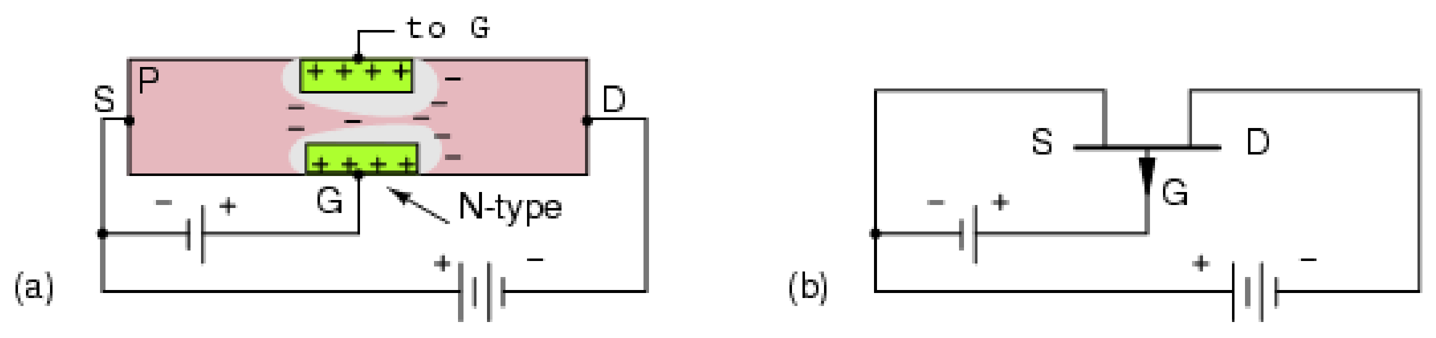
- Source and drain are interchangeable.
- Figure (b) shows the schematic symbol for an N-channel field effect transistor compared to the silicon cross-section at (a). The gate arrow points in the same direction as a junction diode. The“pointing” arrow and “non-pointing” bar correspond to P and N-type semiconductors, respectively.
- N-channel JFET electron current flow from source to drain in (a) cross-section, (b) schematic symbol.



Large electron current flow from (-) battery terminal, to FET source, out the drain, returning to the (+) battery terminal. This current flow may be controlled by varying the gate voltage. A load in series with the battery sees an amplified version of the changing gate voltage.

JFET Architecture (P channel)

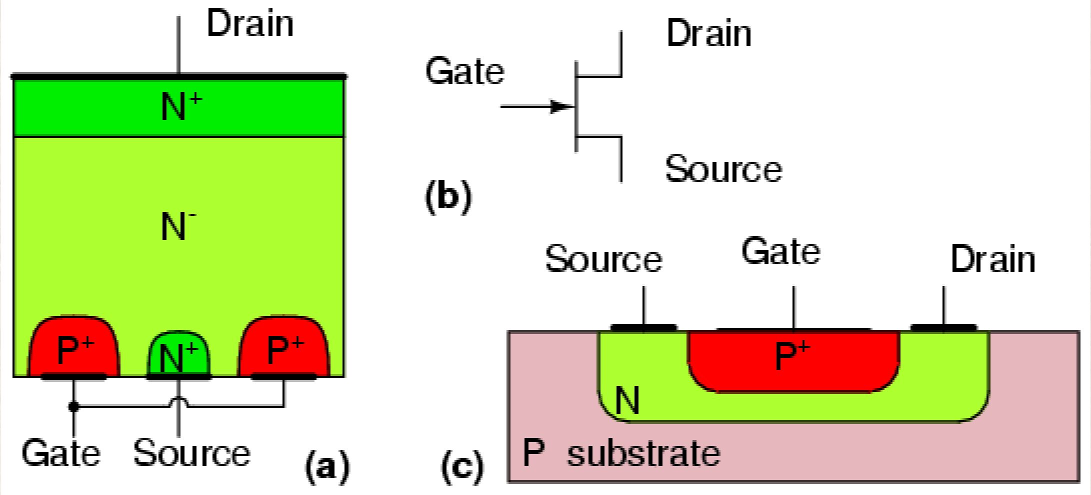
- A P-channel JFET is similar to the N channel version, except with polarities reversed. Note that the arrow points out of the gate of the schematic symbol.
- As the positive gate bias voltage is increased, the resistance of the P-channel increases, decreasing the current flow in the drain circuit.



P-channel JFET: (a) N-type gate, P-type channel, reversed voltage sources compared with N-channel device. (b) Note reversed gate arrow and voltage sources on schematic.

JFET Architecture

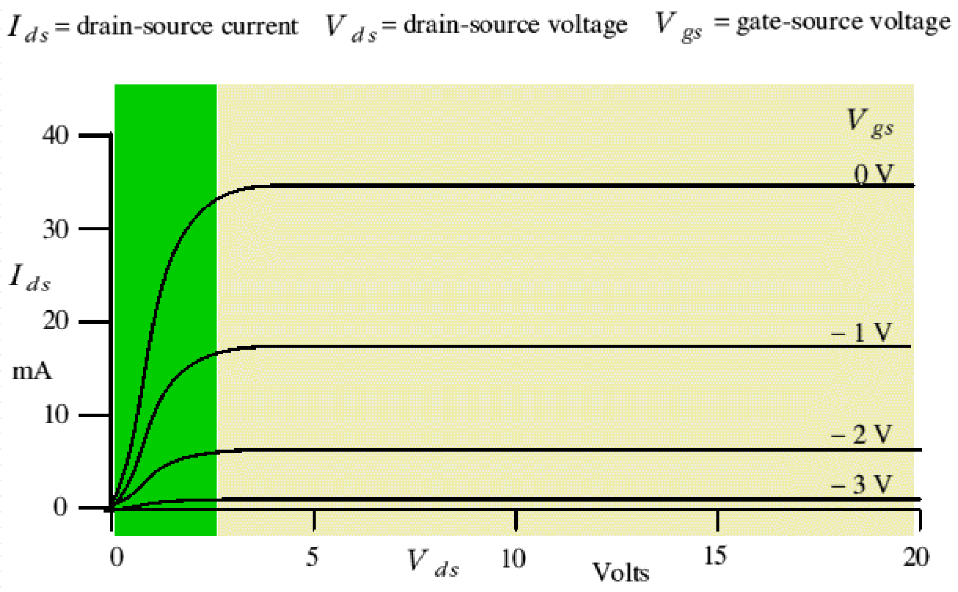
- The basic architecture can be realized in a variety of geometrical relationships while still preserving the basic function.
- Practically realized devices often have the contacts all on one side of the device.



Junction field effect transistor: (a) Discrete device cross-section, (b) schematic symbol, (c) integrated circuit device cross-section.

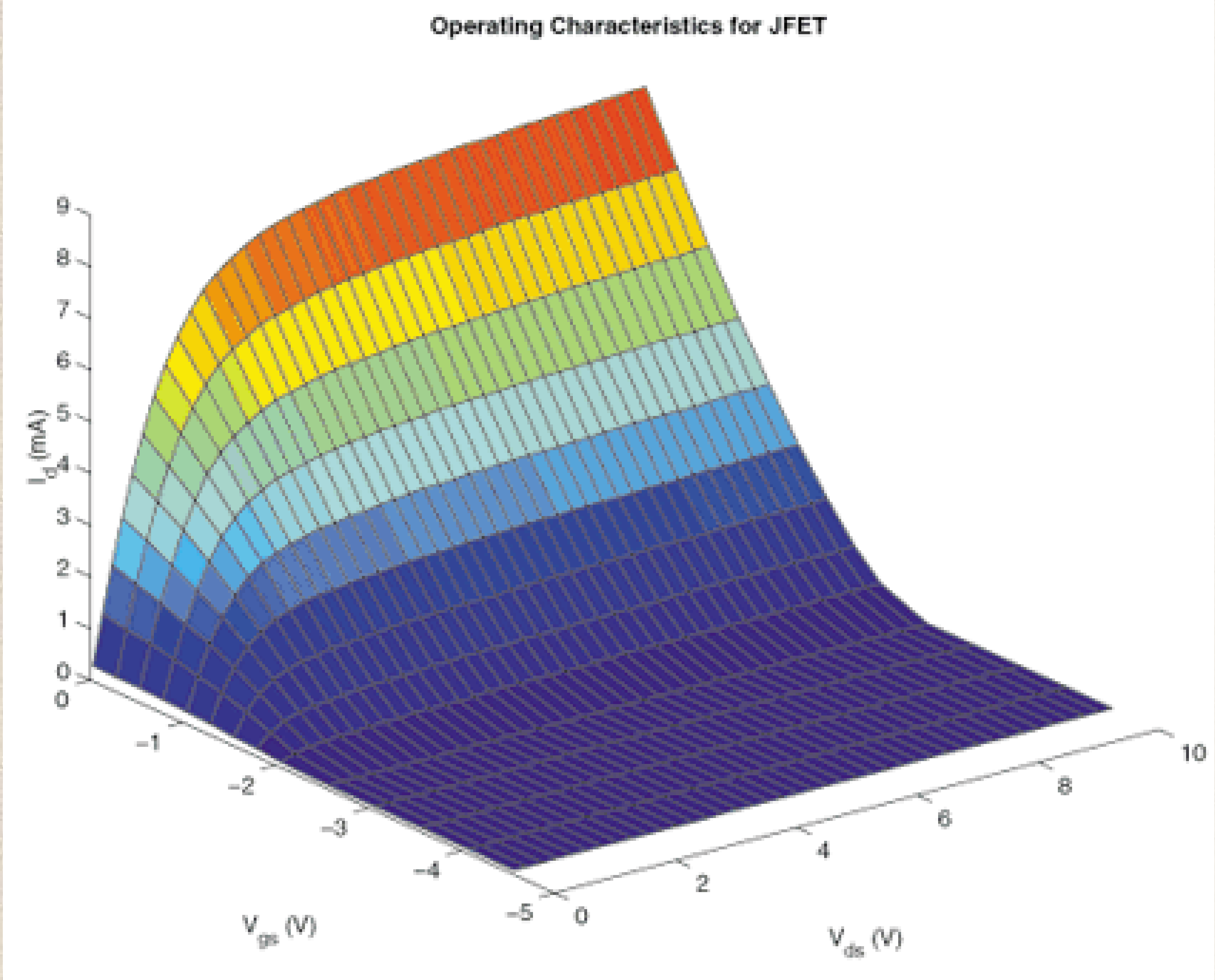
JFET Characteristic Curve

- IV curve shows two areas of operation.
  - At low drain-source voltages it behaves like a variable resistance whose value is controlled by the applied gate-source voltage.
  - At higher drain-source voltages it passes a current whose value depends on the applied gate-source voltage. In most circuits it is used in this ‘high voltage’ region and acts as a voltage controlled current source.



‘Characteristic curves for a typical N-channel JFET.

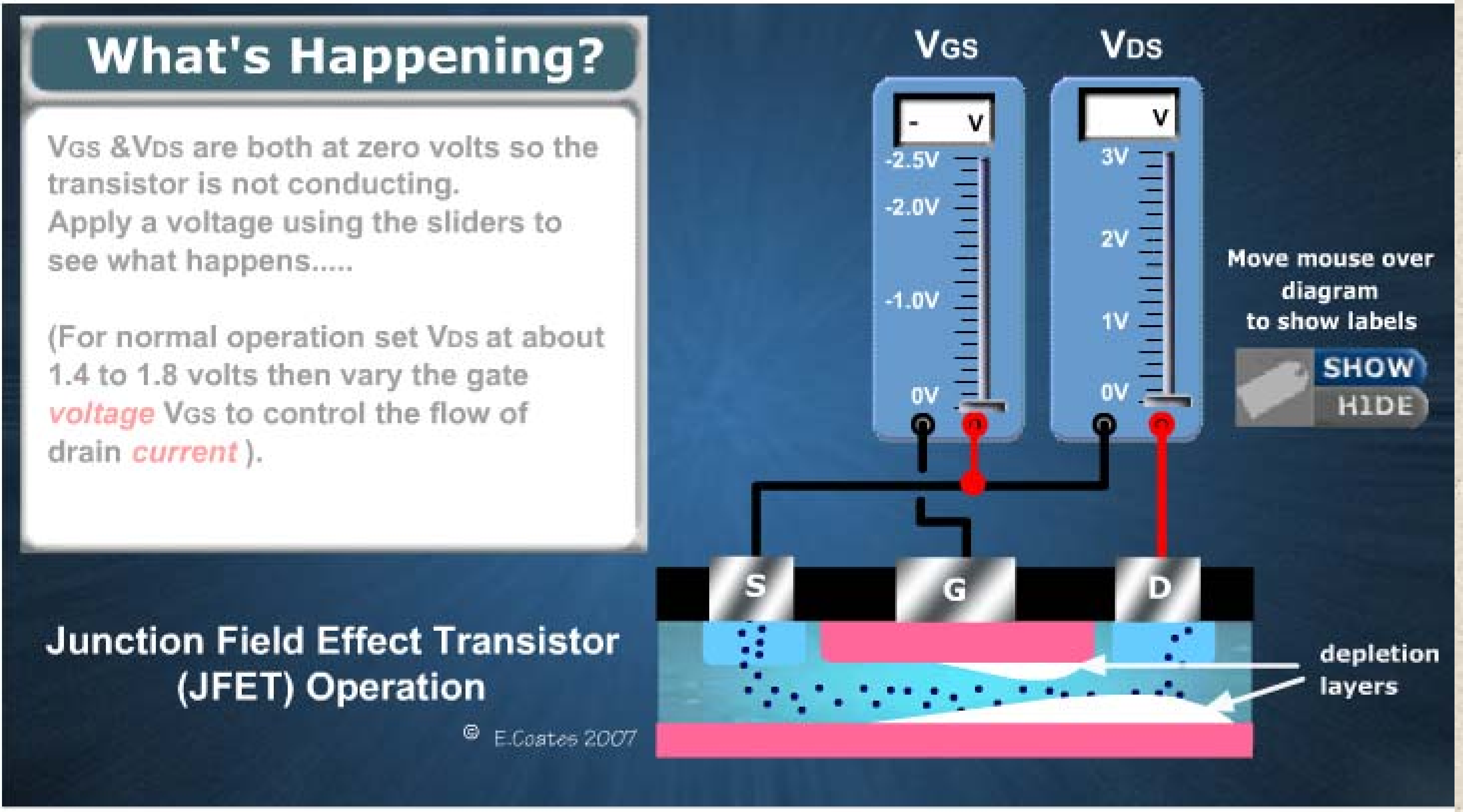
JFET 3D Characteristic Curve



Advantages of JFET

- controlled by the applied gate voltage, they draw very little gate current and hence present a very high input resistance to any signal source
- low noise at low frequency
- the reverse-biased junctions can tolerate a considerable amount of radiation damage without any appreciable change in FET operation.

Operating a FET



What's Happening?

V_{GS} &V_{DS} are both at zero volts so the transistor is not conducting.
Apply a voltage using the sliders to see what happens.....

(For normal operation set V_{DS} at about 1.4 to 1.8 volts then vary the gate *voltage* V_{GS} to control the flow of drain *current*).

Junction Field Effect Transistor (JFET) Operation

© E.Coates 2007

Move mouse over diagram to show labels

JFET Review

- The JFET is called “unipolar” because conduction in the channel is due to one type of carrier.
- The JFET source, gate, and drain correspond to the bipolar junction transistor’s emitter, base, and collector, respectively.
- Application of reverse bias to the gate varies the channel resistance by expanding the gate diode depletion region.
- With sufficient bias, the channel is pinched, and current ceases to flow.
- The input impedance is high vs. BJT, but low vs. MOSFET.
- JFETs are virtually obsolete in ICs, but still used in discretes.

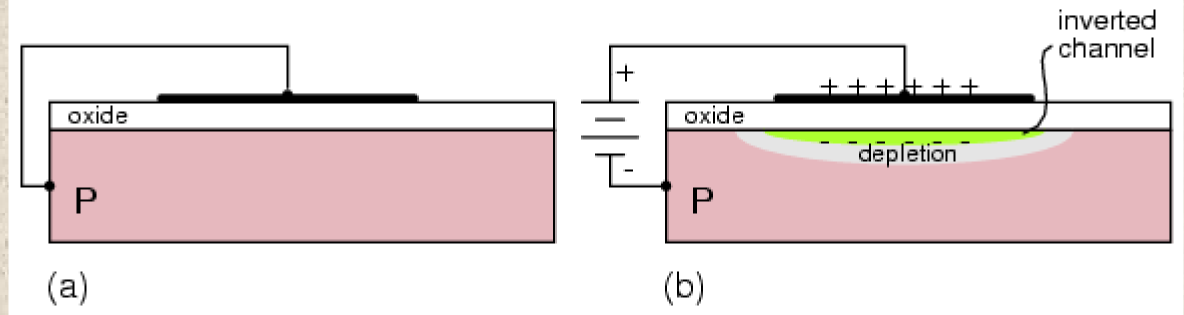
Metal-Oxide Field-Effect Transistor (MOSFET)

Definition of Metal-Oxide FET (MOSFET)

- A MOSFET is a FET with an insulated gate.
- Today, most transistors are MOSFETs in digital integrated circuits.
- While the MOSFET has source, gate, and drain terminals like the FET, its gate lead is not in contact with the silicon.
- The MOSFET has an higher input impedance than the JFET (10 to 100 million megohms). Therefore, the MOSFET is even less of a load on preceding circuits.

MOSFET Architecture

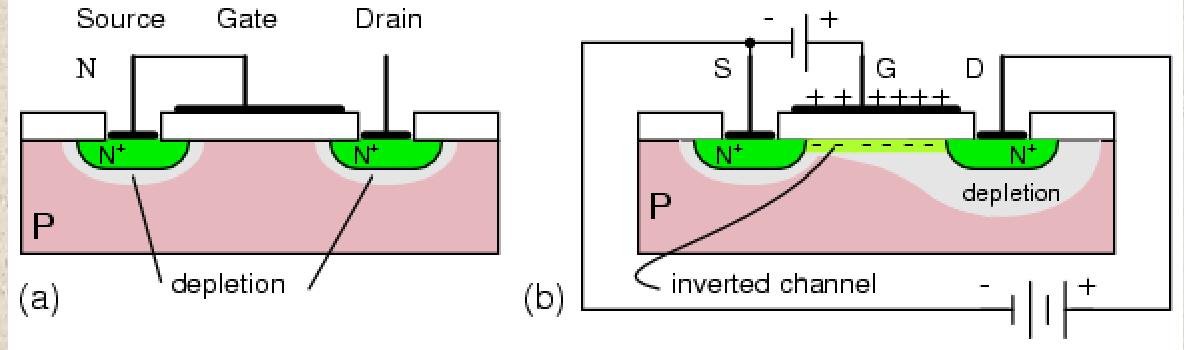
- The MOSFET gate is a metallic or polysilicon layer atop a silicon dioxide insulator. The gate bears a resemblance to a metal oxide semiconductor (MOS) capacitor.
- When charged, the plates of the capacitor take on the charge polarity of the respective battery terminals. The lower plate is P-type silicon from which electrons are repelled by the negative (-) battery terminal toward the oxide, and attracted by the positive (+) top plate.
- This excess of electrons near the oxide creates an inverted (excess of electrons) channel under the oxide. This channel is also accompanied by a depletion region isolating the channel from the bulk silicon substrate.



N-channel MOS capacitor: (a) no charge, (b) charged.

MOSFET Architecture

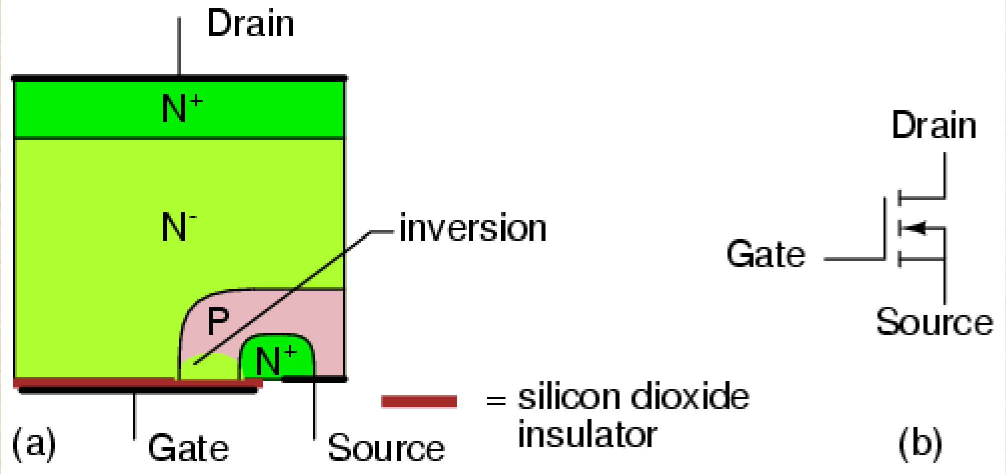
- Consider a MOS capacitor between a pair of N-type diffusions in a P-type substrate. With no charge on the capacitor, no bias on the gate, the N-type diffusions, the source and drain, remain electrically isolated.
- A positive bias charges the capacitor.
- The P-type substrate below the gate takes on a negative charge.
- An inversion region of electrons forms below the gate oxide, connecting source and drain.
- One type of charge carrier is responsible for conduction (unipolar).



N-channel MOSFET (enhancement type): (a) 0 V gate bias, (b) positive gate bias.

MOSFET Architecture

- The cross-section of an N-channel discrete MOSFET is shown in the figure:
  - The N+ indicates that the source and drain are heavily N-type doped. This minimizes resistive losses in the high current path from source to drain.
  - The N-indicates light doping.
  - The P-region under the gate, between source and drain can be inverted by application of a positive bias voltage.



N-channel MOSFET (enhancement type): (a) Cross-section, (b) schematic symbol.

MOSFET Review

- MOSFET's are unipoar conduction devices, conduction with one type of charge carrier, like a FET, but unlike a BJT.
- A MOSFET is a voltage controlled device like a FET. A gate voltage input controls the source to drain current.
- The MOSFET gate draws no continuous current, except leakage. However, a considerable initial surge of current is required to charge the gate capacitance.

JFET versus MOSFET

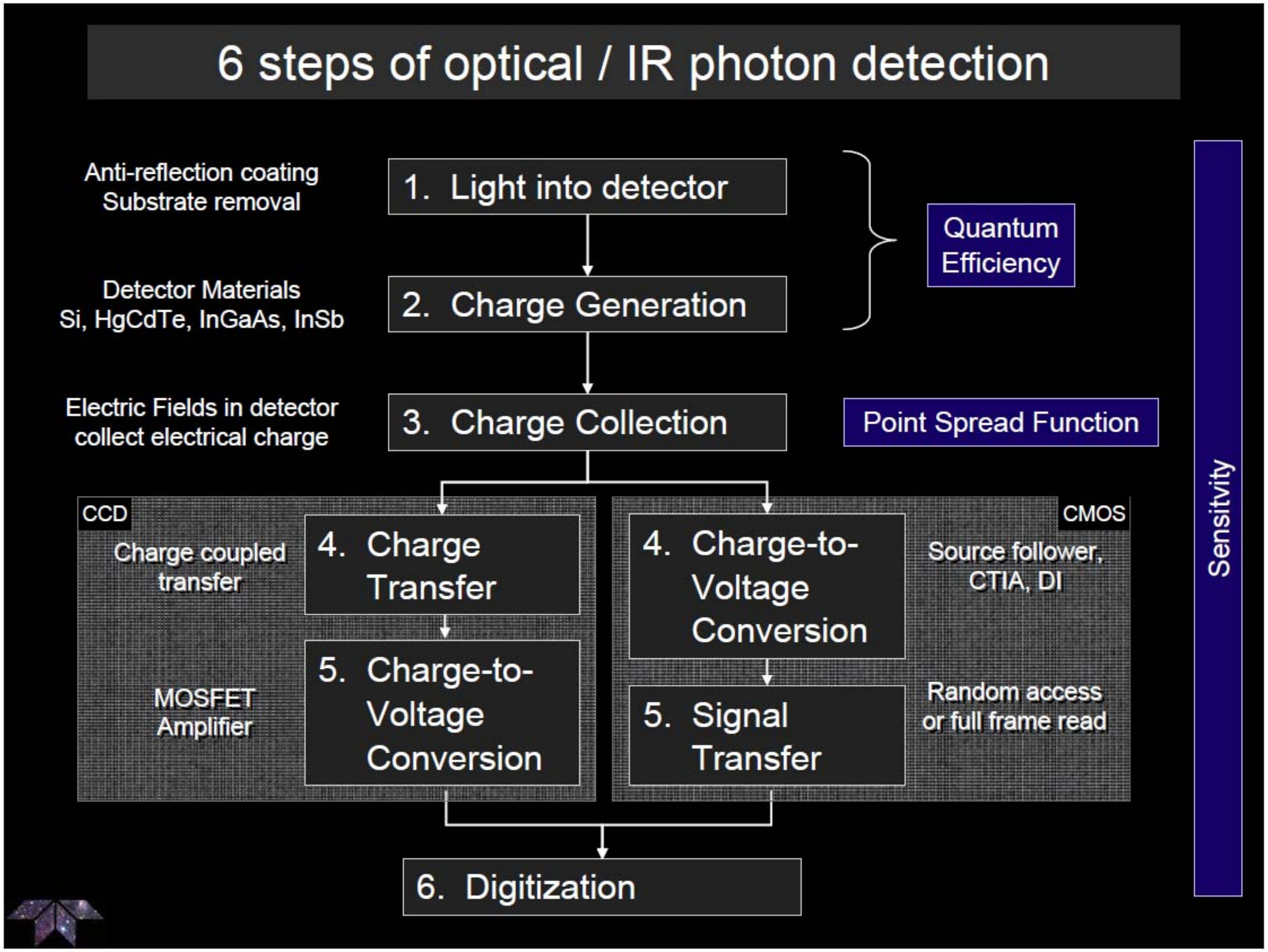
- The MOSFET has the advantage of extremely low gate current because of the insulating oxide between the gate and channel.
- JFET has higher transconductance than the MOSFET.
- JFET has low noise at low frequency.

Detector Applications

The Purpose of Detector Circuits

- Electronic circuits serve the purpose of operating and reading detectors.
- Ideally, the electronics would not degrade the signal of interest.
- Of course, electronics are “real” devices and are thus imperfect.
- Therefore, electronics should carefully be designed and implemented such that non-electronic sources of signal degradation dominate.
- As an example, the electronic read noise should be less than the signal shot noise.

Converting Light to Signal



6 steps of optical / IR photon detection

Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InGaAs, InSb

2. Charge Generation

Quantum Efficiency

Electric Fields in detector
collect electrical charge

3. Charge Collection

Point Spread Function

CCD

Charge coupled transfer

4. Charge Transfer

MOSFET Amplifier

5. Charge-to-Voltage Conversion

CMOS

Source follower, CTIA, DI

4. Charge-to-Voltage Conversion

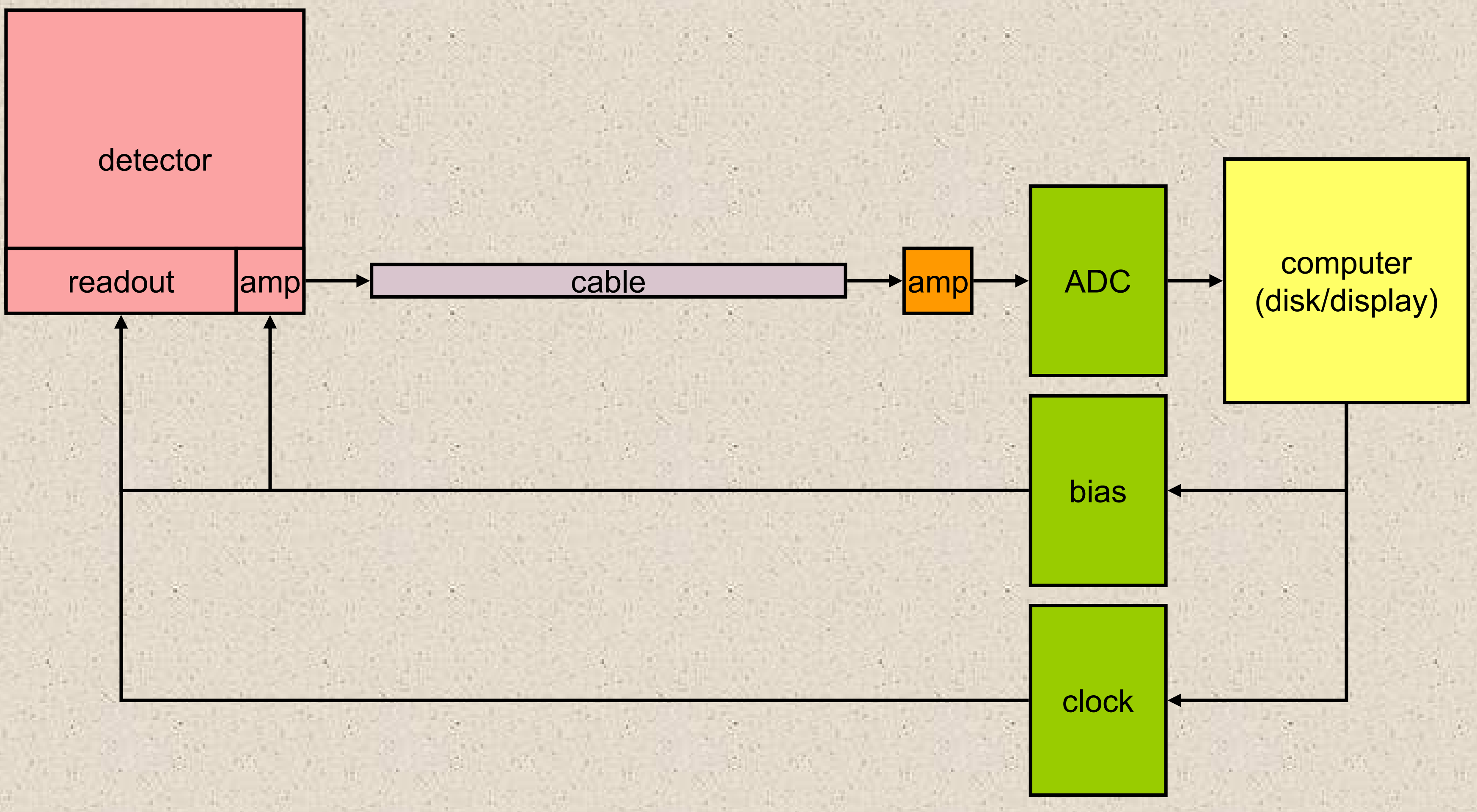
Random access or full frame read

5. Signal Transfer

6. Digitization

Sensitivity

Detector Electronics System Block Diagram



pn Junction in Pixel Photodiode

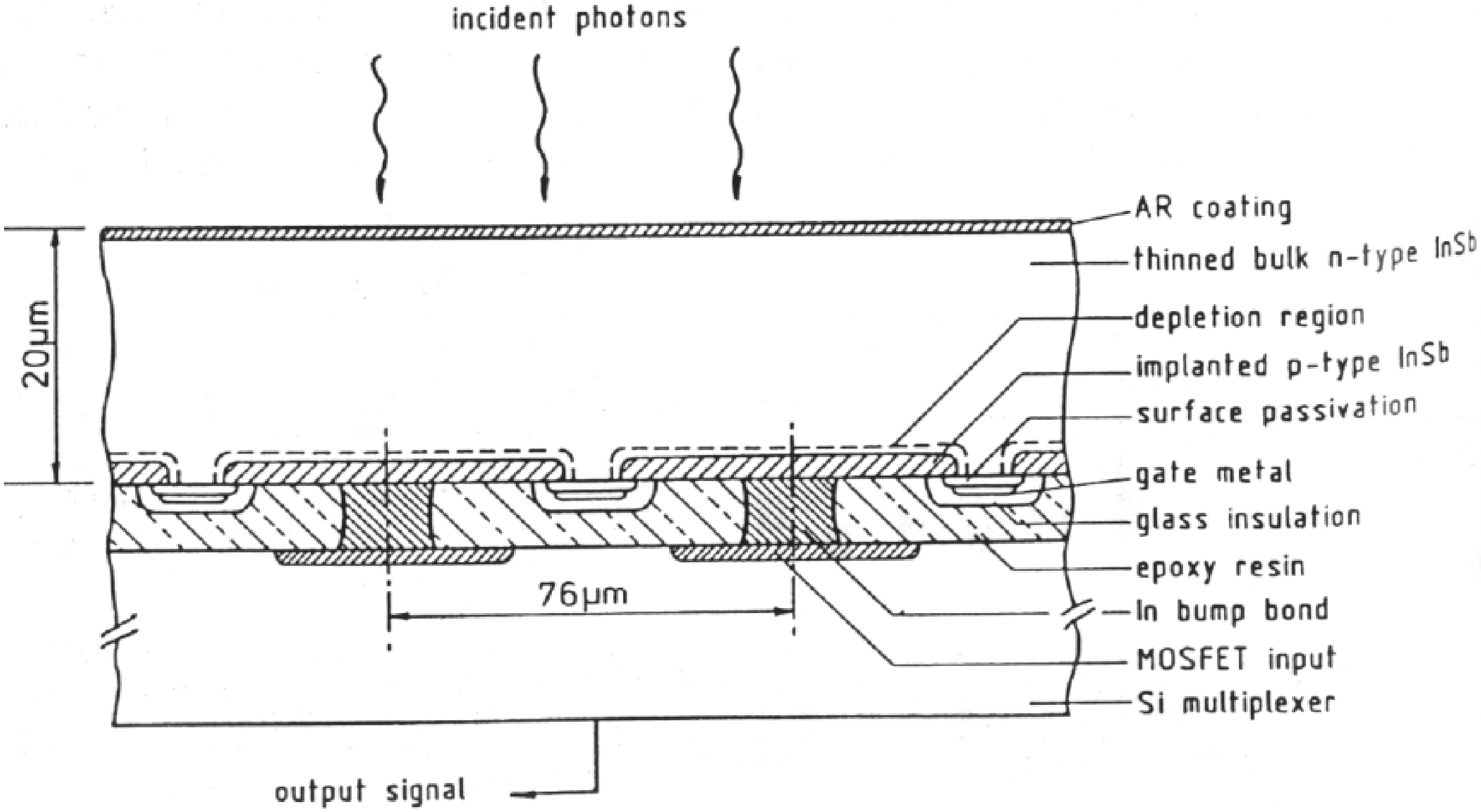


Fig. 8.13. The detailed construction of the original 62 x 58 InSb array from SBRC. A different passivation has allowed the gate electrode to be eliminated in later devices, but the basic bump

Architecture of an Indium antimonide hybrid array

Detector Readout Multiplexer Circuit

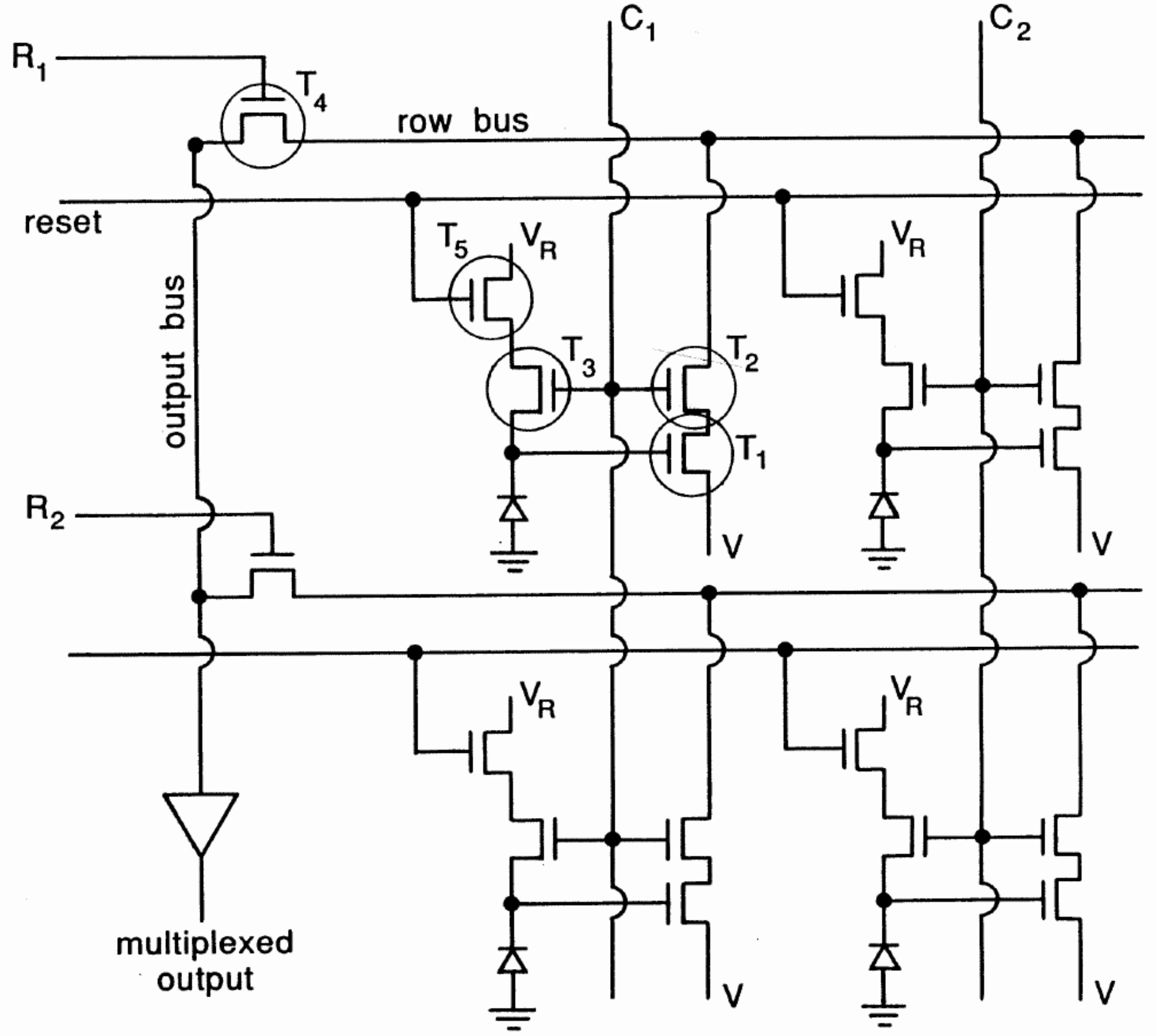
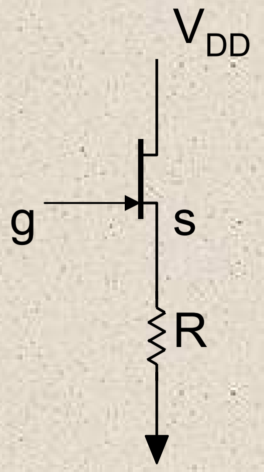


Figure 6.2. Four cells of the readout for a hybrid photodiode array. The detectors are indicated by diode symbols, and T_1 is the integrating amplifier FET.

Source Follower Output FET

- A “source follower” circuit uses a FET in a circuit that converts the output impedance of a signal from high to low. This is useful for driving long cables with small signals.



$v_s=Ri_d$
$i_d=g_mv_{gs}=g_m(v_g-v_s)$
$v_s=[Rg_m/(1+Rg_m)]v_g$

$\text{gain}=v_s/v_g=1/(1+1/Rg_m)$

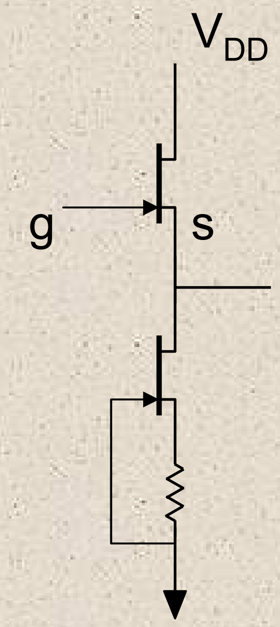
So, gain~1 for $Rg_m>>1$.

Note that g_m is the transconductance, and $1/g_m$ is the output impedance, typically ~a few hundred Ohms.

By replacing the resistor with a current source, R~infinite, so gain is nearer to 1.

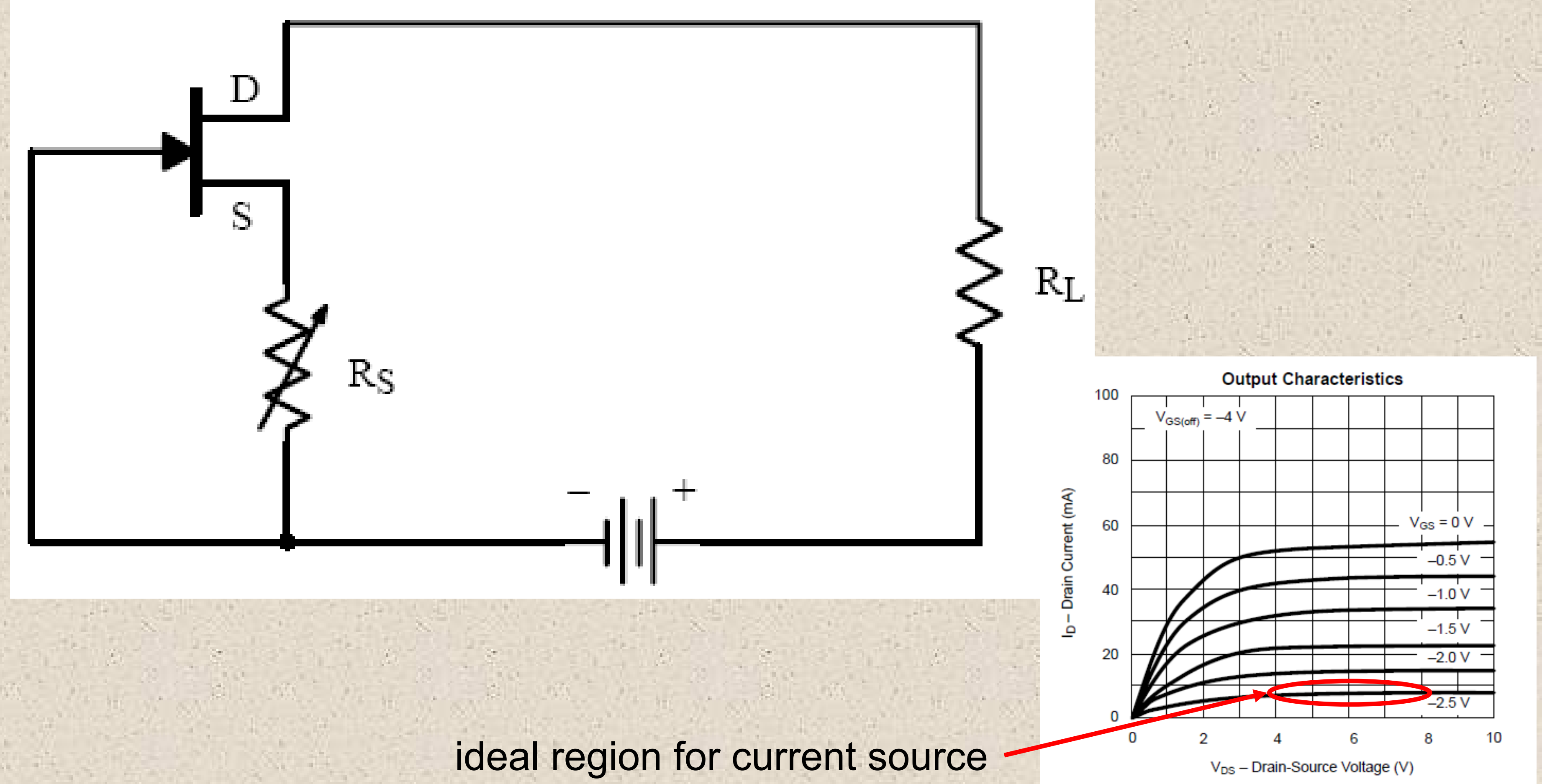
Source Follower with Current Source Load

- By replacing the resistor with a current source, R~infinite, so gain is nearer to 1.
- The current source is made of a FET with grounded gate.
- This circuit is sometimes referred to as a buffer.



FET Current Source: Schematic

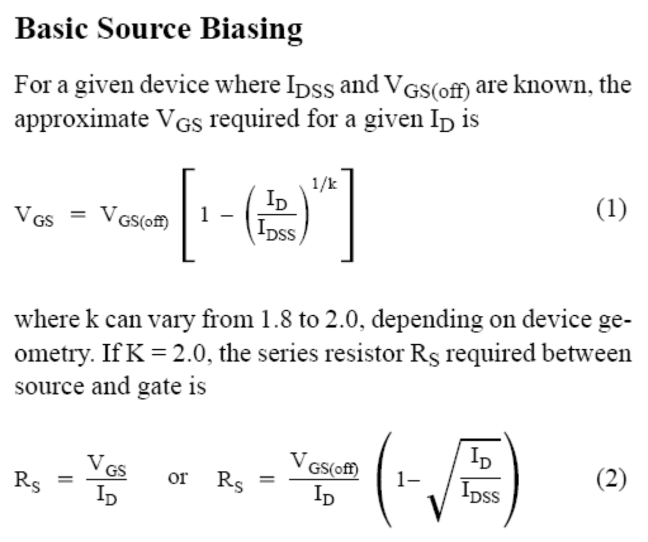
- A self-biased FET will deliver a nearly fixed current regardless of load if operated in the saturation region.



ideal region for current source

FET Current Source: Biasing

- The current source is most stable at V_{GS} just above the cutoff voltage ($V_{GS,off}$).
- The is where the transconductance goes to zero.



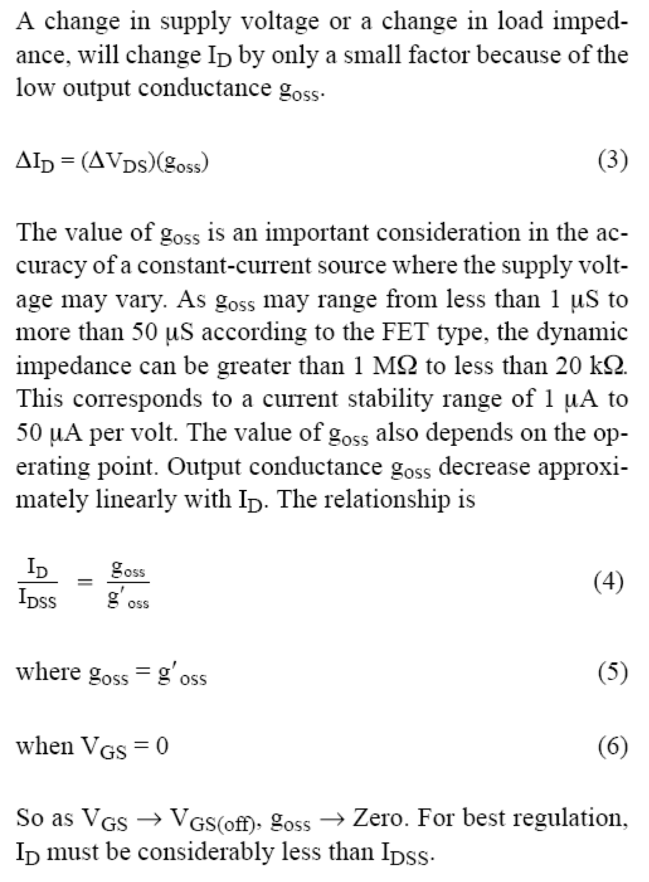
Basic Source Biasing

For a given device where I_{DSS} and $V_{GS(off)}$ are known, the approximate V_{GS} required for a given I_D is

$$V_{GS} = V_{GS(off)}\left[1 - \left(\frac{I_D}{I_{DSS}}\right)^{1/k}\right] \quad (1)$$

where k can vary from 1.8 to 2.0, depending on device geometry. If K = 2.0, the series resistor R_S required between source and gate is

$$R_S = \frac{V_{GS}}{I_D} \quad \text{or} \quad R_S = \frac{V_{GS(off)}}{I_D}\left(1 - \sqrt{\frac{I_D}{I_{DSS}}}\right) \quad (2)$$



A change in supply voltage or a change in load impedance, will change I_D by only a small factor because of the low output conductance g_{oss}.

$$\Delta I_D = (\Delta V_{DS})(g_{oss}) \quad (3)$$

The value of g_{oss} is an important consideration in the accuracy of a constant-current source where the supply voltage may vary. As g_{oss} may range from less than 1 µS to more than 50 µS according to the FET type, the dynamic impedance can be greater than 1 MΩ to less than 20 kΩ. This corresponds to a current stability range of 1 µA to 50 µA per volt. The value of g_{oss} also depends on the operating point. Output conductance g_{oss} decrease approximately linearly with I_D. The relationship is

$$\frac{I_D}{I_{DSS}} = \frac{g_{oss}}{g'_{oss}} \quad (4)$$

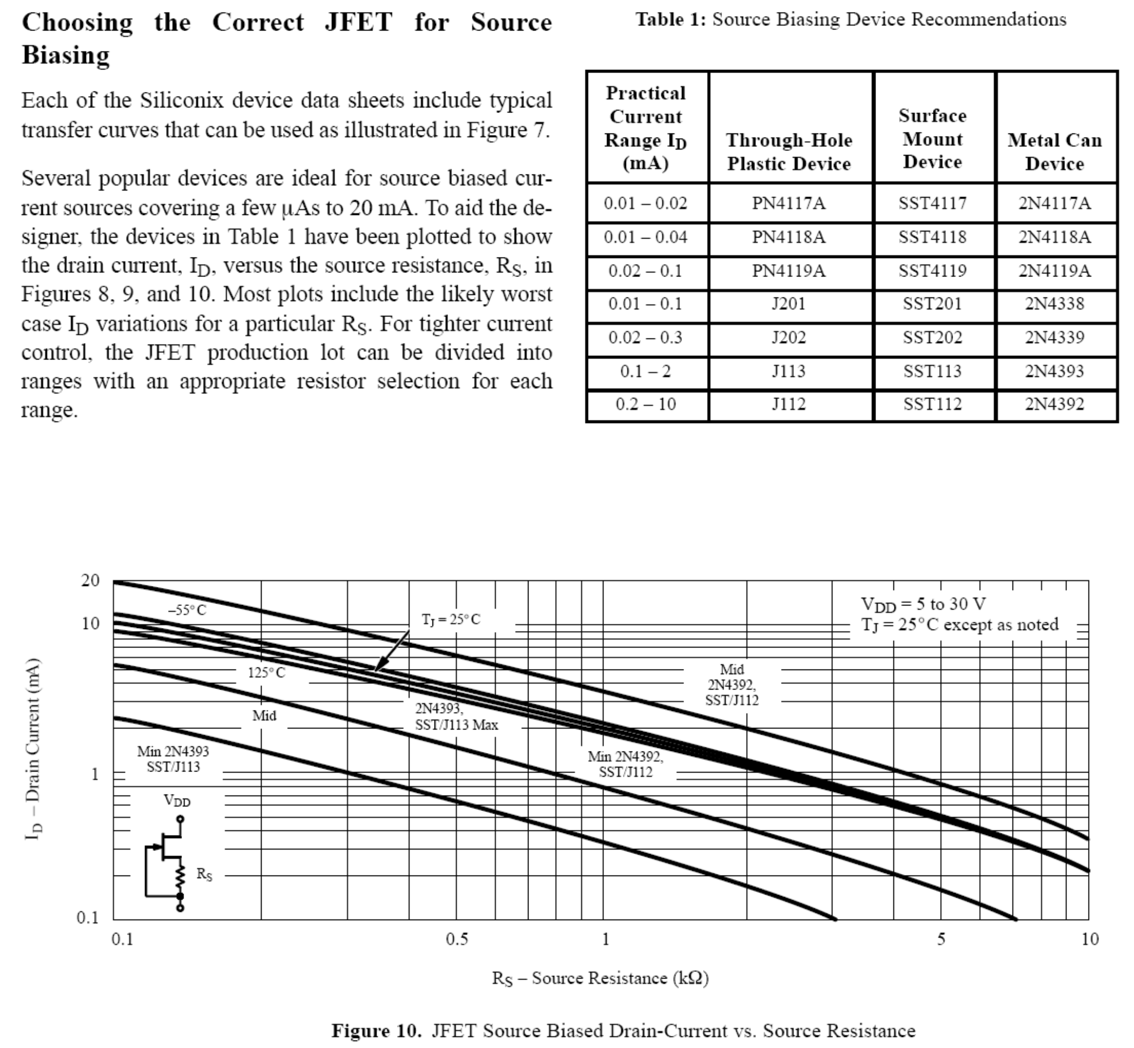
where $g_{oss} = g'_{oss}$ (5)

when $V_{GS} = 0$ (6)

So as $V_{GS} \to V_{GS(off)}$, $g_{oss} \to$ Zero. For best regulation, I_D must be considerably less than I_{DSS}.

FET Current Source: Parts

- The following table gives output current versus bias resistance for a var



Choosing the Correct JFET for Source Biasing

Each of the Siliconix device data sheets include typical transfer curves that can be used as illustrated in Figure 7.

Several popular devices are ideal for source biased current sources covering a few μAs to 20 mA. To aid the designer, the devices in Table 1 have been plotted to show the drain current, I_D, versus the source resistance, R_S, in Figures 8, 9, and 10. Most plots include the likely worst case I_D variations for a particular R_S. For tighter current control, the JFET production lot can be divided into ranges with an appropriate resistor selection for each range.

Table 1: Source Biasing Device Recommendations

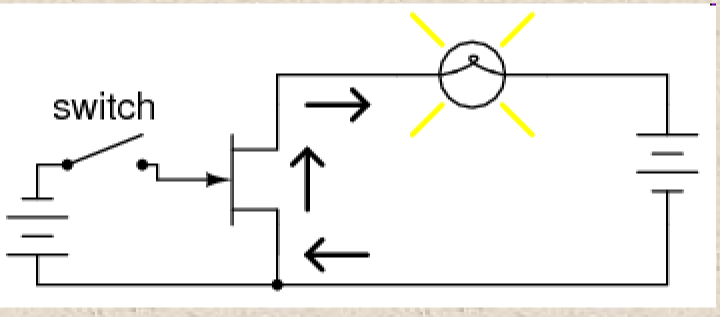
Practical Current Range I_D (mA)	Through-Hole Plastic Device	Surface Mount Device	Metal Can Device
0.01 – 0.02	PN4117A	SST4117	2N4117A
0.01 – 0.04	PN4118A	SST4118	2N4118A
0.02 – 0.1	PN4119A	SST4119	2N4119A
0.01 – 0.1	J201	SST201	2N4338
0.02 – 0.3	J202	SST202	2N4339
0.1 – 2	J113	SST113	2N4393
0.2 – 10	J112	SST112	2N4392

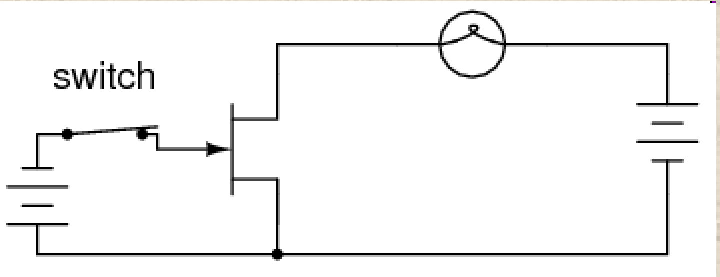
Figure 10. JFET Source Biased Drain-Current vs. Source Resistance

Switch

JFET Switch

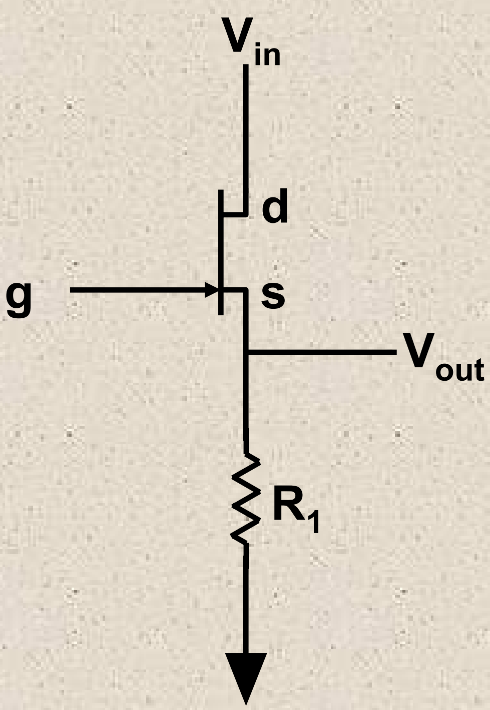
- An ideal switch would make a short-circuit connection when “on” and an open connection when “off.” In other words, it would behave like a mechanical switch.
- The following switch quenches current flow when the JFET gate is reverse-biased below the cutoff level.





JFET Switch

On state = signal passed ► R_{DS} ~ 25 - 100Ω
Off state = open circuit ► R_{DS} ~ 10 GΩ



- $V_{out}=V_{in}$ when switch is “on”
- $V_{out}=0$ when switch is “off”
- circuit behaves like a voltage divider when on.

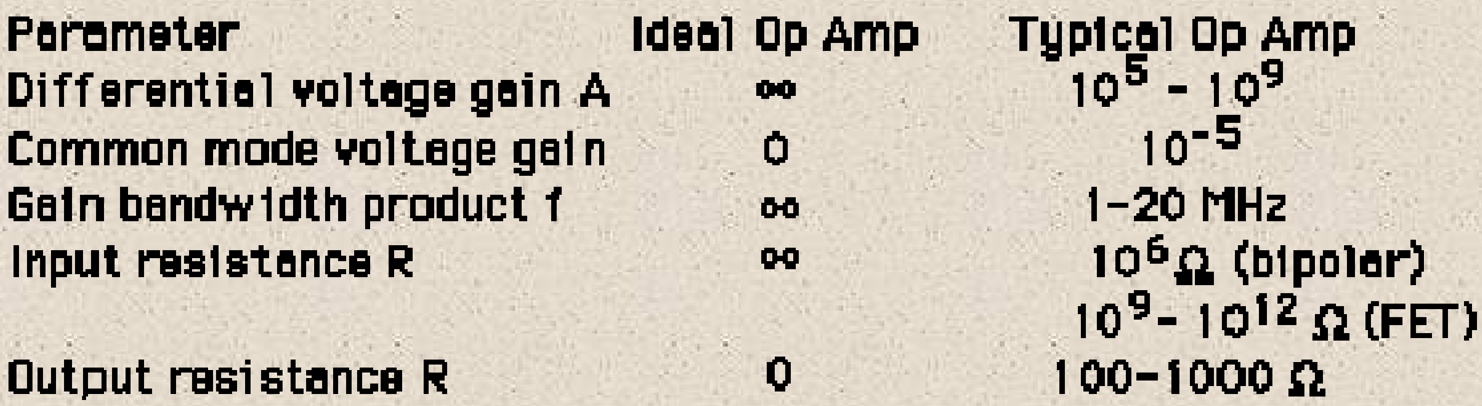
$$v_{out} = \frac{v_{in} R_1}{R_1 + R_{JFET}}$$

$$\begin{aligned} &R_1 >> R_{JFET} \\ &\qquad v_{out} \approx \quad v_{in} \\ &R_1 << R_{JFET} \\ &\qquad v_{out} \approx \quad 0 \end{aligned}$$

Pre-Amplifier

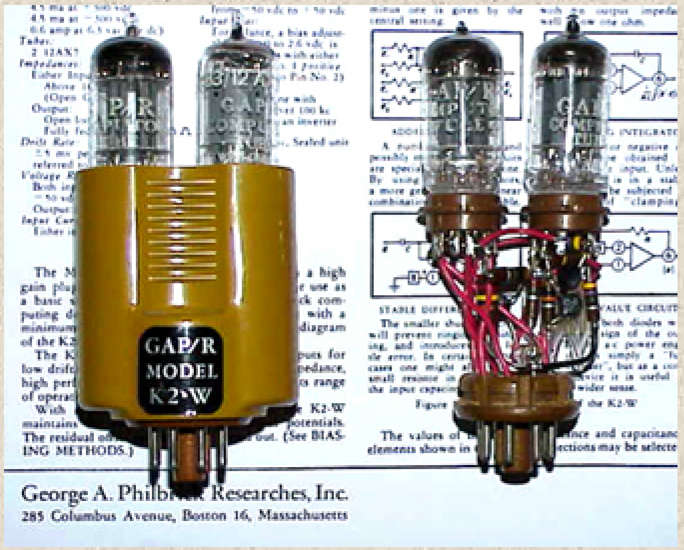
Op-amps

- Ideal IC Op-amp has
  - Infinite voltage gain
  - Infinite input impedance
  - Zero output impedance
  - Infinite bandwidth
  - Zero input offset voltage (i.e., exactly zero out if zero in).
- Golden Rules (Horowitz & Hill)
  - I. The output attempts to do whatever is necessary to make the voltage difference between the inputs zero. (The Voltage Rule)
  - II. The inputs draw no current. (The Current Rule)

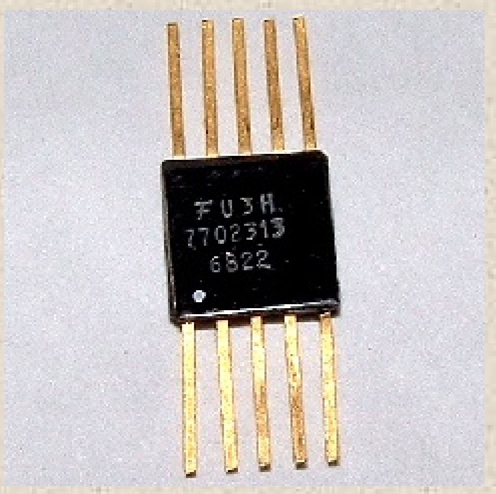


Parameter	Ideal Op Amp	Typical Op Amp
Differential voltage gain A	∞	$10^5 - 10^9$
Common mode voltage gain	0	10^{-5}
Gain bandwidth product f	∞	1-20 MHz
Input resistance R	∞	$10^6\,\Omega$ (bipolar) $10^9 - 10^{12}\,\Omega$ (FET)
Output resistance R	0	100-1000 Ω

Op-amps Through History



1952
K2-W tube op-amp
GAP Researches, Inc.



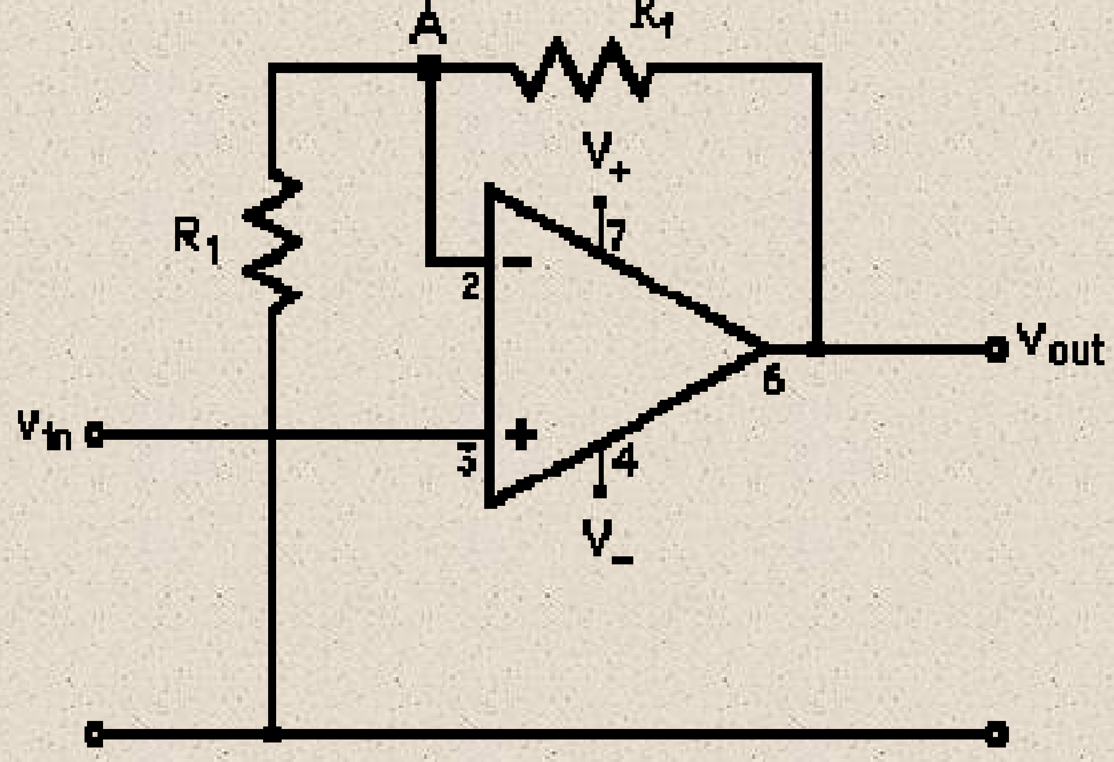
1964
uA702 op-amp
Fairchild Semiconductor
~$1300 (2009$)

1967
uA709 op-amp
Fairchild Semiconductor
~$50 (2009$)

- Bob Widlar designed the uA709. He requested a raise from his boss, Charles Sporck, but he was denied.
- So, he quit, and went to National Semiconductor.
- One year later, Sporck became President of National Semiconductor!
- Widlar got his raise and retired in 1970, just before his 30th birthday.

Op-amps: non-inverting amplifier

- According to the golden rules, V_2=V_3, and the current into terminal 2 is zero.

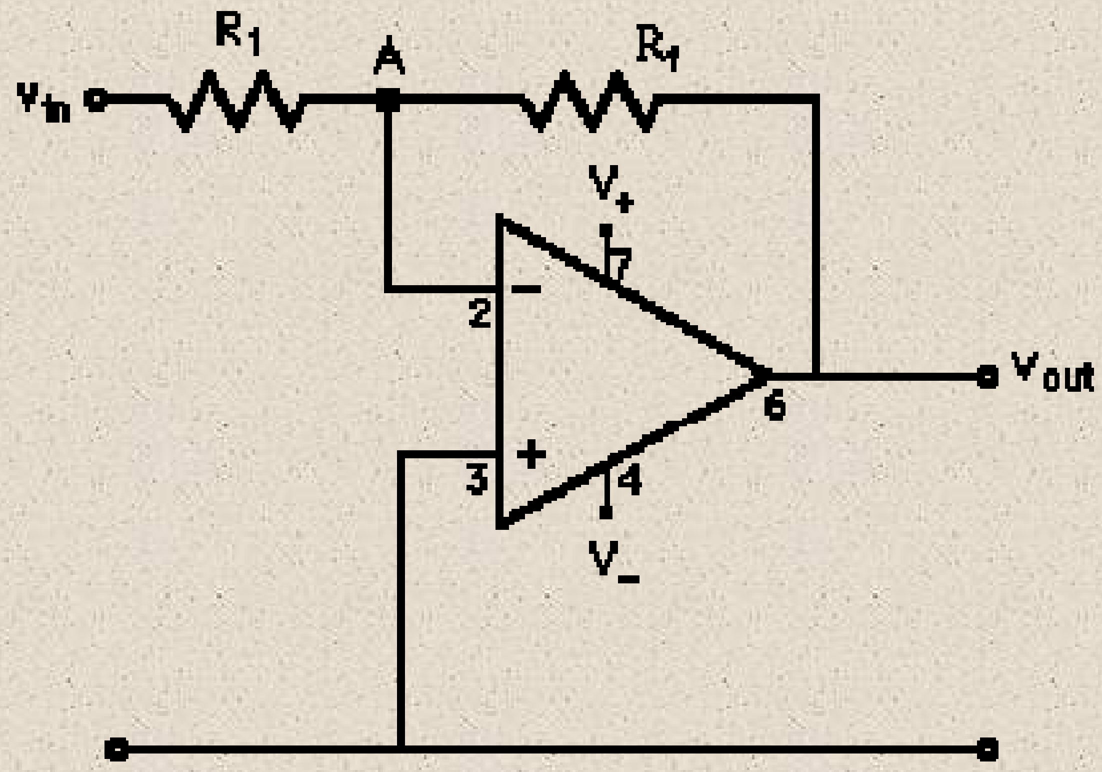


$$\frac{V_{in}}{R_1} = \frac{V_{out} - V_{in}}{R_f}$$

$$\frac{V_{out}}{V_{in}} = 1 + \frac{R_f}{R_1}$$

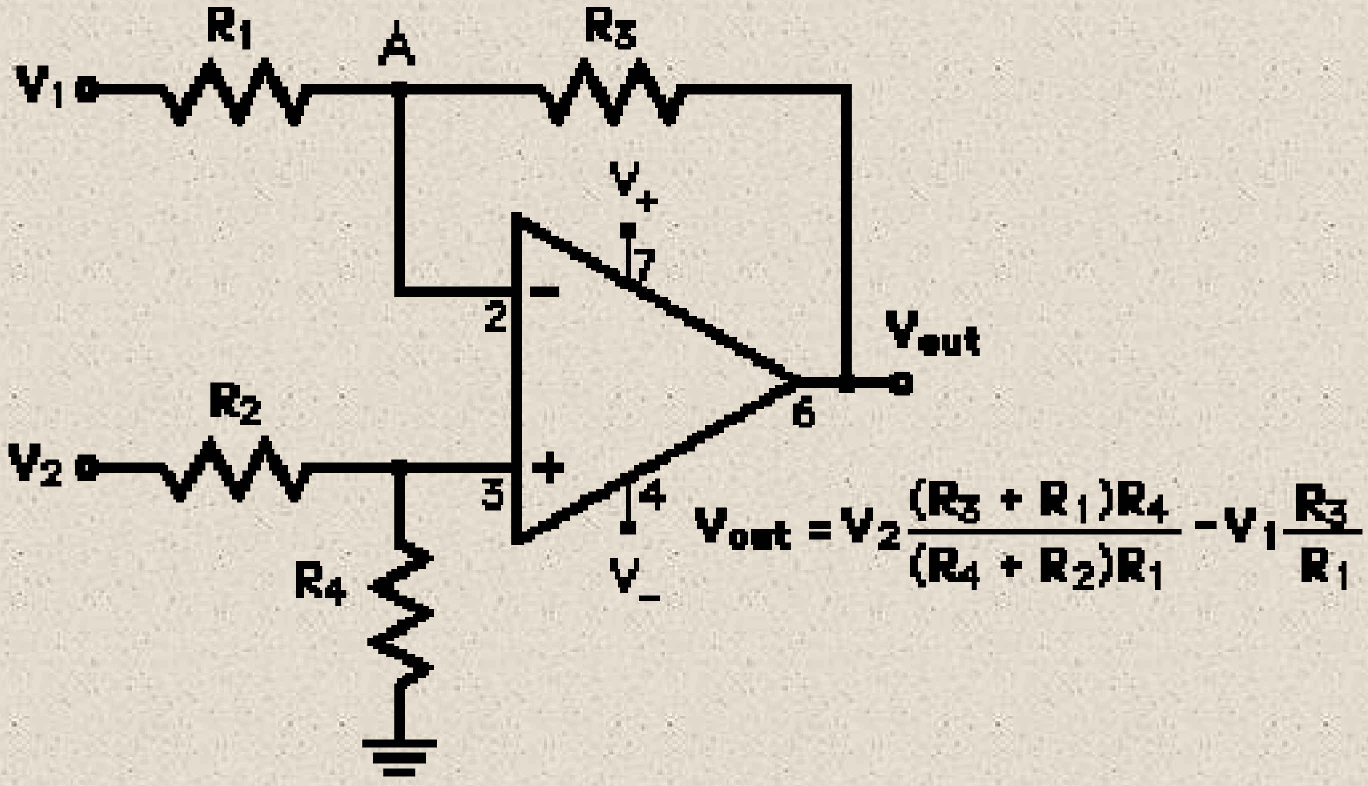
Op-amps: inverting amplifier

- According to the golden rules, the current into terminal 2 is zero.



$$\frac{V_{in}}{R_1} = -\frac{V_{out}}{R_f} \qquad \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_1}$$

Op-amps: differential amplifier

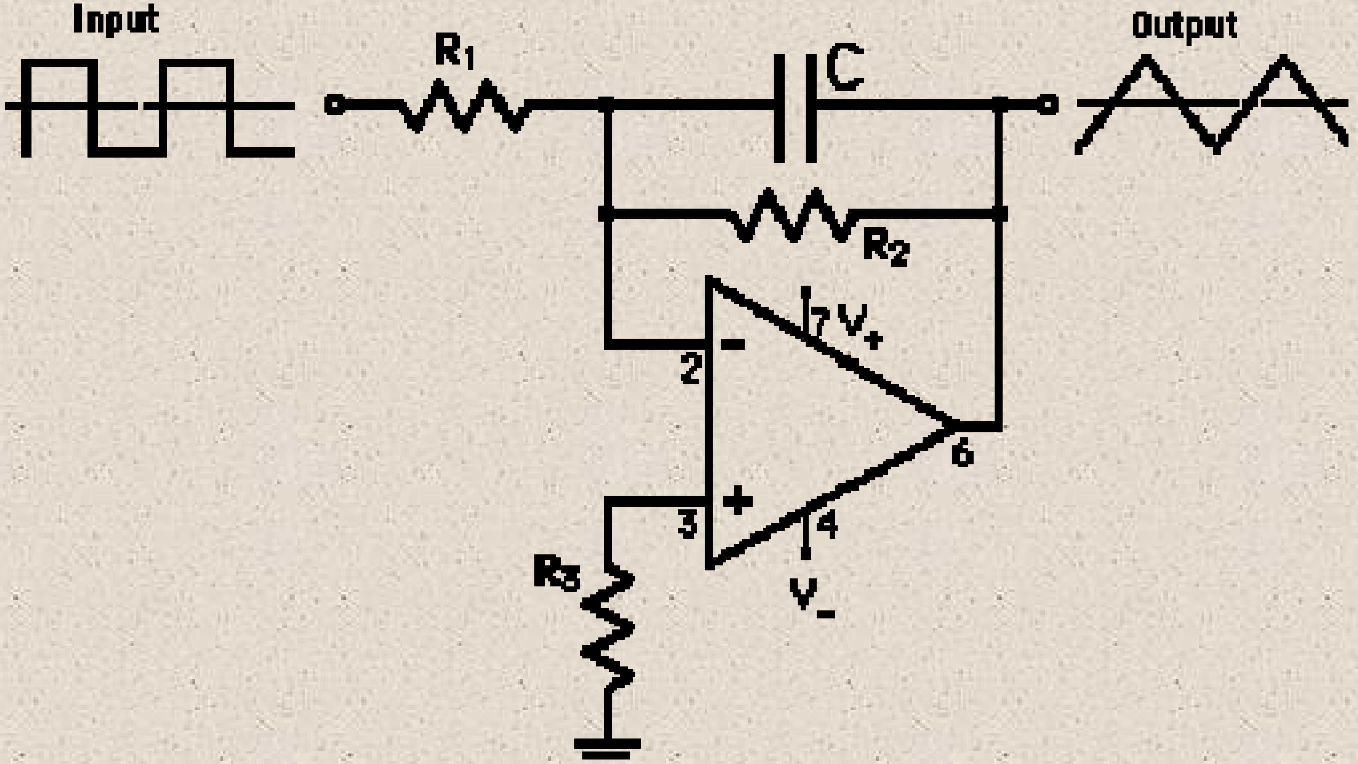


$$V_{out} = V_2 \frac{(R_3 + R_1)R_4}{(R_4 + R_2)R_1} - V_1 \frac{R_3}{R_1}$$

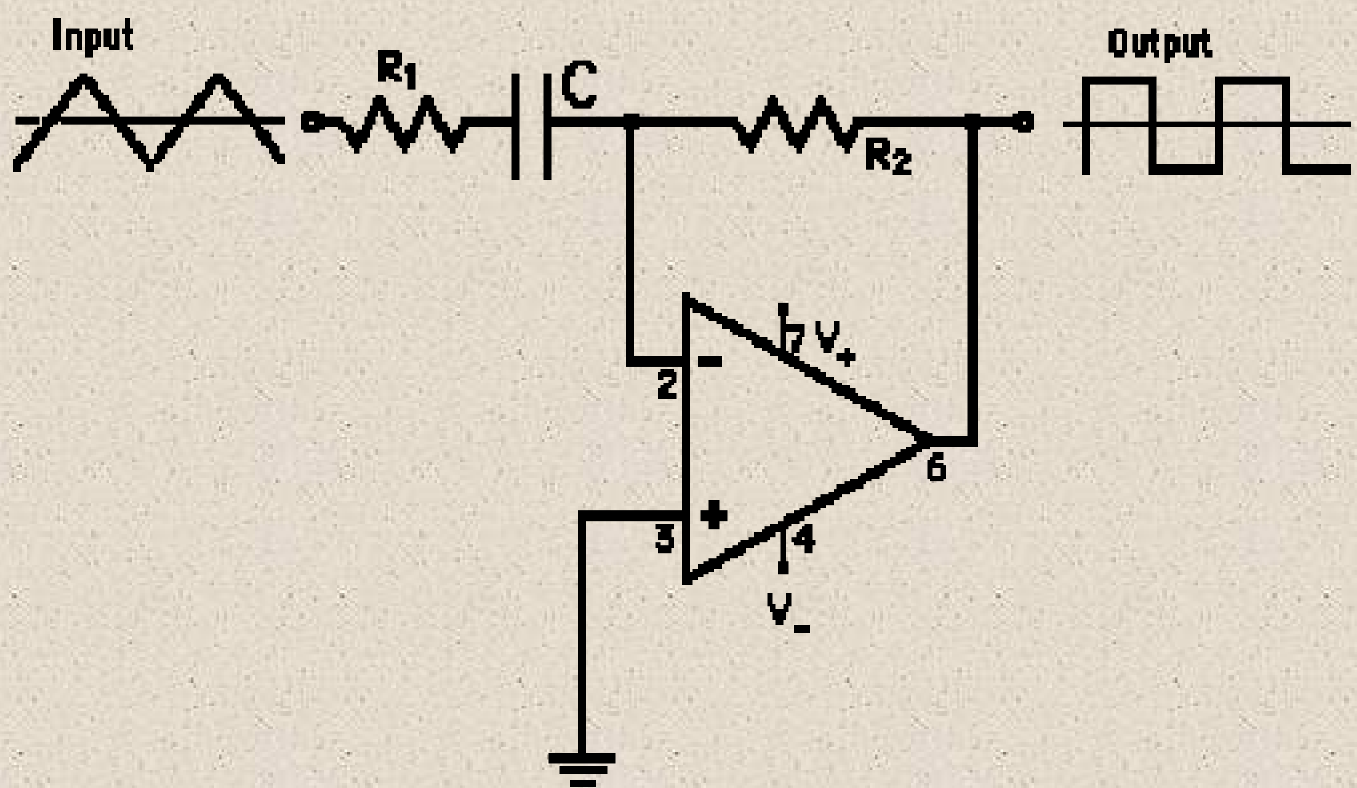
$$V_2 \frac{R_4}{R_2 + R_4} = V_A \qquad \frac{V_1 - V_A}{R_1} = -\frac{V_{out} - V_A}{R_3}$$

- If all resistors are equal, then the output is the difference.
- If R3=R4 and R1=R2, then the output is the amplified difference.

Op-amps: integrator

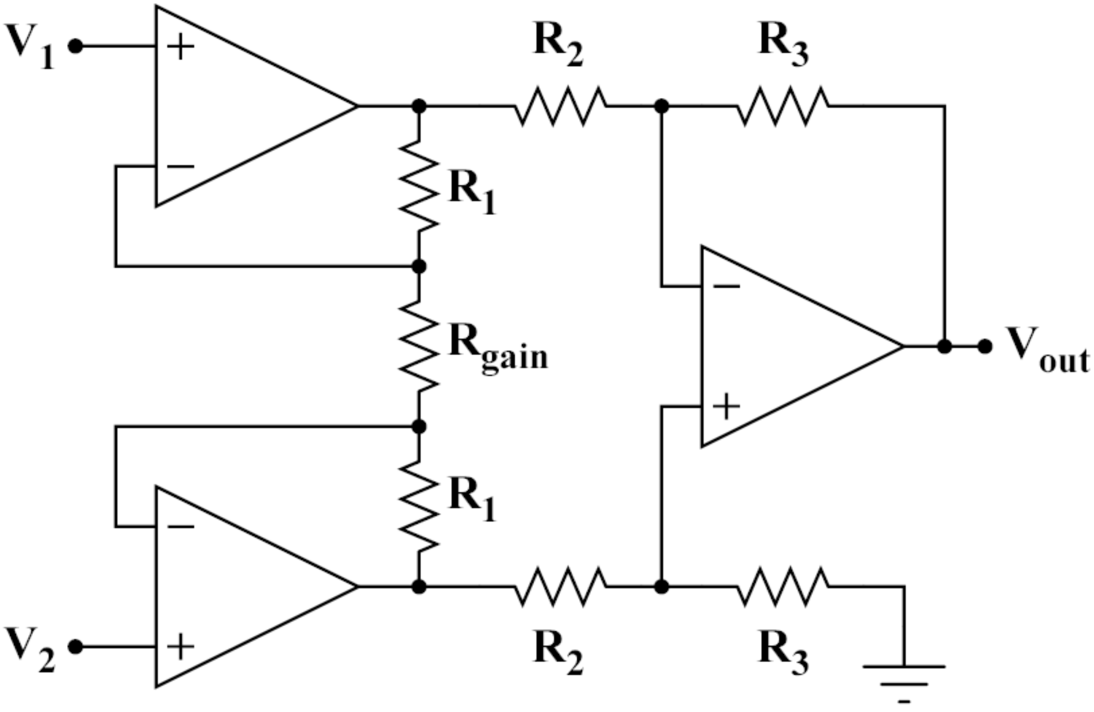


Op-amps: differentiator



Instrumentation Amplifier

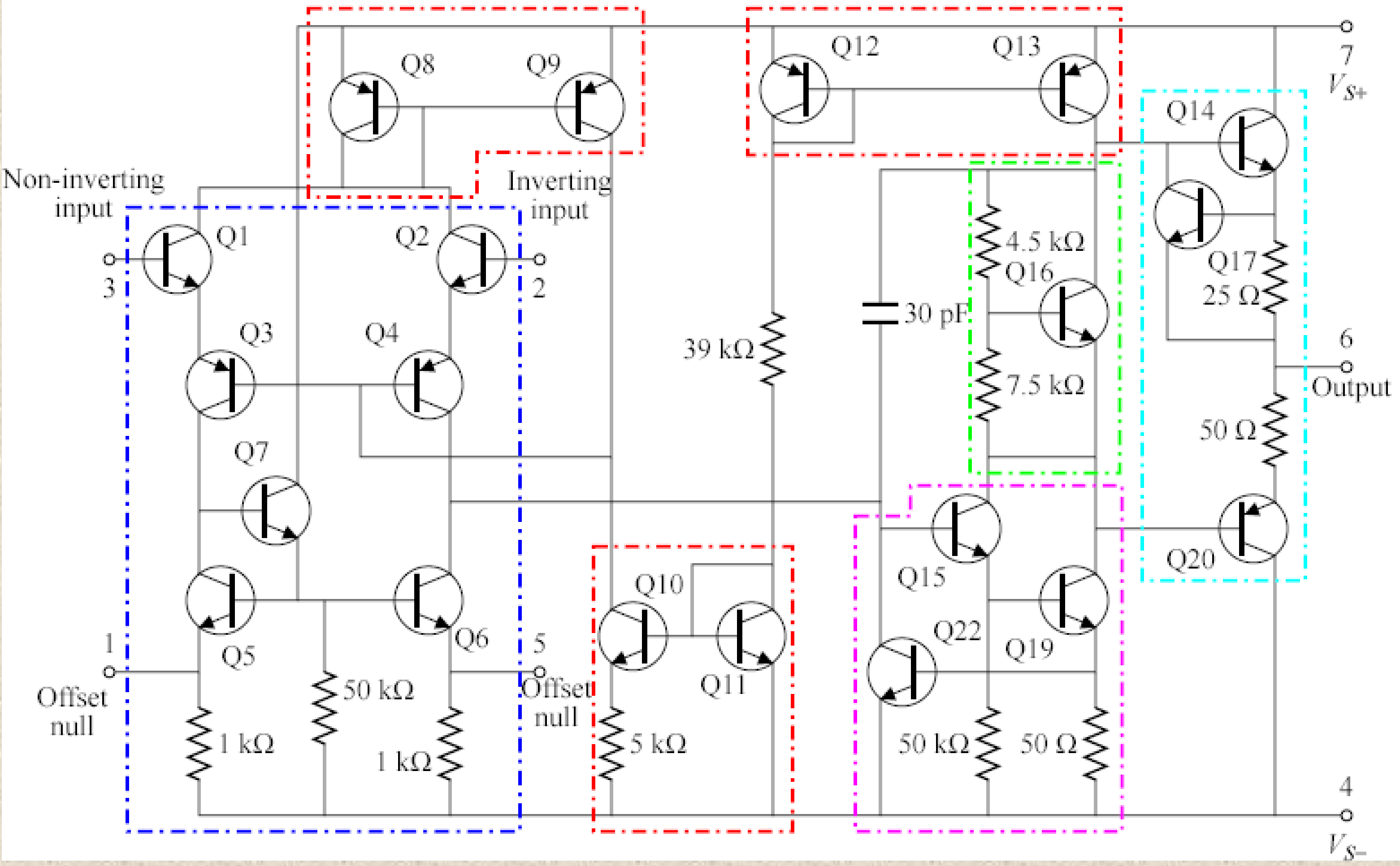
- IAs have low noise, high gain, high impedance input.



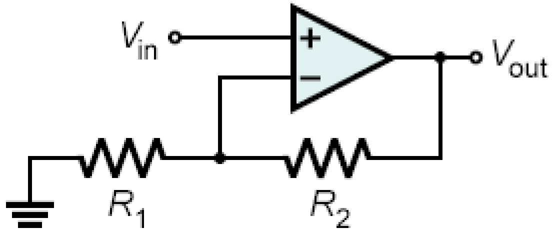
$$\frac{V_{\text{out}}}{V_2 - V_1} = \left(1 + \frac{2R_1}{R_{\text{gain}}}\right)\frac{R_3}{R_2}$$

Operational Amplifier

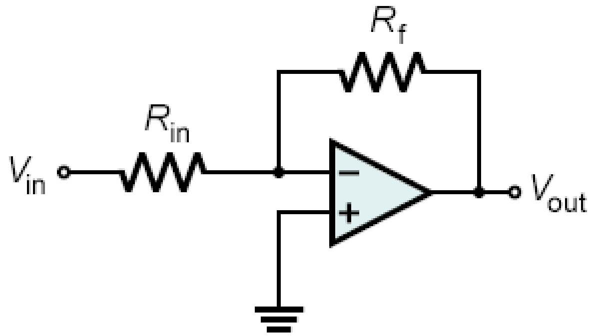
- Operational amplifier 741



Operationanl Amplifier – Equivalent Symbol



$$V_{\text{out}} = V_{\text{in}}\left(1 + \frac{R_2}{R_1}\right)$$

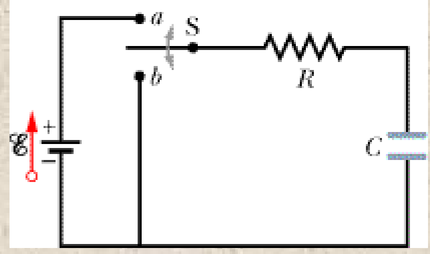


$$V_{\text{out}} = -V_{\text{in}}(R_{\text{f}}/R_{\text{in}})$$

Filter

RC Filter Time Constant

A capacitor of capacitance *C* is initially uncharged. To charge it, we close switch S on point *a*. This completes an *RC series circuit* consisting of the capacitor, an ideal battery, and a resistance *R*.



When switch S is closed on *a*, the capacitor is *charged* through the resistor. When the switch is afterward closed on *b*, the capacitor *discharges* through the resistor.

As soon as the circuit is complete, charge flows between a capacitor plate and a battery terminal on each side of the capacitor. This current increases the charge *q* on the plates and the potential difference V_C (= q/C) across the capacitor. When that potential difference equals the potential difference across the battery, the current is zero. The *equilibrium* (final) *charge* on the then fully charged capacitor satisfies q = CV.

Here we want to examine the charging process. In particular we want to know how the charge $q(t)$ on the capacitor plates, the potential difference $V_C(t)$ across the capacitor, and the current $i(t)$ in the circuit vary with time during the charging process. We begin by applying the loop rule to the circuit, traversing it clockwise from the negative terminal of the battery. We find

$$\mathscr{E} - iR - \frac{q}{C} = 0.$$

The last term on the left side represents the potential difference across the capacitor. The term is negative because the capacitor's top plate, which is connected to the battery's positive terminal, is at a higher potential than the lower plate. Thus, there is a drop in potential as we move down through the capacitor.

Note that $i = \frac{dq}{dt}$.

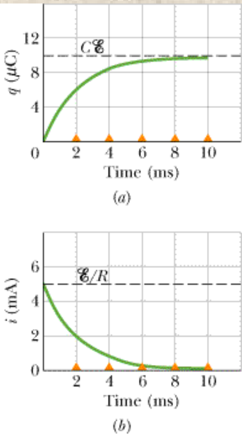
Substituting, we find $R\frac{dq}{dt} + \frac{q}{C} = \mathscr{E}$ (charging equation).

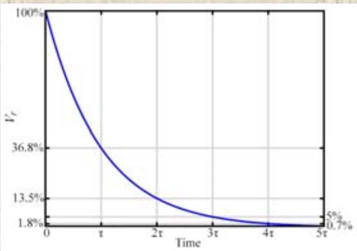
Solving, we find

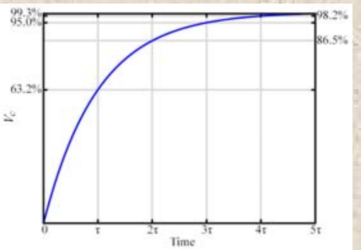
$$q = C\mathscr{E}(1 - e^{-t/RC}) \quad \text{(charging a capacitor)}.$$

$$i = \frac{dq}{dt} = \left(\frac{\mathscr{E}}{R}\right)e^{-t/RC} \quad \text{(charging a capacitor)}.$$

$$V_C = \frac{q}{C} = \mathscr{E}(1 - e^{-t/RC}) \quad \text{(charging a capacitor)}.$$



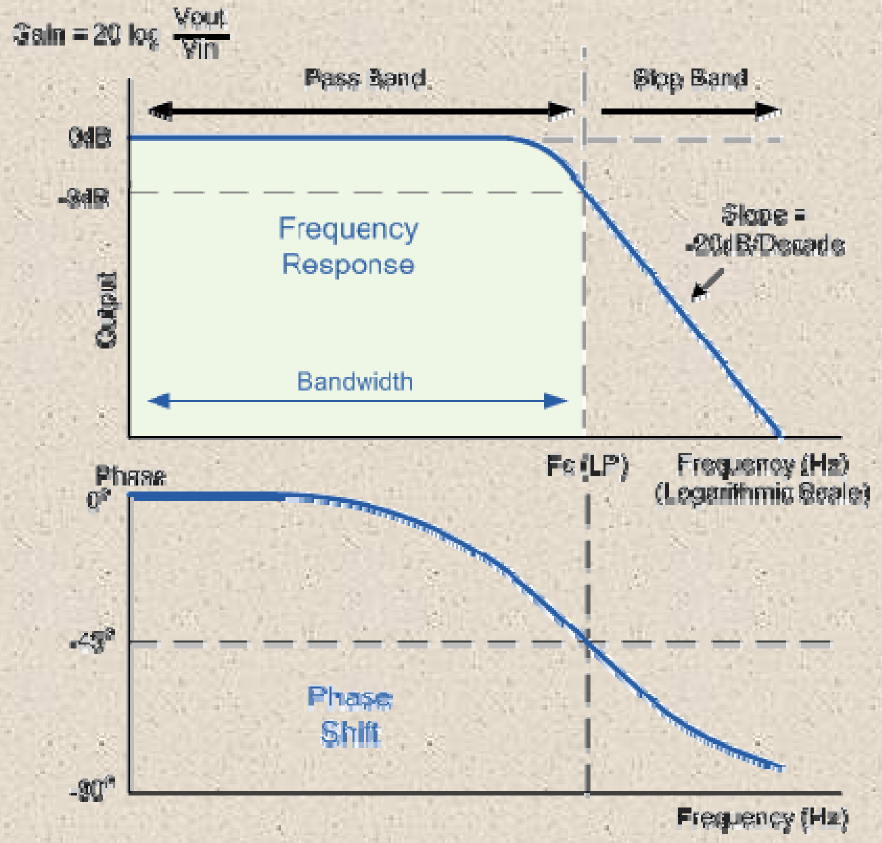




RC time constant

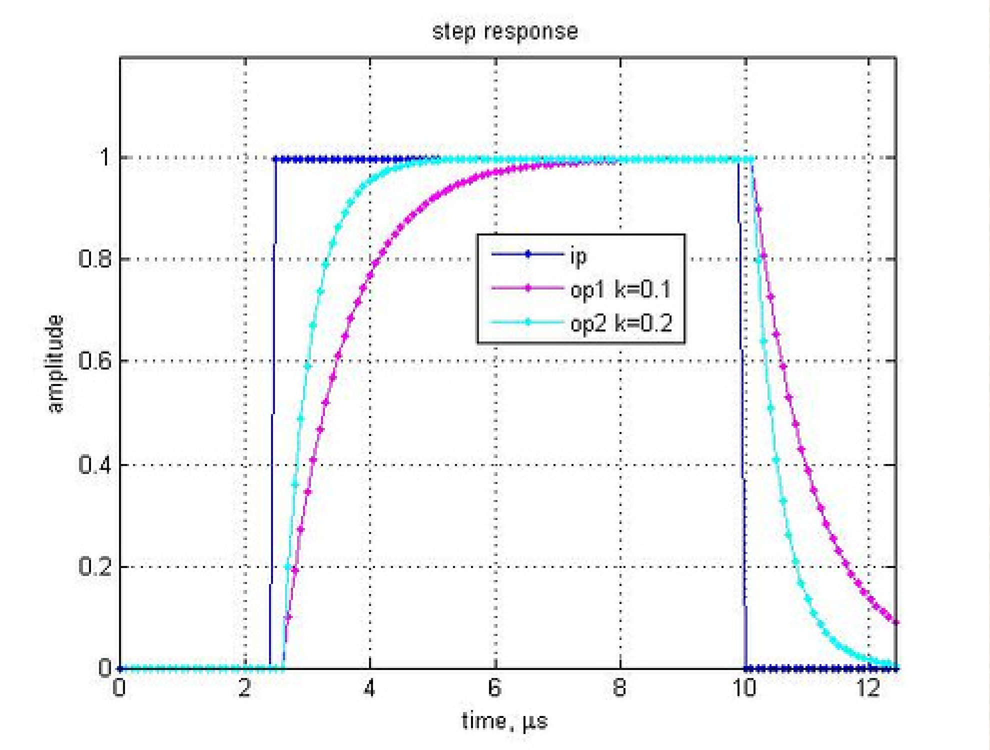
- The RC filter attenuates voltage fluctations.
- The gain is $A_v = \frac{1}{\sqrt{1 + (f/f_0)^2}}$

f_0=1/(2πτ)=1/(2πRC).

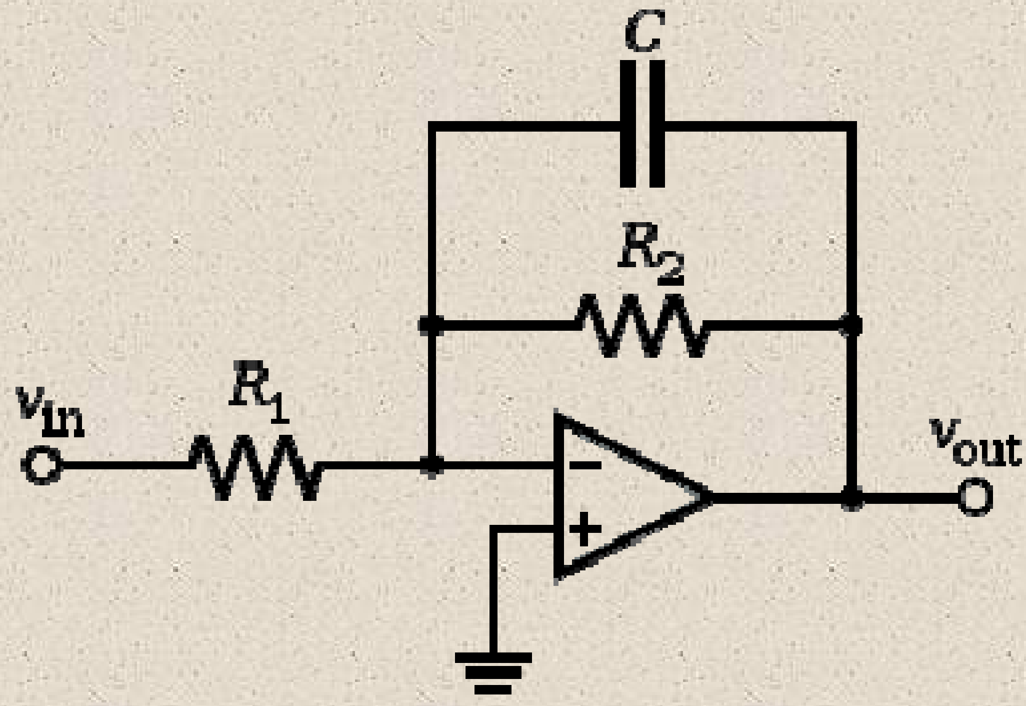


RC Filter Step Response

- Any system with resistance and capacitance will have a slow response to a step function.
- This effect limits the speed of switching circuits, i.e. pixel clocking in a detector.



RC Filter Active Implementation



Frequency Limitation of MOSFET

- A MOSFET has some capacitance and resistance that limit its frequency response.
- Consider a typical example:

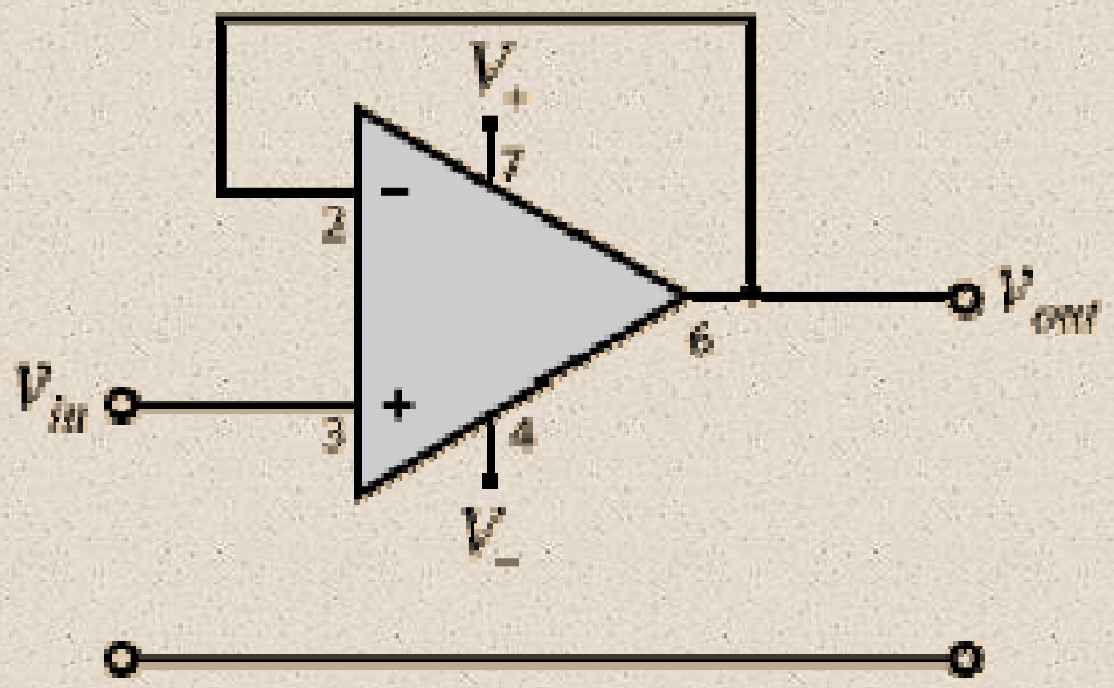
$$f = \frac{1}{2\pi RC} = \frac{1}{2\pi\left(\frac{1}{g_m}\right)\left(\frac{\kappa\varepsilon_0 A}{d}\right)} = \frac{1}{2\pi\left(\frac{1}{g_m}\right)\left(\frac{\kappa\varepsilon_0 lw}{d}\right)} = \frac{1}{2\pi\left(\frac{1}{10^{-4}}\right)\left(\frac{4\times 8.85(10^{-12})\times 5(10^{-6})\times 30(10^{-6})}{70(10^{-9})}\right)}$$

$$\approx 200\ MHz\ .$$

Buffer/Driver

Op-amps: buffer

- According to the golden rules, $V_2=V_3$, so $V_{out}=V_{in}$.

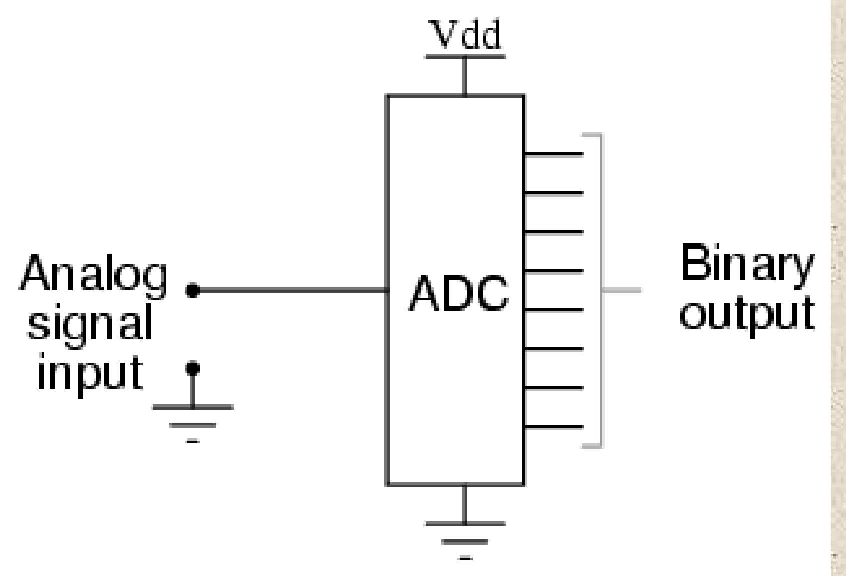


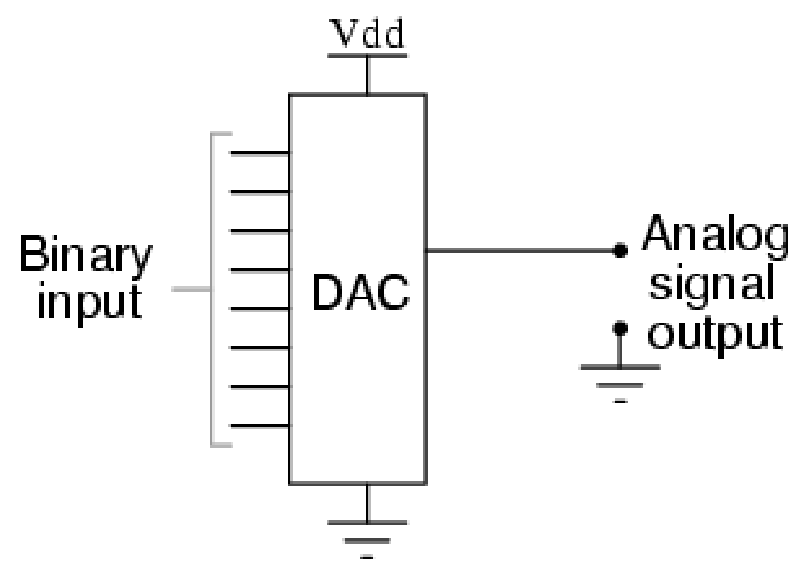
$$v_{out} = v_{in}$$

ADCs

ADCs and DACs

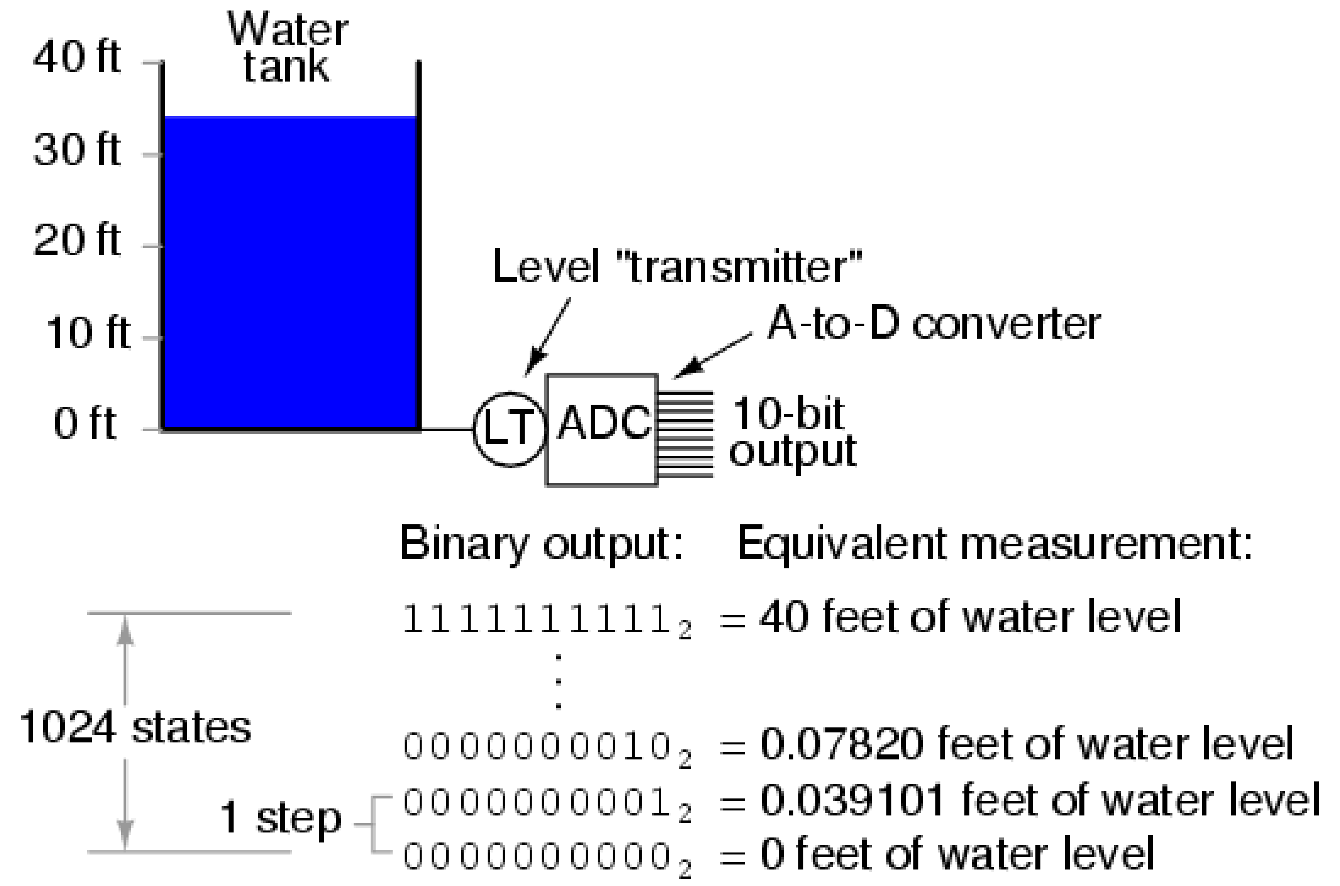
- An Analog-to-Digital Converter (ADC) converts an analog signal to a digital signal.
- A Digital-to-Analog Converter (DAC) does the opposite.





ADCs and Resolution

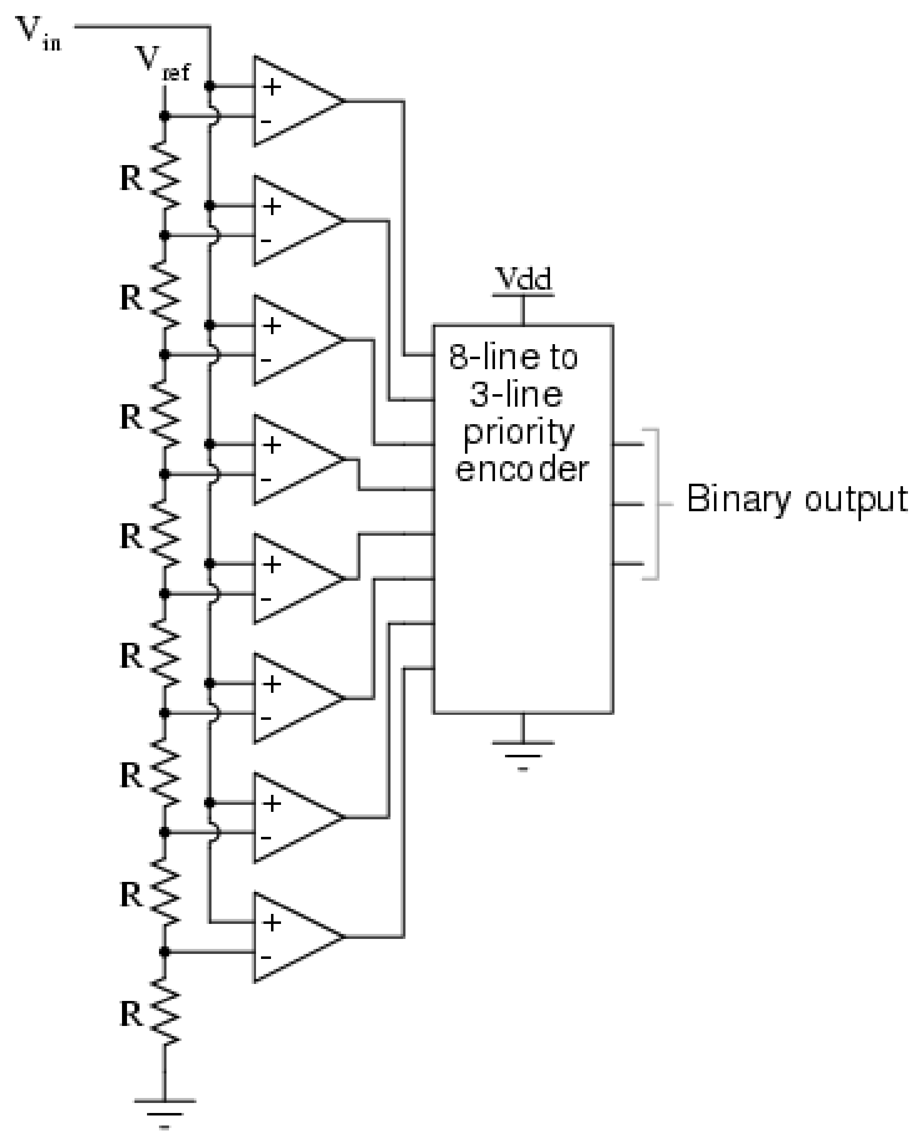
- Resolution sets the smallest increment that can be measured.
- In the water tank analogy, the resolution sets the minimum increment of depth that can be measured.



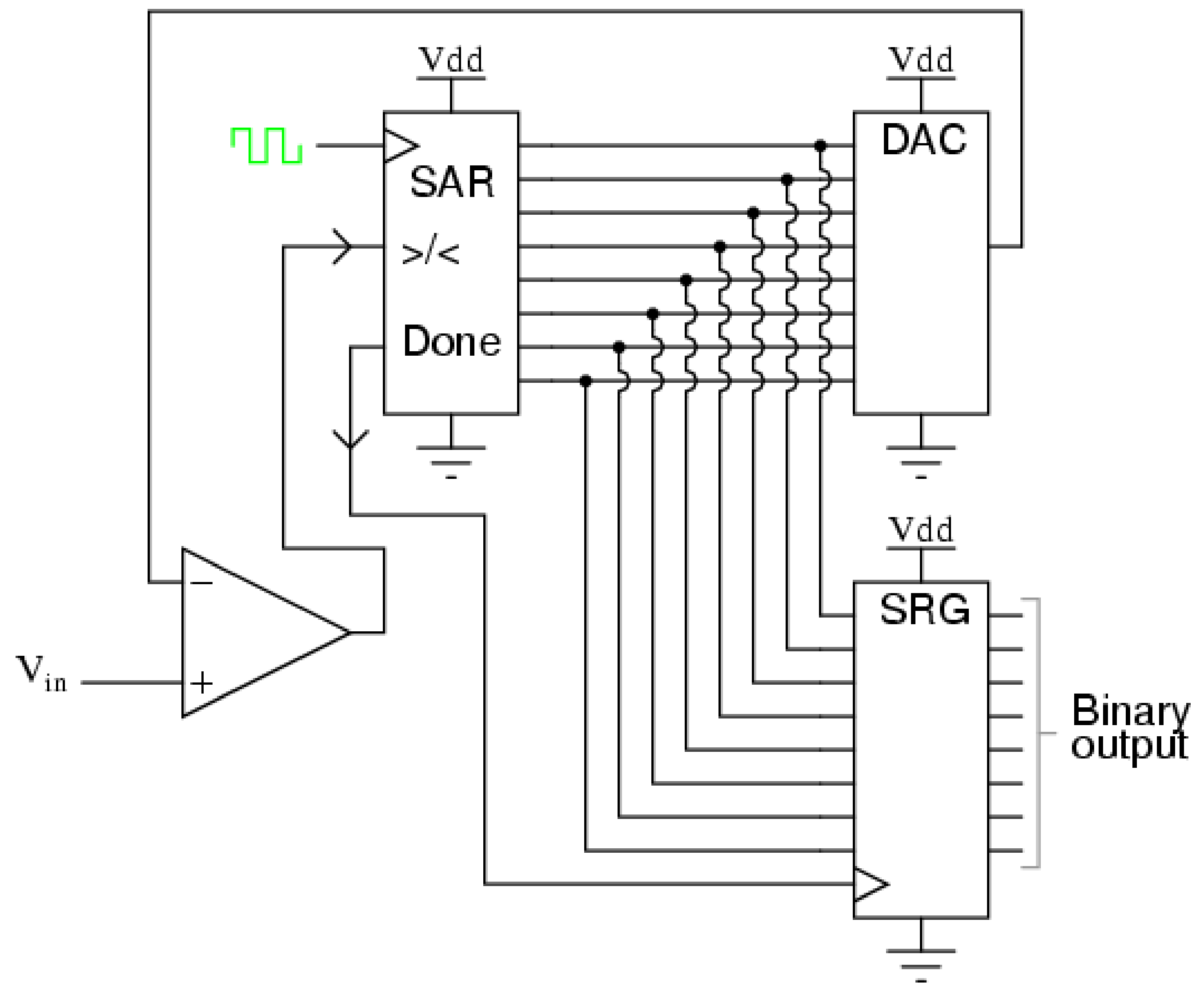
ADCs

- There are a half-dozen or so ADC architectures in common usage.
  - A **flash** ADC has a bank of comparators, each firing for their decoded voltage range. The comparator bank feeds a logic circuit that generates a code for each voltage range. Direct conversion is very fast, but usually has only 8 bits of resolution (255 comparators - since the number of comparators required is $2^n - 1$) or fewer, as it needs a large, expensive circuit.
  - A **successive-approximation** ADC uses a comparator to reject ranges of voltages, eventually settling on a final voltage range. Successive approximation works by constantly comparing the input voltage to the output of an internal digital to analog converter (DAC, fed by the current value of the approximation) until the best approximation is achieved. At each step in this process, a binary value of the approximation is stored in a successive approximation register (SAR).
  - A **ramp-compare** ADC produces a saw-tooth signal that ramps up, then quickly falls to zero. When the ramp starts, a timer starts counting. When the ramp voltage matches the input, a comparator fires, and the timer's value is recorded.
  - An **integrating** ADC (also dual-slope or multi-slope ADC) applies the unknown input voltage to the input of an integrator and allows the voltage to ramp for a fixed time period (the run-up period). Then a known reference voltage of opposite polarity is applied to the integrator and is allowed to ramp until the integrator output returns to zero (the run-down period).
  - A **delta-encoded** ADC or Counter-ramp has an up-down counter that feeds a digital to analog converter (DAC). The input signal and the DAC both go to a comparator. The comparator controls the counter. The circuit uses negative feedback from the comparator to adjust the counter until the DAC's output is close enough to the input signal.
  - A **pipeline** ADC (also called subranging quantizer) uses two or more steps of subranging. First, a coarse conversion is done. In a second step, the difference to the input signal is determined with a digital to analog converter (DAC). This difference is then converted finer, and the results are combined in a last step.
  - A **Sigma-Delta** ADC (also known as a Delta-Sigma ADC) oversamples the desired signal by a large factor and filters the desired signal band. Generally a smaller number of bits than required are converted using a Flash ADC after the Filter. The resulting signal, along with the error generated by the discrete levels of the Flash, is fed back and subtracted from the input to the filter.

Flash ADC

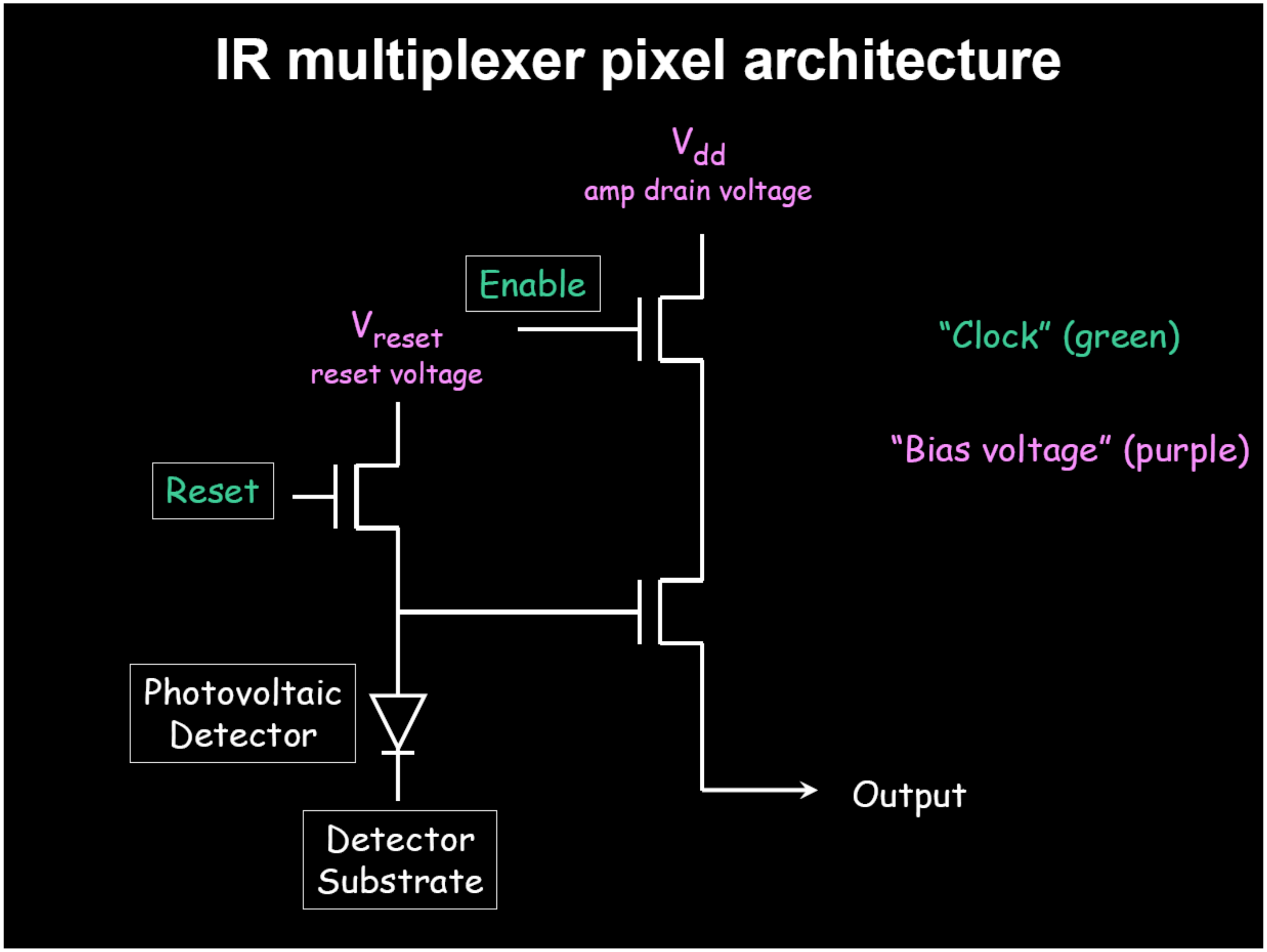

V_{in}
V_{ref}
R
R
R
R
R
R
R
R
+
-
Vdd
8-line to 3-line priority encoder
Binary output

Successive Approximation ADC



Detector Clocking/Biasing Operation

Pixel-level Cross Section

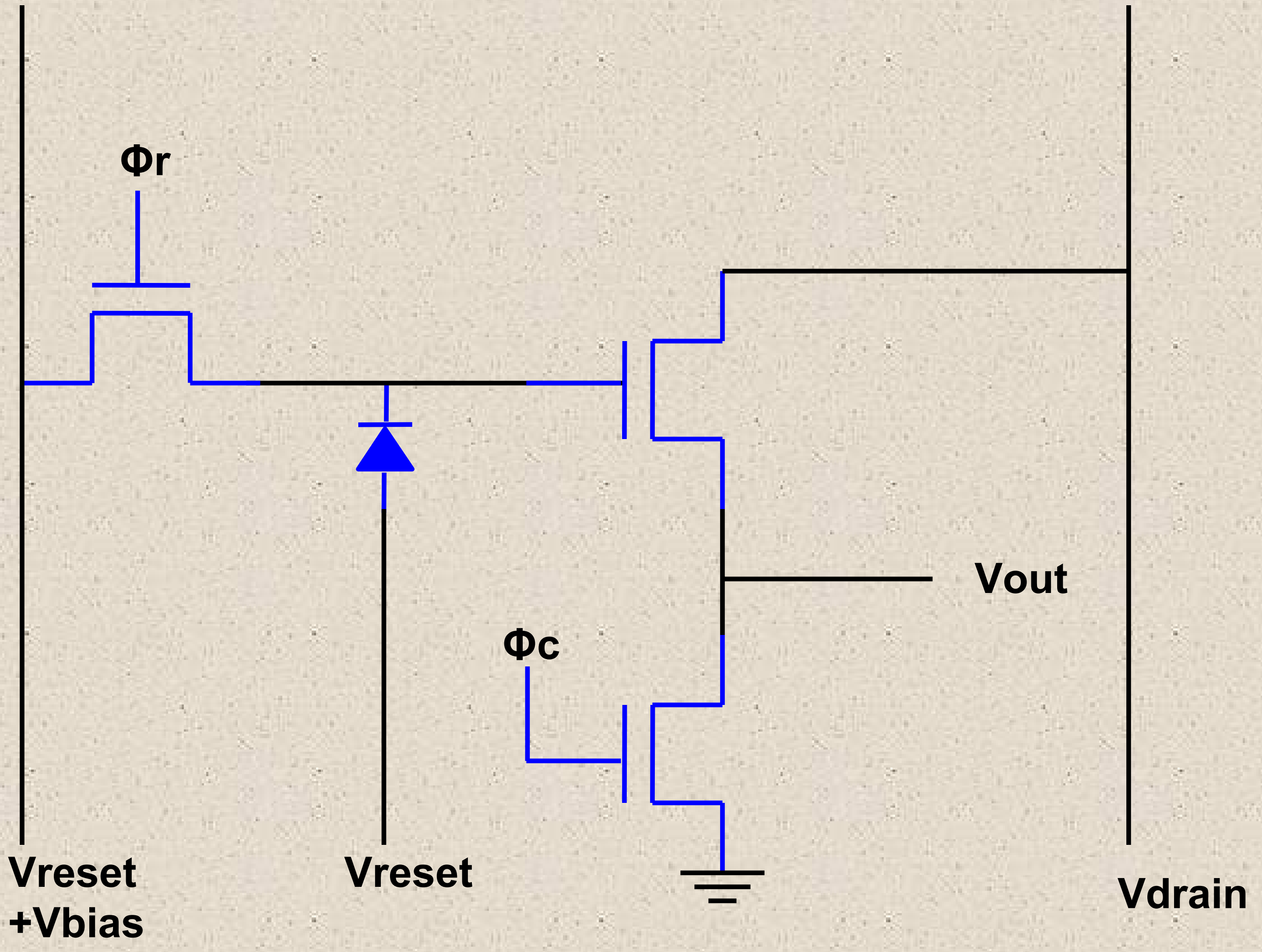


IR multiplexer pixel architecture

"Clock" (green)

"Bias voltage" (purple)

Unit Cell Circuit Schematic



Multiplexer Circuit

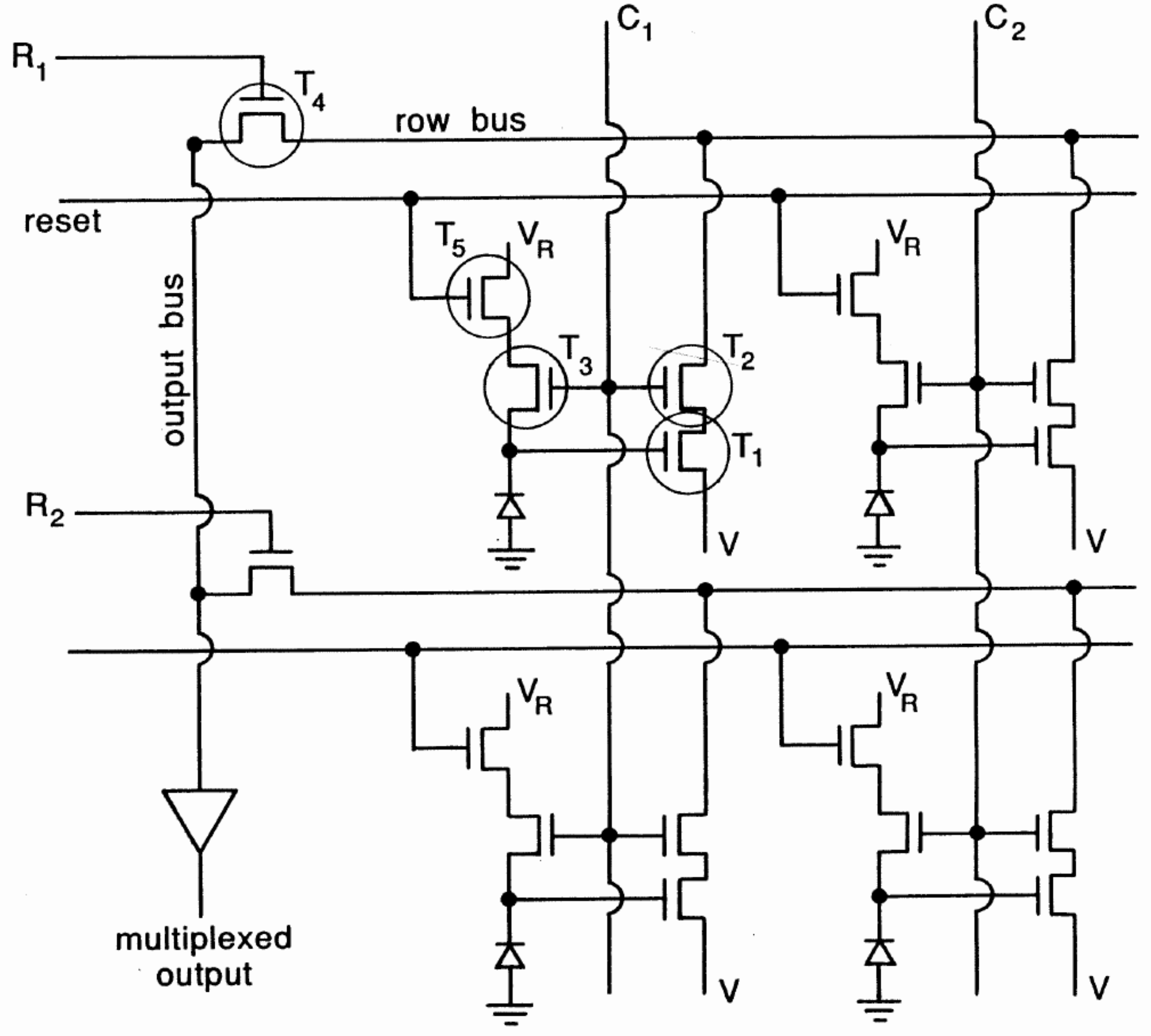
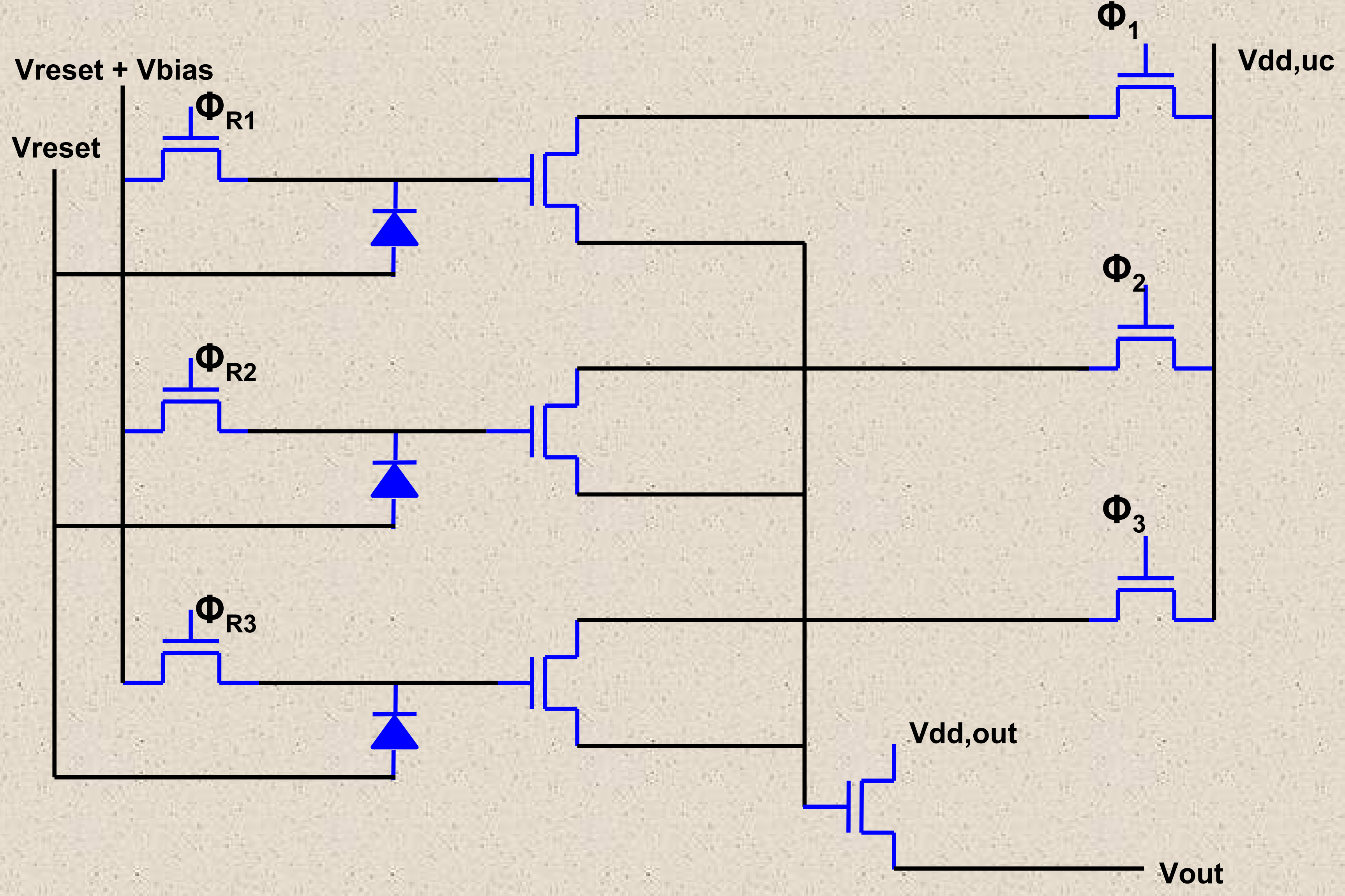
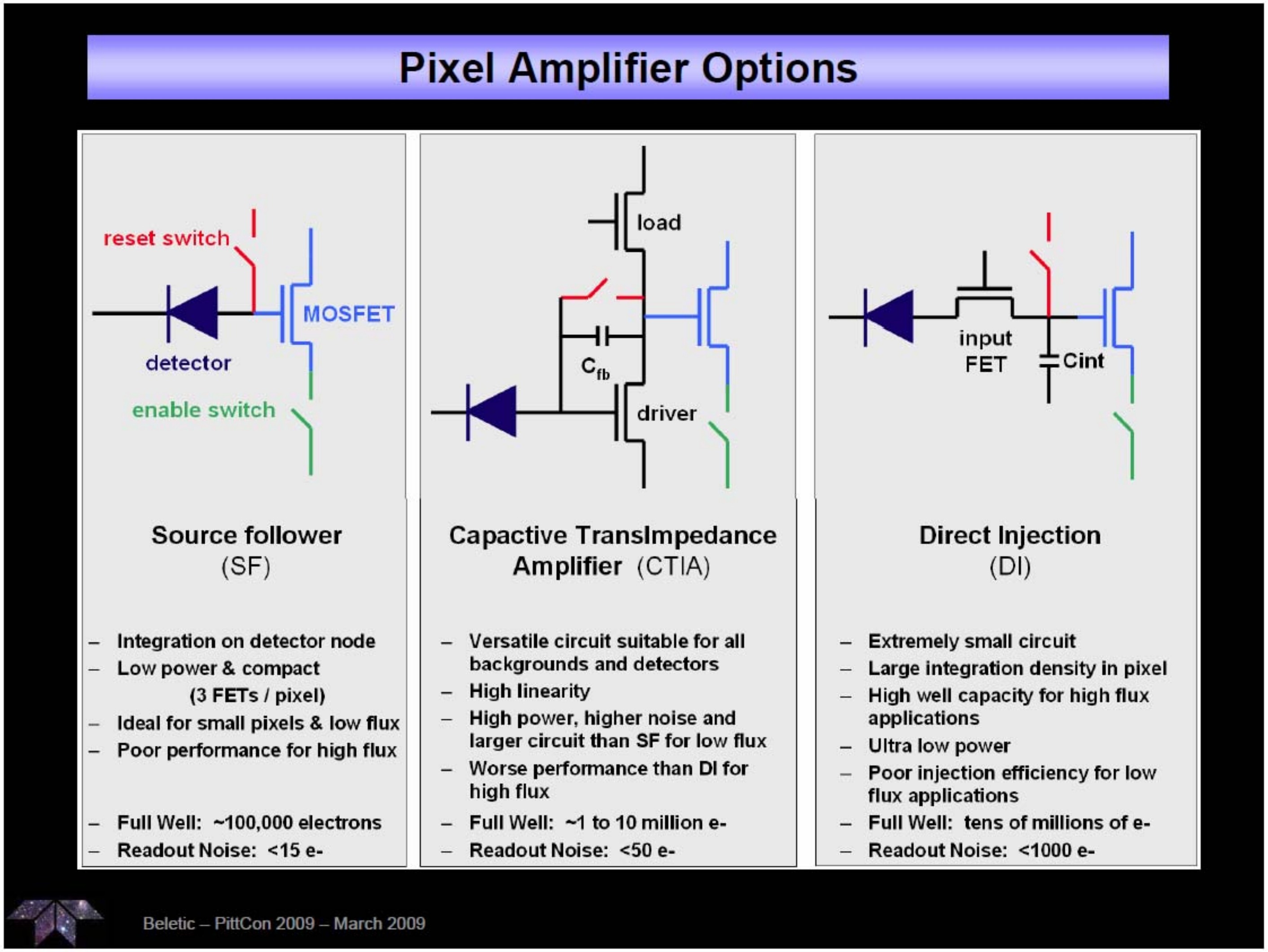


Figure 6.2. Four cells of the readout for a hybrid photodiode array. The detectors are indicated by diode symbols, and T_1 is the integrating amplifier FET.

Multiplexer Circuit



ROIC Output Options



Pixel Amplifier Options

Source follower
(SF)

- Integration on detector node
- Low power & compact (3 FETs / pixel)
- Ideal for small pixels & low flux
- Poor performance for high flux
- Full Well: ~100,000 electrons
- Readout Noise: <15 e-

Capactive TransImpedance Amplifier (CTIA)

- Versatile circuit suitable for all backgrounds and detectors
- High linearity
- High power, higher noise and larger circuit than SF for low flux
- Worse performance than DI for high flux
- Full Well: ~1 to 10 million e-
- Readout Noise: <50 e-

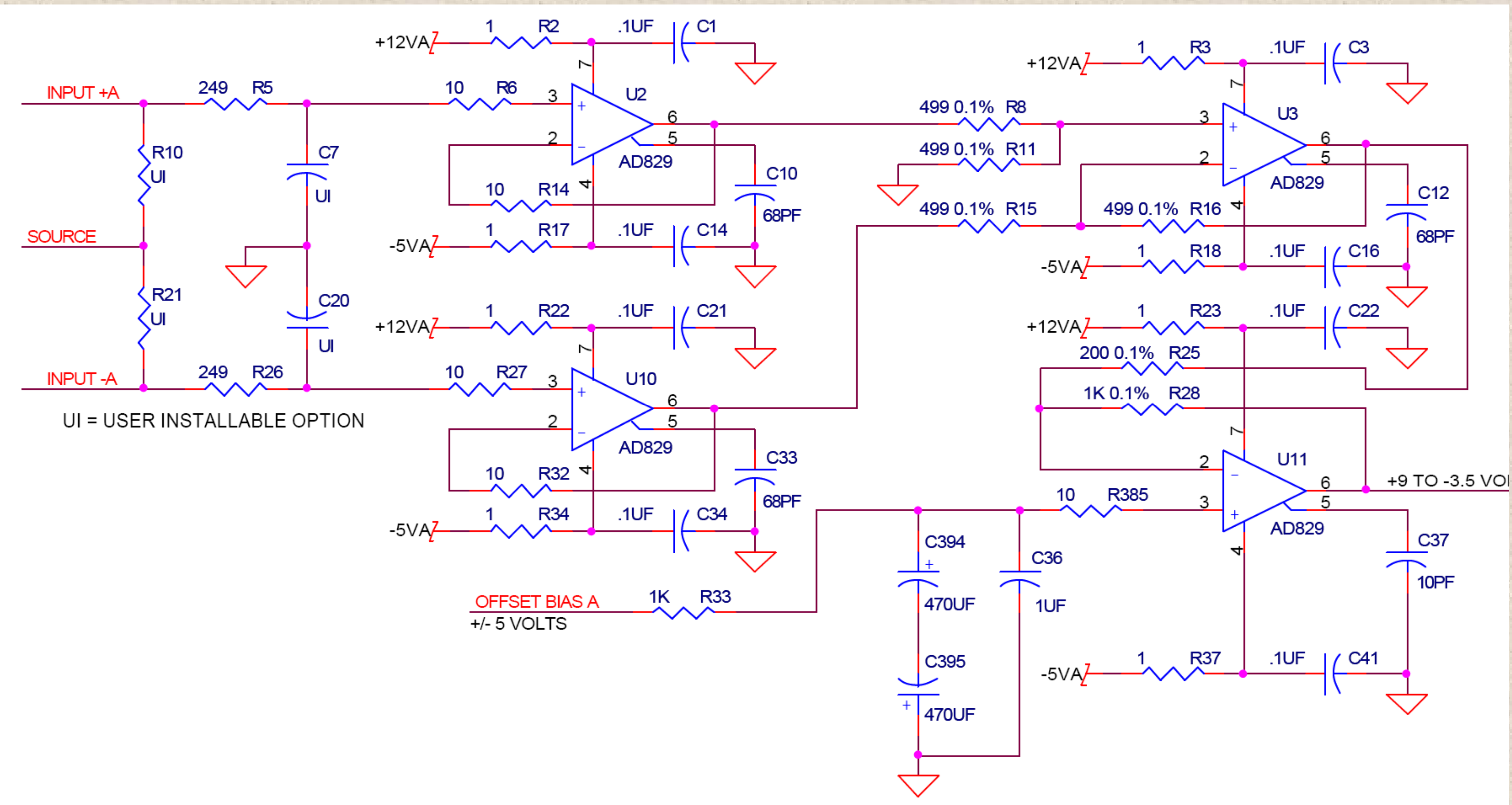
Direct Injection
(DI)

- Extremely small circuit
- Large integration density in pixel
- High well capacity for high flux applications
- Ultra low power
- Poor injection efficiency for low flux applications
- Full Well: tens of millions of e-
- Readout Noise: <1000 e-

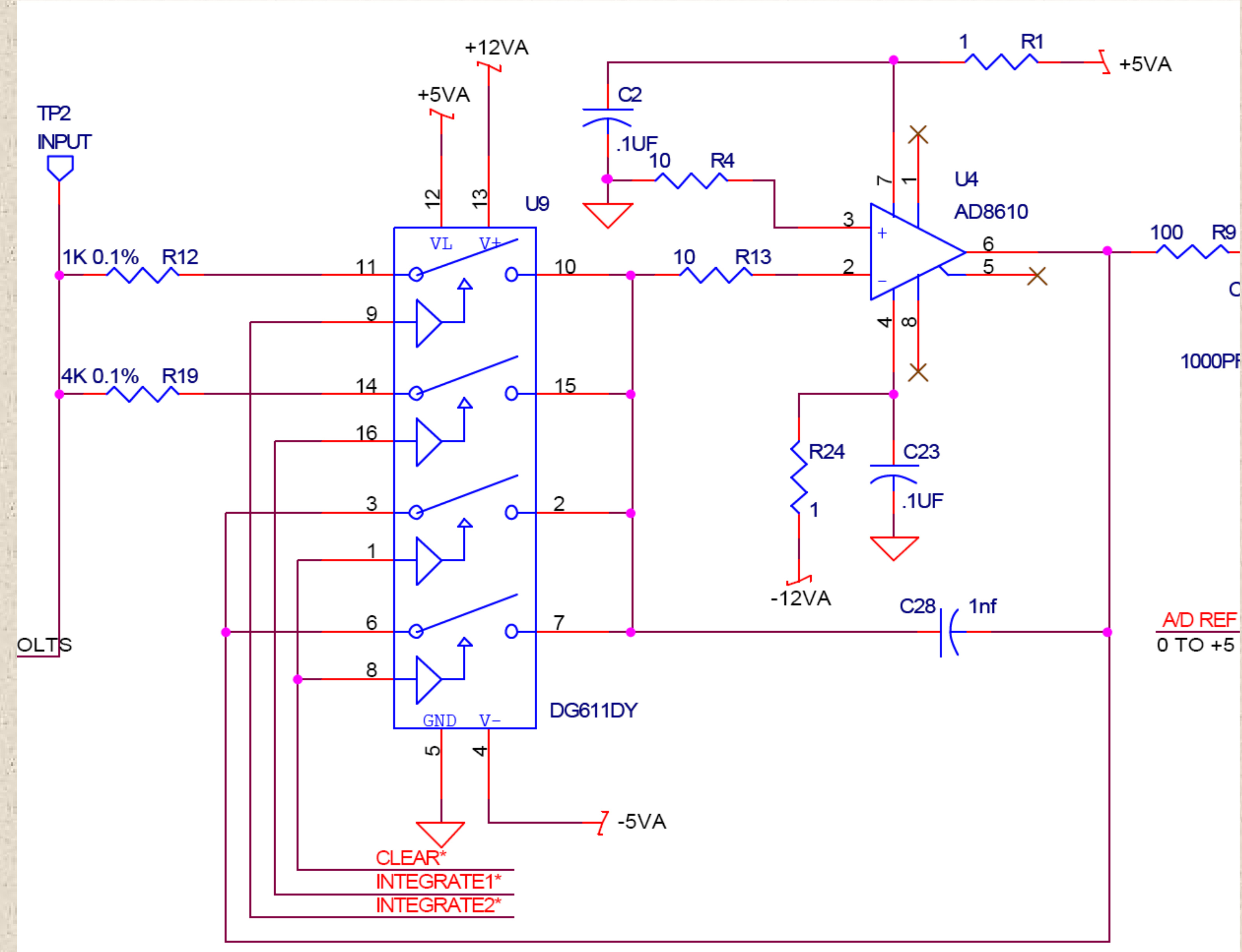
Beletic – PittCon 2009 – March 2009

SDSU (Leach) Electronics

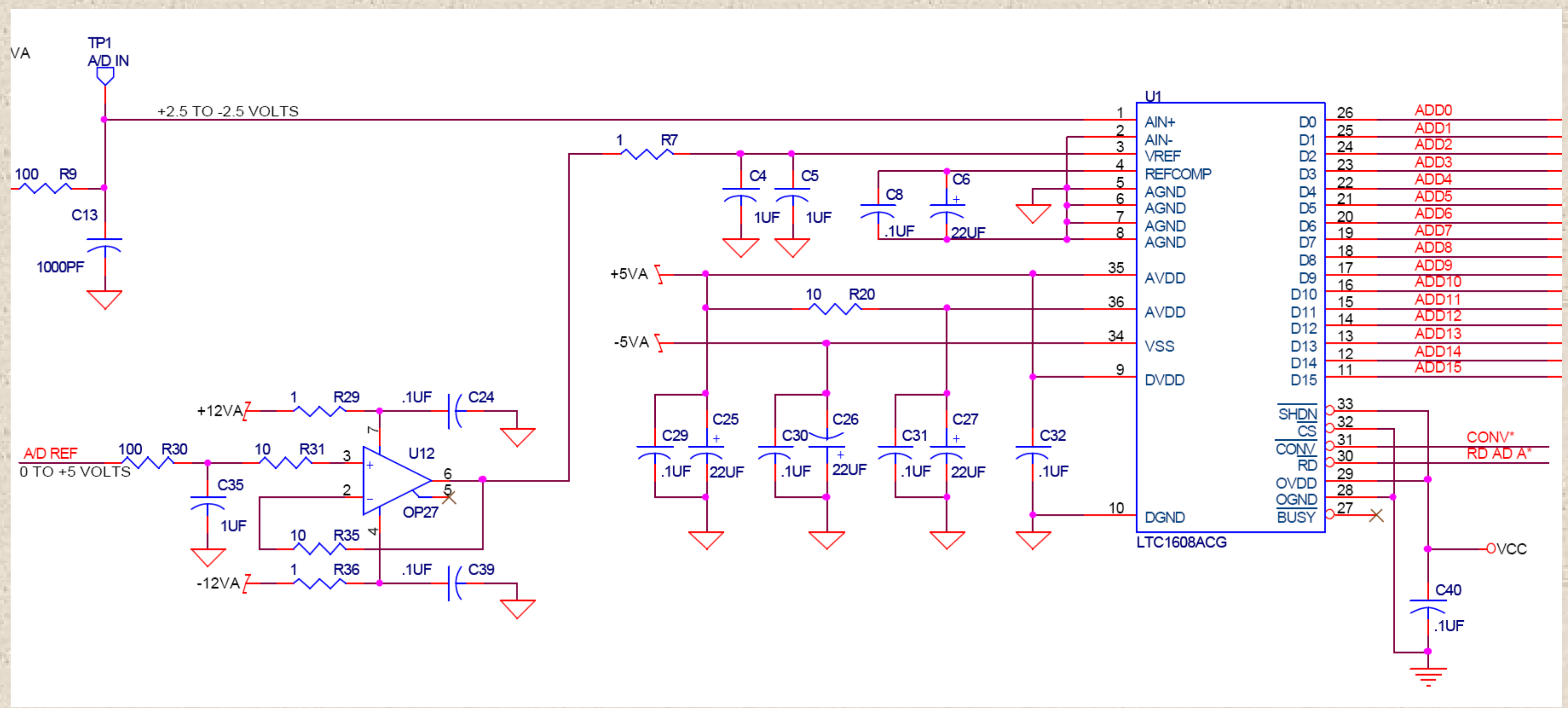
SDSU Electronics Video Input Stage



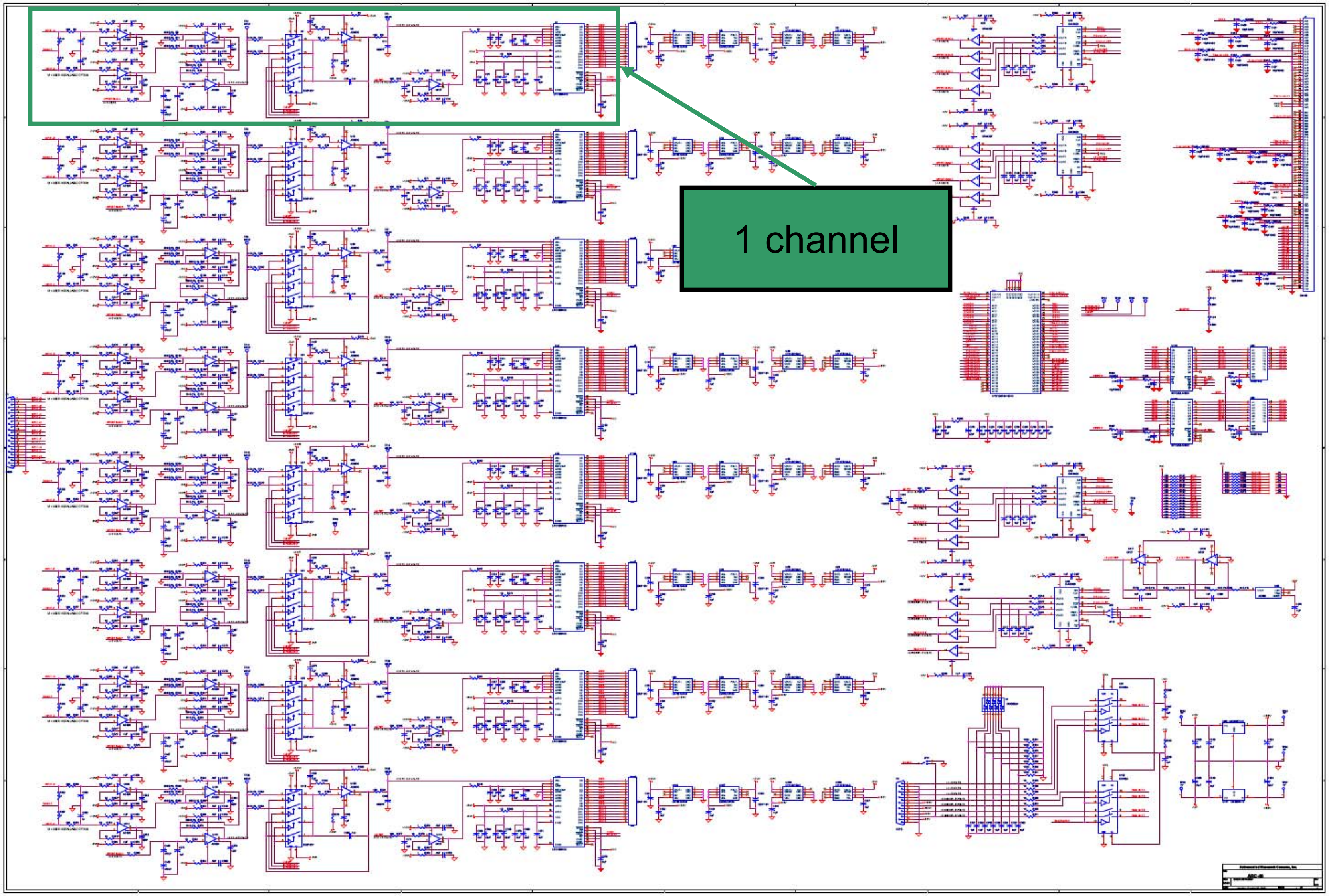
SDSU Electronics Video Integrator



SDSU Electronics ADC

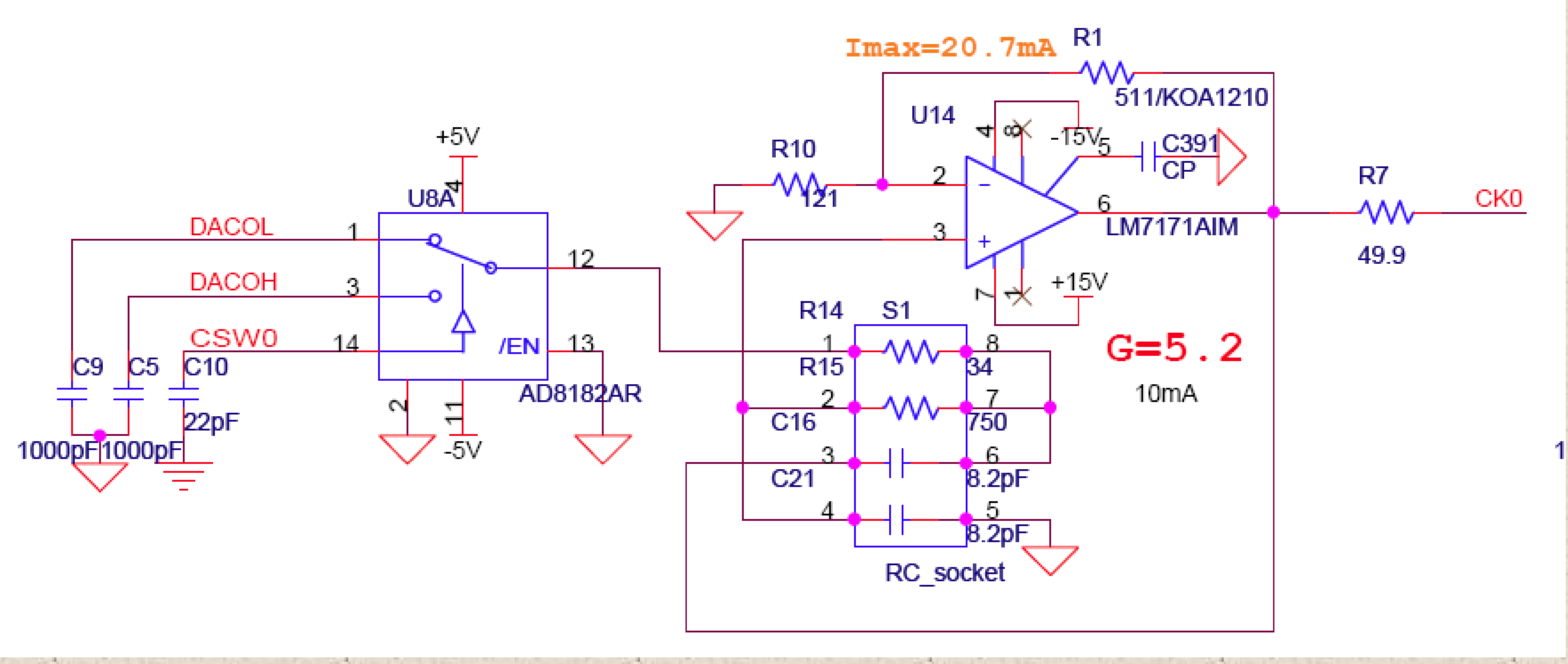


SDSU Electronics 8-Channel Video Board

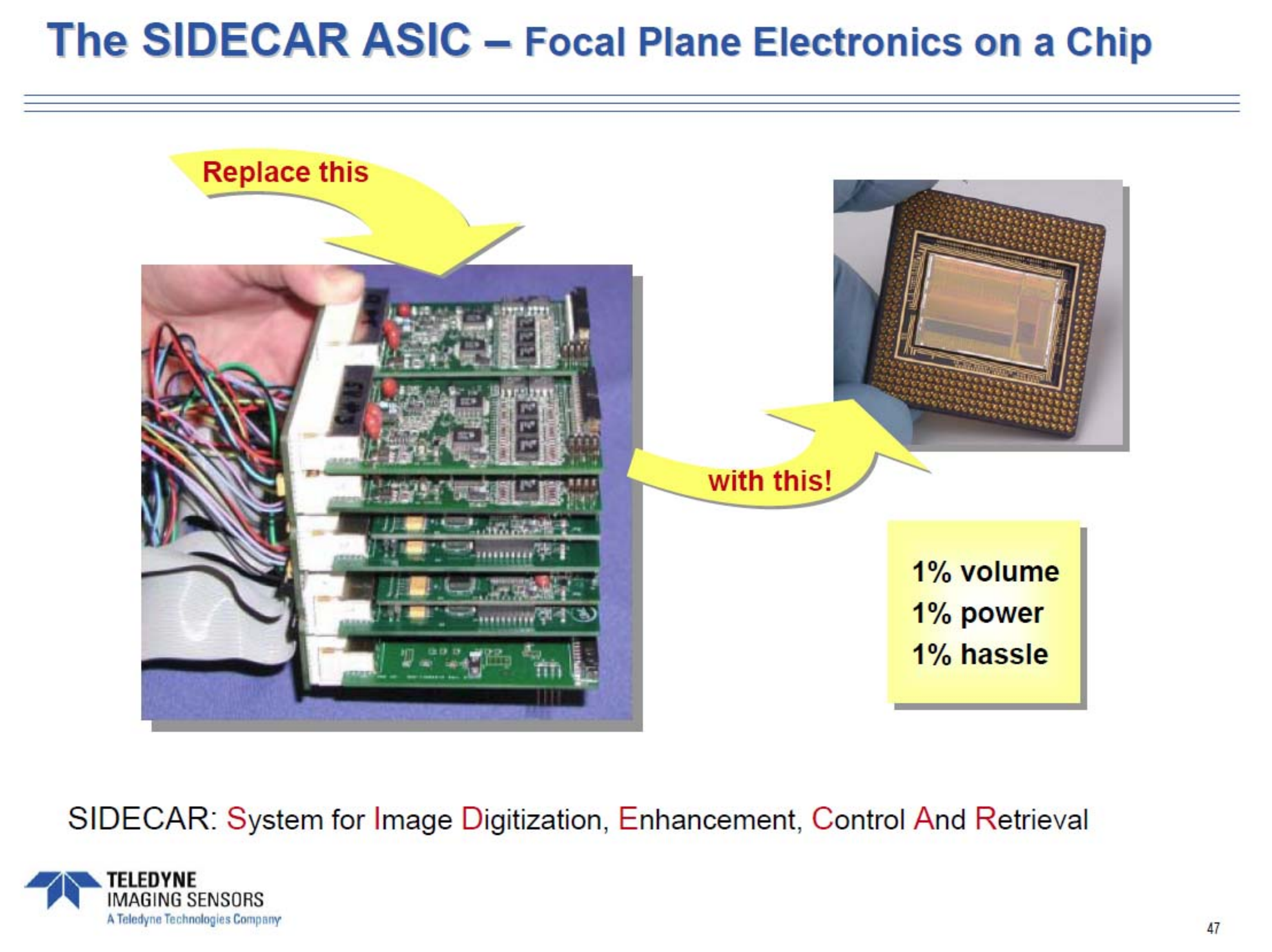


1 channel

SDSU Electronics Clock Channel



Application-Specific Integrated Circuit=ASIC



The SIDECAR ASIC – Focal Plane Electronics on a Chip

Replace this

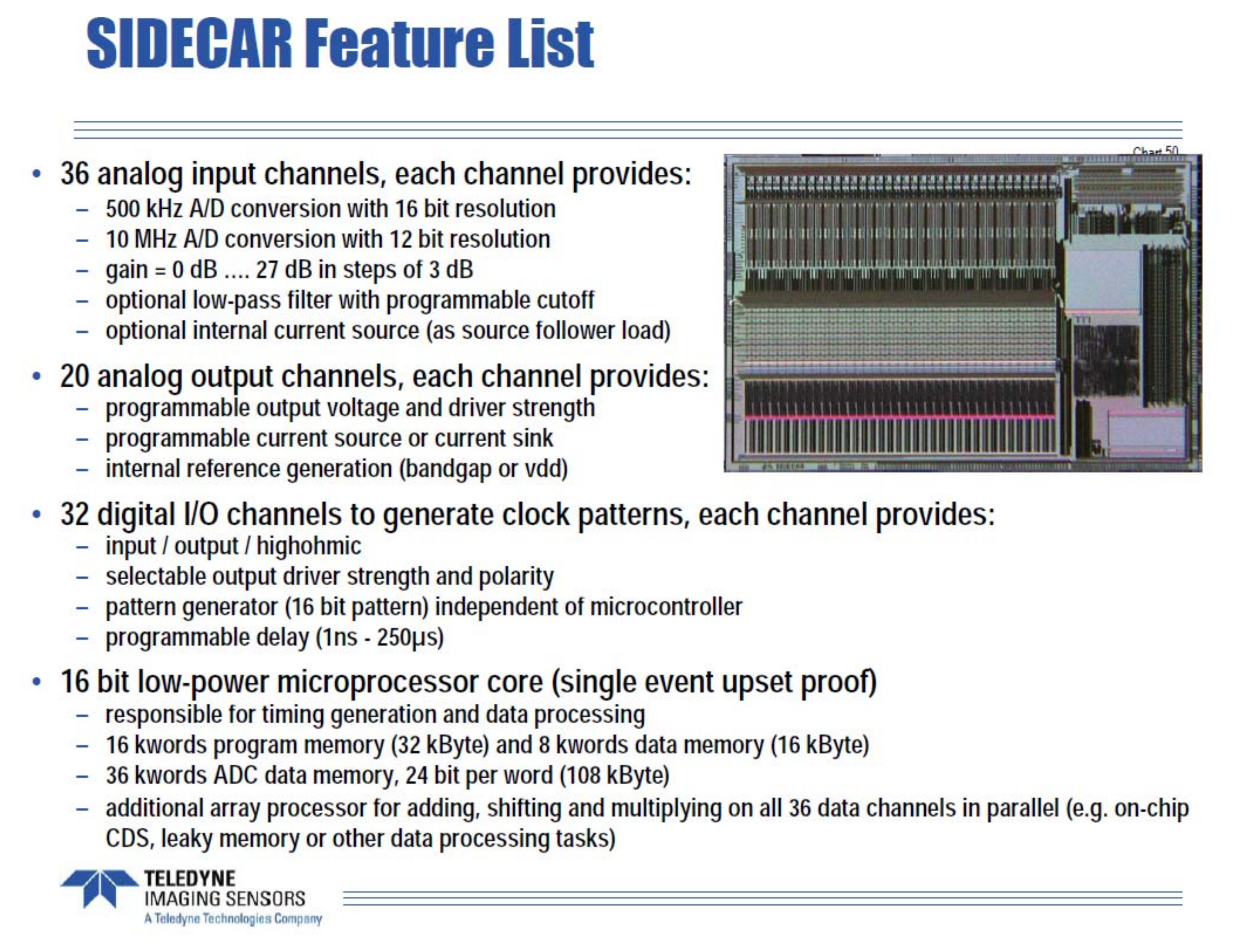
with this!

1% volume
1% power
1% hassle

SIDECAR: System for Image Digitization, Enhancement, Control And Retrieval

TELEDYNE
IMAGING SENSORS
A Teledyne Technologies Company

SIDECAR ASIC Specifications



SIDECAR Feature List

Chart 50

- 36 analog input channels, each channel provides:
  - 500 kHz A/D conversion with 16 bit resolution
  - 10 MHz A/D conversion with 12 bit resolution
  - gain = 0 dB .... 27 dB in steps of 3 dB
  - optional low-pass filter with programmable cutoff
  - optional internal current source (as source follower load)
- 20 analog output channels, each channel provides:
  - programmable output voltage and driver strength
  - programmable current source or current sink
  - internal reference generation (bandgap or vdd)
- 32 digital I/O channels to generate clock patterns, each channel provides:
  - input / output / highohmic
  - selectable output driver strength and polarity
  - pattern generator (16 bit pattern) independent of microcontroller
  - programmable delay (1ns - 250µs)
- 16 bit low-power microprocessor core (single event upset proof)
  - responsible for timing generation and data processing
  - 16 kwords program memory (32 kByte) and 8 kwords data memory (16 kByte)
  - 36 kwords ADC data memory, 24 bit per word (108 kByte)
  - additional array processor for adding, shifting and multiplying on all 36 data channels in parallel (e.g. on-chip CDS, leaky memory or other data processing tasks)

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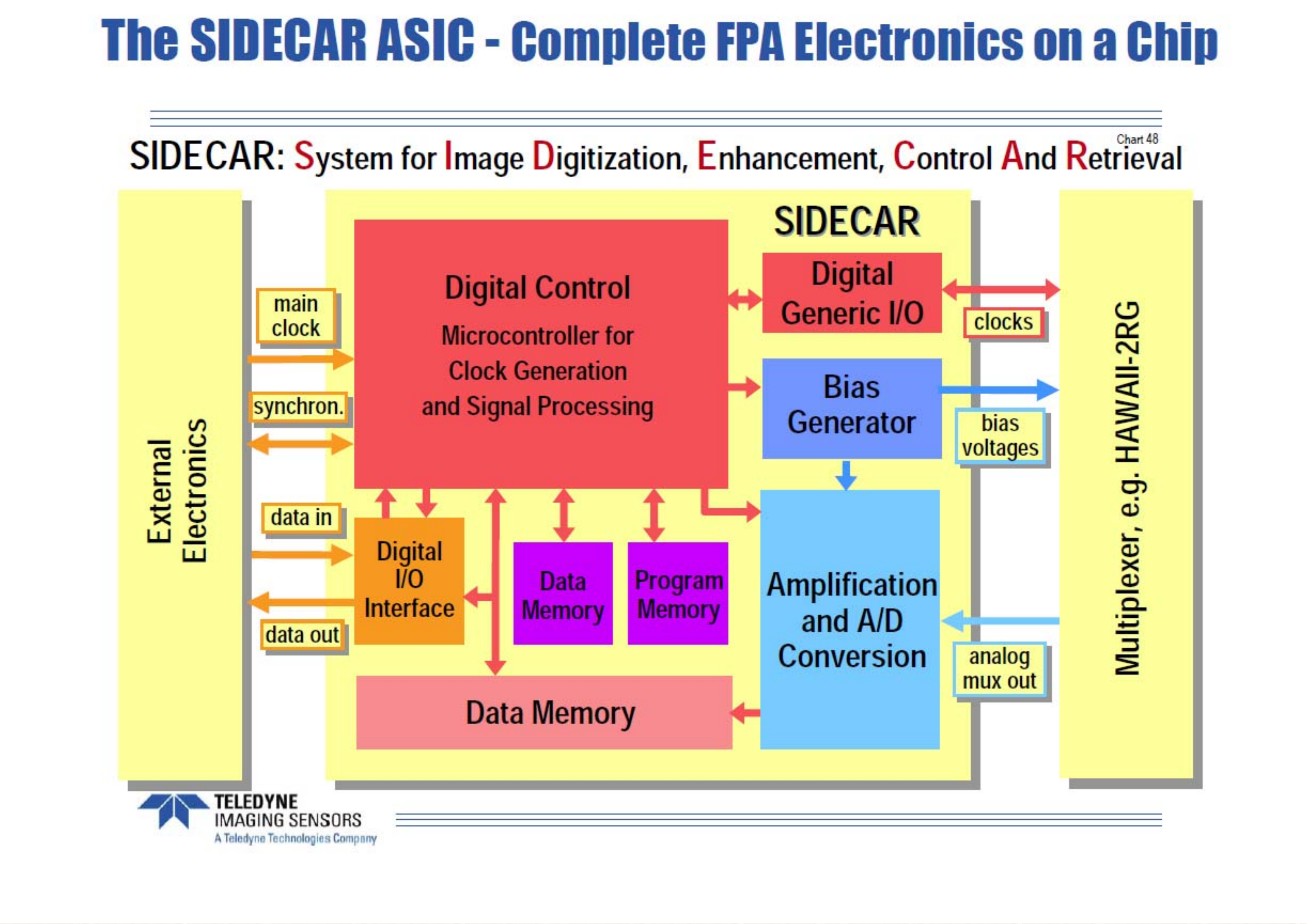
A Teledyne Technologies Company

SIDECAR ASIC Block Diagram



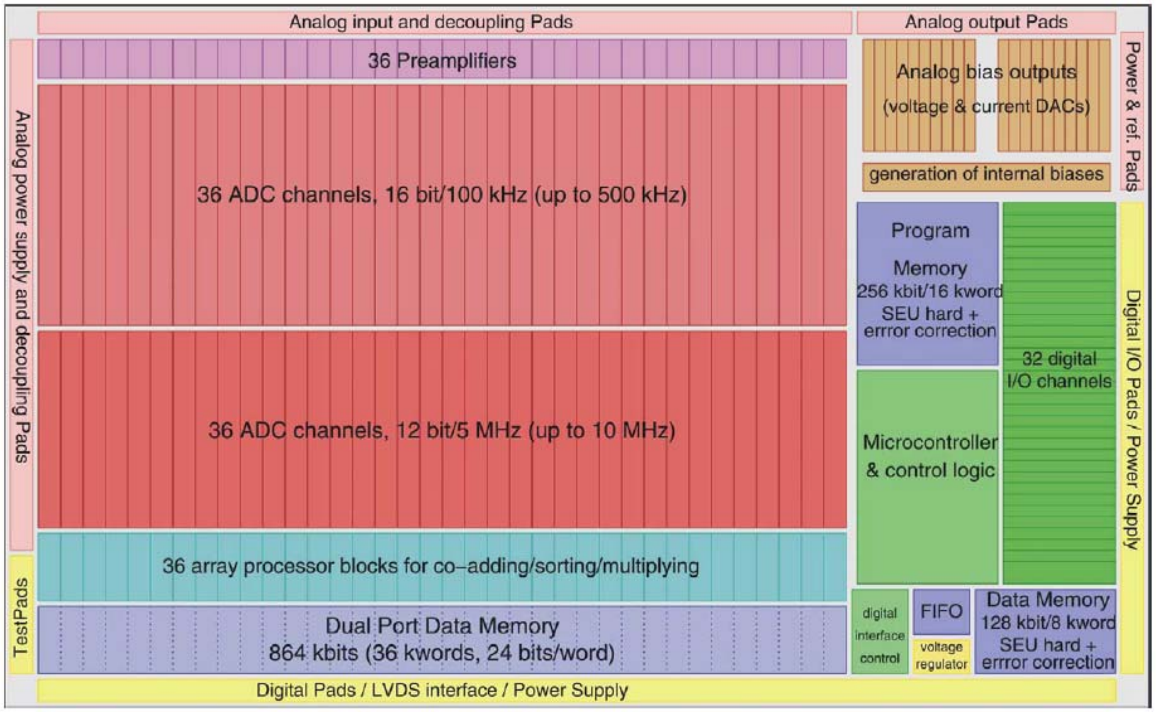
The SIDECAR ASIC - Complete FPA Electronics on a Chip

SIDECAR: System for Image Digitization, Enhancement, Control And Retrieval

SIDECAR ASIC Floorplan

ASIC Floorplan

Chart 49



Analog input and decoupling Pads

Analog output Pads

36 Preamplifiers

Analog bias outputs (voltage & current DACs)

generation of internal biases

Power & ref. Pads

Analog power supply and decoupling Pads

36 ADC channels, 16 bit/100 kHz (up to 500 kHz)

36 ADC channels, 12 bit/5 MHz (up to 10 MHz)

Program Memory 256 kbit/16 kword SEU hard + errror correction

32 digital I/O channels

Microcontroller & control logic

Digital I/O Pads / Power Supply

36 array processor blocks for co–adding/sorting/multiplying

TestPads

Dual Port Data Memory 864 kbits (36 kwords, 24 bits/word)

digital interface control

FIFO

voltage regulator

Data Memory 128 kbit/8 kword SEU hard + errror correction

Digital Pads / LVDS interface / Power Supply

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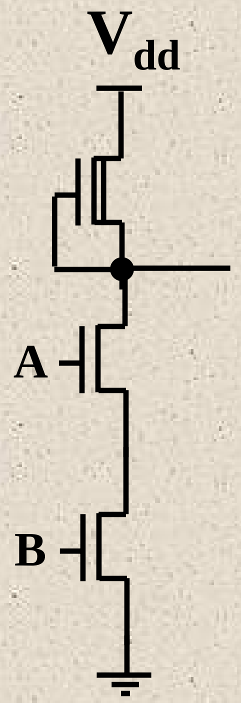
Logic Circuits

NAND

- The NAND circuit output is high when both A and B are not high.

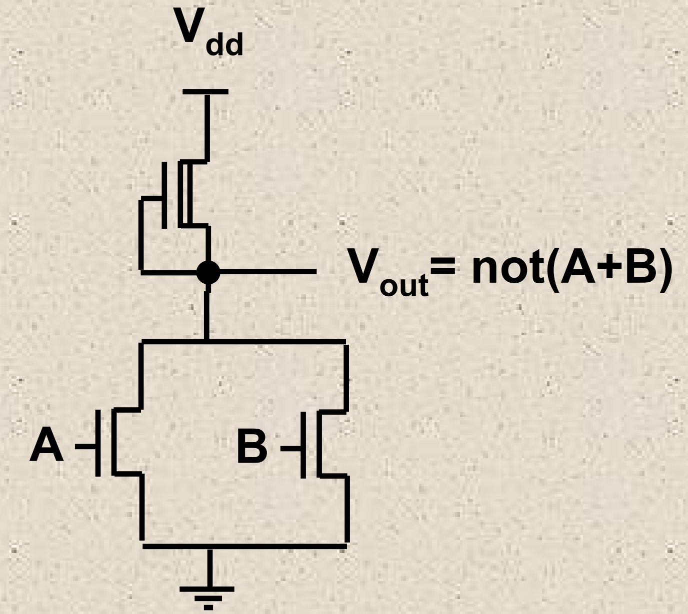


V_{out}= not(A.B)

A	B	Vout
0	0	1
0	1	1
1	0	1
1	1	0

NOR

- The NOR circuit output is high when neither A nor B are high.

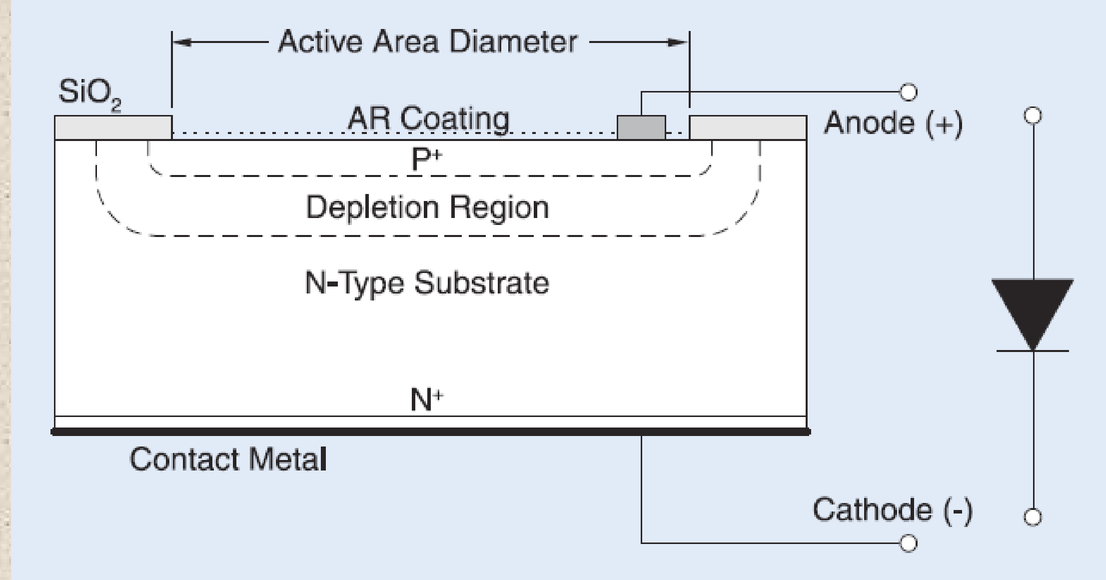


A	B	Vout
0	0	1
0	1	0
1	0	0
1	1	0

Photodiode

Definition of Photodiode

- A photodiode is a diode that responds to light. It differs from a regular diode primarily in construction, i.e. it must have a mechanism for coupling to light.
- A photodiode generates current as a function of the intensity of absorbed light.
- Photodiodes can be used as light measuring devices or energy conversion devices.



Photodiode Principles of Operation

- A pn junction is reverse biased in order to enhance the width of the depletion region, and thereby reduce the capacitance. Recall that:

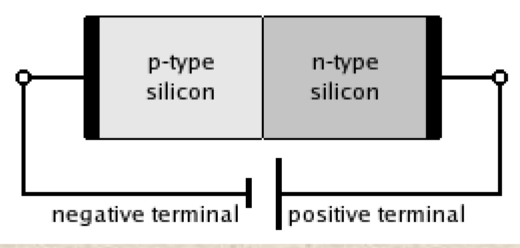
$$C = \frac{\kappa \varepsilon_0 A}{d}, \text{ where}$$

$$\kappa = \text{dielectric constant,}$$

$$\varepsilon_0 = \text{permittivity of free space,}$$

$$\text{A} = \text{area of capacitor, and}$$

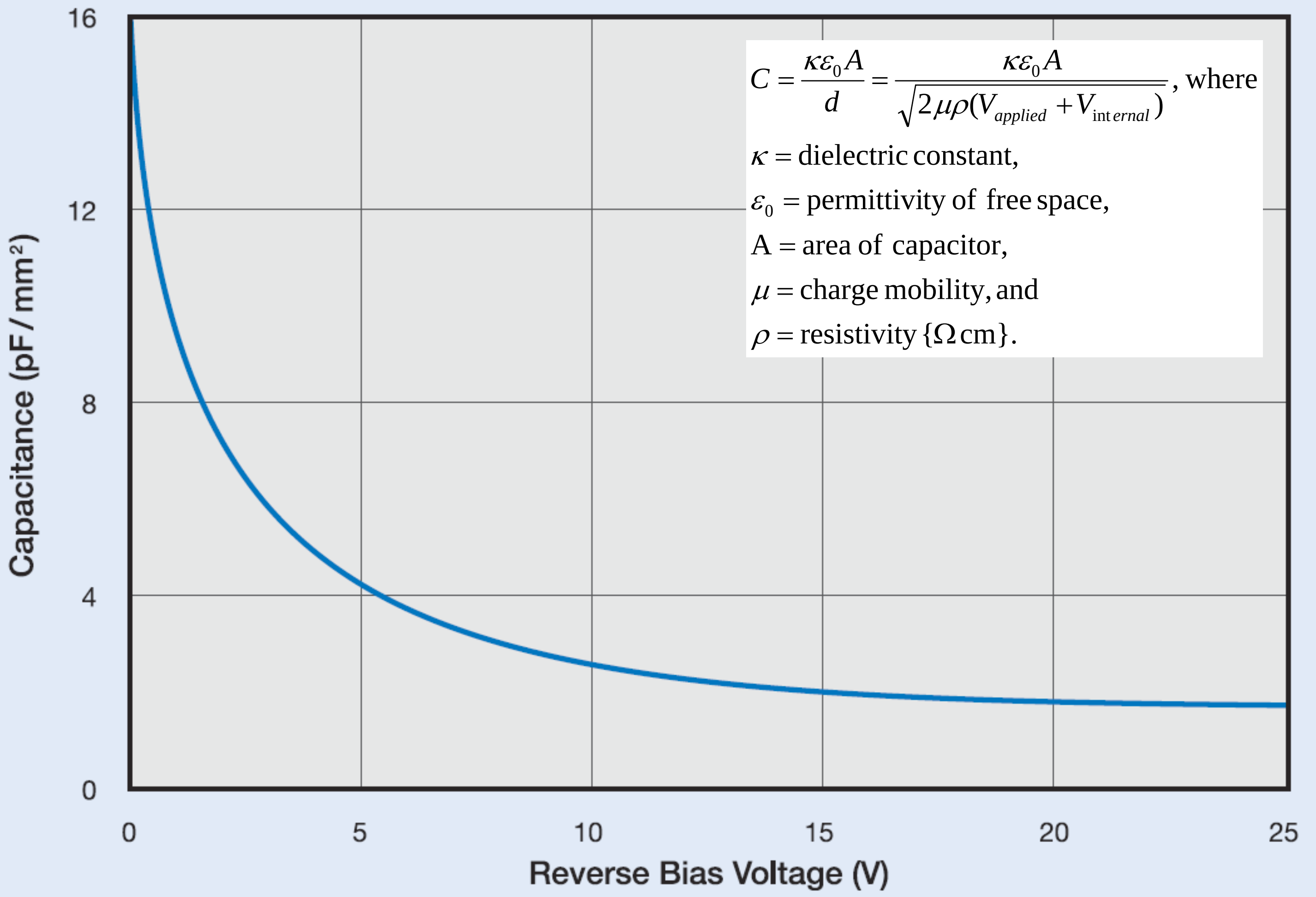
$$\text{d} = \text{distance between plates of capacitor.}$$



- Photons of sufficient energy ($E>E_{bandgap}$) are absorbed and generate photogenerated electron-hole pairs.
- The charge flows across the depletion region and recombines with charge on the capacitor, thereby reducing the voltage difference across the depletion region by a small amount.
- The reduction in voltage can be sensed as an indication that light has been absorbed.

C vs. Reverse Bias

■ **Typical Capacitance vs. Reverse Bias**



$$C = \frac{\kappa\varepsilon_0 A}{d} = \frac{\kappa\varepsilon_0 A}{\sqrt{2\mu\rho(V_{applied} + V_{internal})}}, \text{ where}$$

κ = dielectric constant,

ε_0 = permittivity of free space,

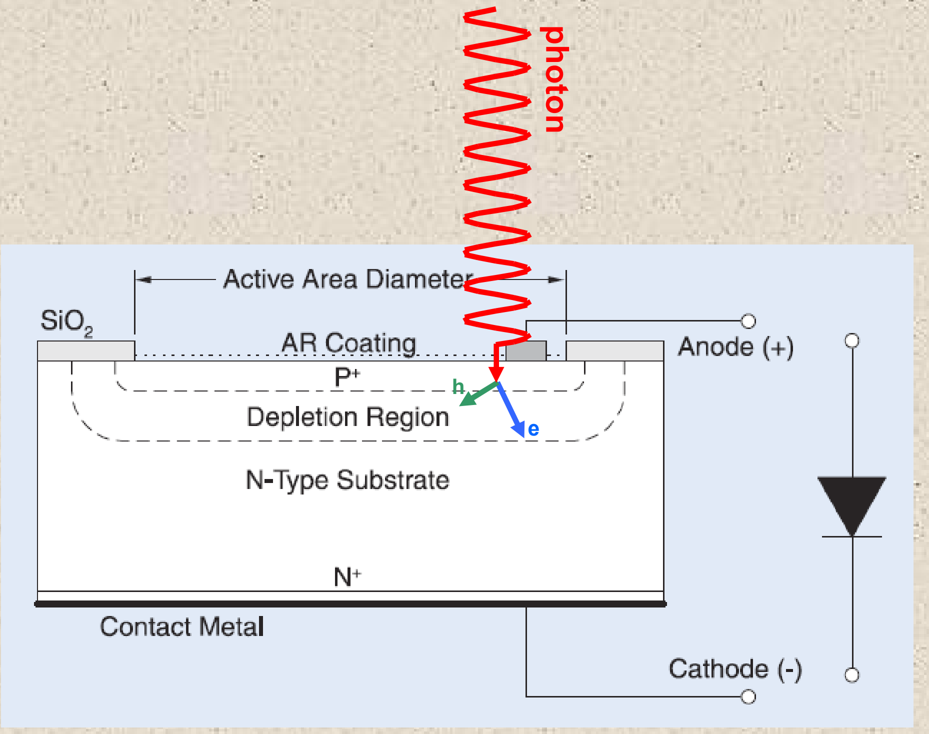
A = area of capacitor,

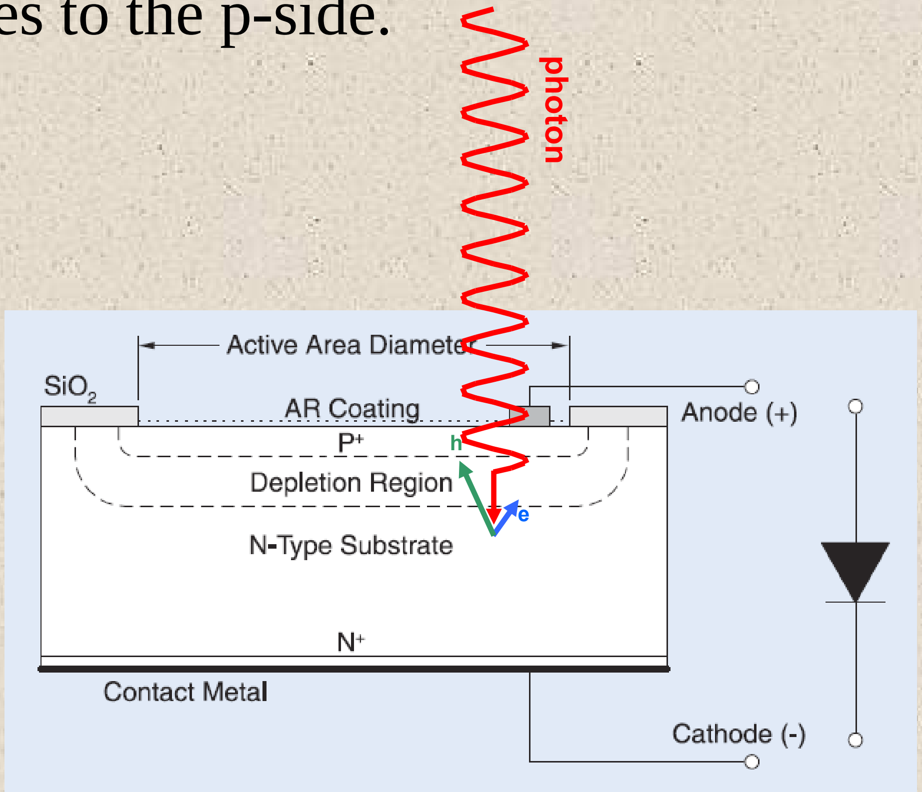
μ = charge mobility, and

ρ = resistivity $\{\Omega\,\text{cm}\}$.

Photon Absorption in Photodiode

- A photon will be absorbed at a depth that depends on its wavelength.
- As long as the absorption is near enough to the depletion region, the photogenerated charge (eh pair) will contribute electrons to the n-side and holes to the p-side.





Penetration Depth

■ Penetration Depth

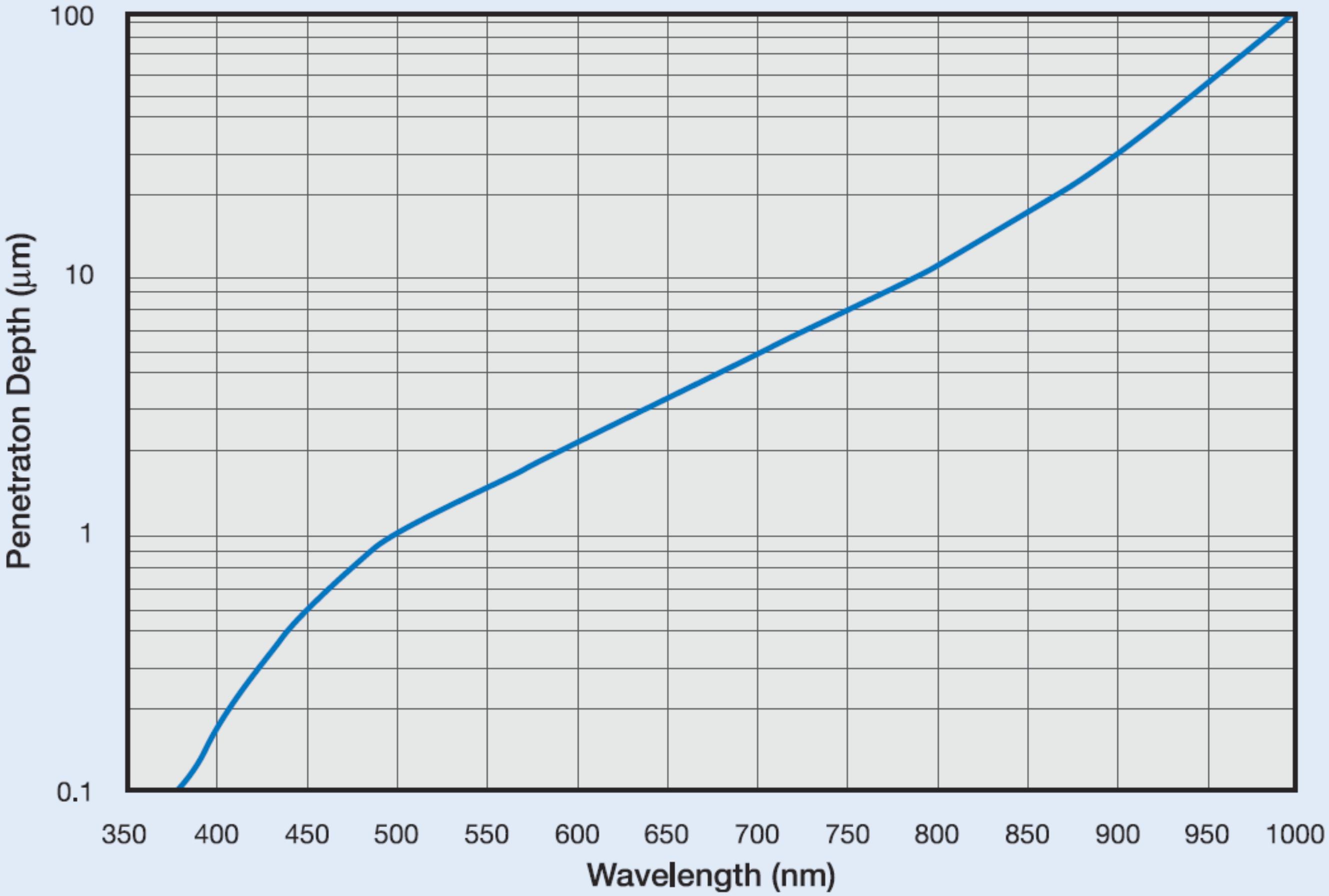
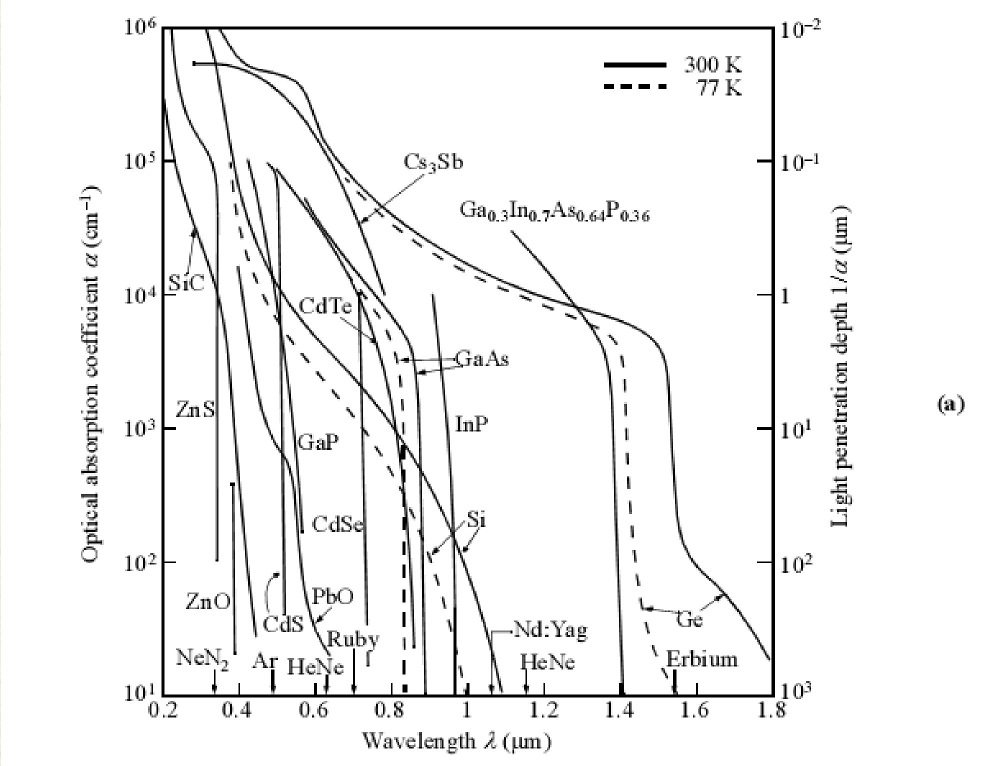
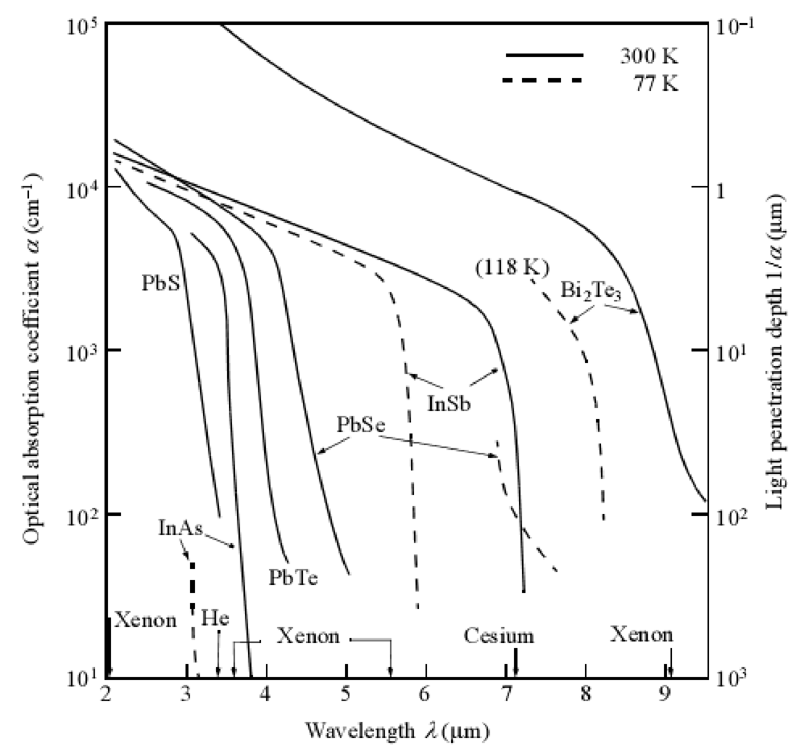


Figure 2. Penetration depth (1/e) of light into silicon substrate for various wavelengths.

Material Absorption/penetration Depths





$$I(x) = I_0 e^{-\alpha x}$$, where

I(x) = intensity at depth x,

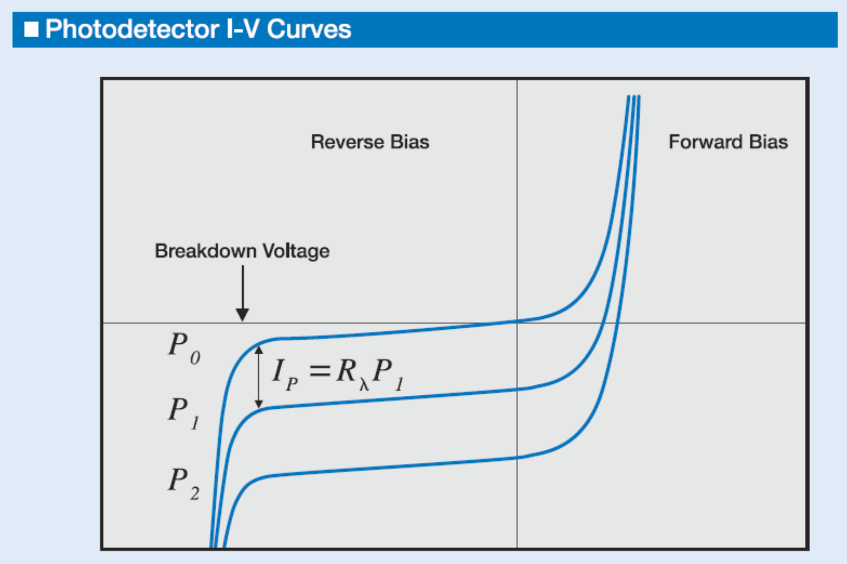
I_0 = initial intensity,

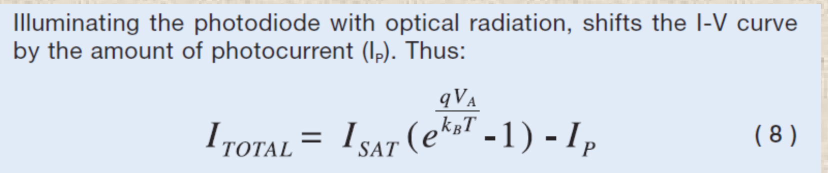
α = absorption coefficient $\{\mathrm{cm}^{-1}\}$,

x = depth {cm}.

Conduction in Photodiode

- If the pn junction is not biased, then the extra photogenerated charge will induce a current. Note that there is no extra charge with which to recombine because there is no reverse bias.
- The photogenerated current can be used to drive a load, thereby converting light into electrical power.
- This mode of operation defines photovoltaic devices that are often used to convert solar energy into electricity.


■ Photodetector I-V Curves

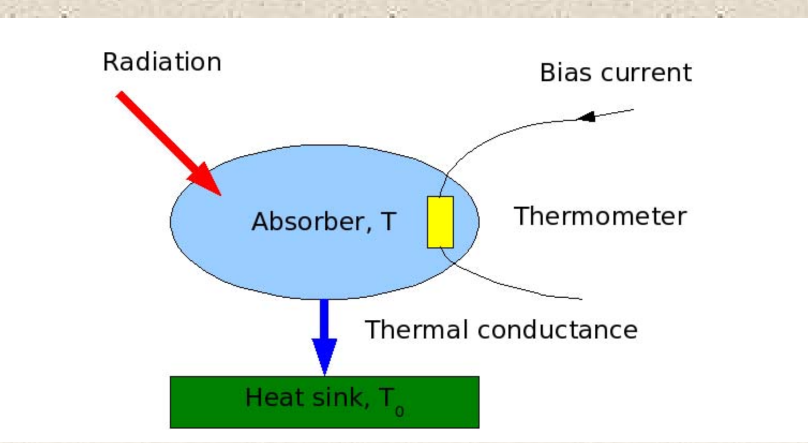

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent (I_P). Thus:

$$I_{TOTAL} = I_{SAT}\left(e^{\frac{qV_A}{k_BT}} - 1\right) - I_P \quad (8)$$

Bolometers

Definition of Bolometer

- A bolometer is a device that changes temperature when it absorbs the energy of a particle.
- In light detection, a bolometer changes temperature when photons are absorbed.
- This temperature change is usually sensed by measuring a resultant change in electrical resistance in a thermometer that is thermally coupled to the bolometer.
- The bolometer was invented by Astronomer Samuel P. Langley in ~1880.



Bolometer Principles of Operation

- A photon has energy hν.
- This energy is absorbed and produces a change in temperature that depends on the heat capacity of the material.
- A small heat capacity will induce a larger temperature change.
- Low fluxes correspond to relatively small changes in temperature, resistance, and thus voltage; therefore, thermal noise needs to be minimized through cooling.

$$\Delta E = C\Delta T,$$

$$\Delta T = \frac{1}{C}\Delta E, \text{ where,}$$

$$C = mc,$$

$\Delta\mathrm{E}$ = change in energy,

$\Delta\mathrm{T}$ = change in temperature,

C = heat capacity of absorber,

c = specific heat capacity of absorber, and

m = mass of absorber.

Bolometer Thermal Time Constant

- As each photon is absorbed, the temperature of the bolometer temporarily increases.
- The bolometer cools down at a rate that depends on the thermal conductance of its connection to a nearby thermal bath (heat sink).
- Typically, some small amount of bias power is injected into the bolometer to elevate the temperature (T_1) slightly above that of the heat sink (T_0).

$$\text{thermal conductance} \equiv G = \frac{P_{\text{bias}}}{T_1},$$

$$\tau = \frac{C}{G}.$$

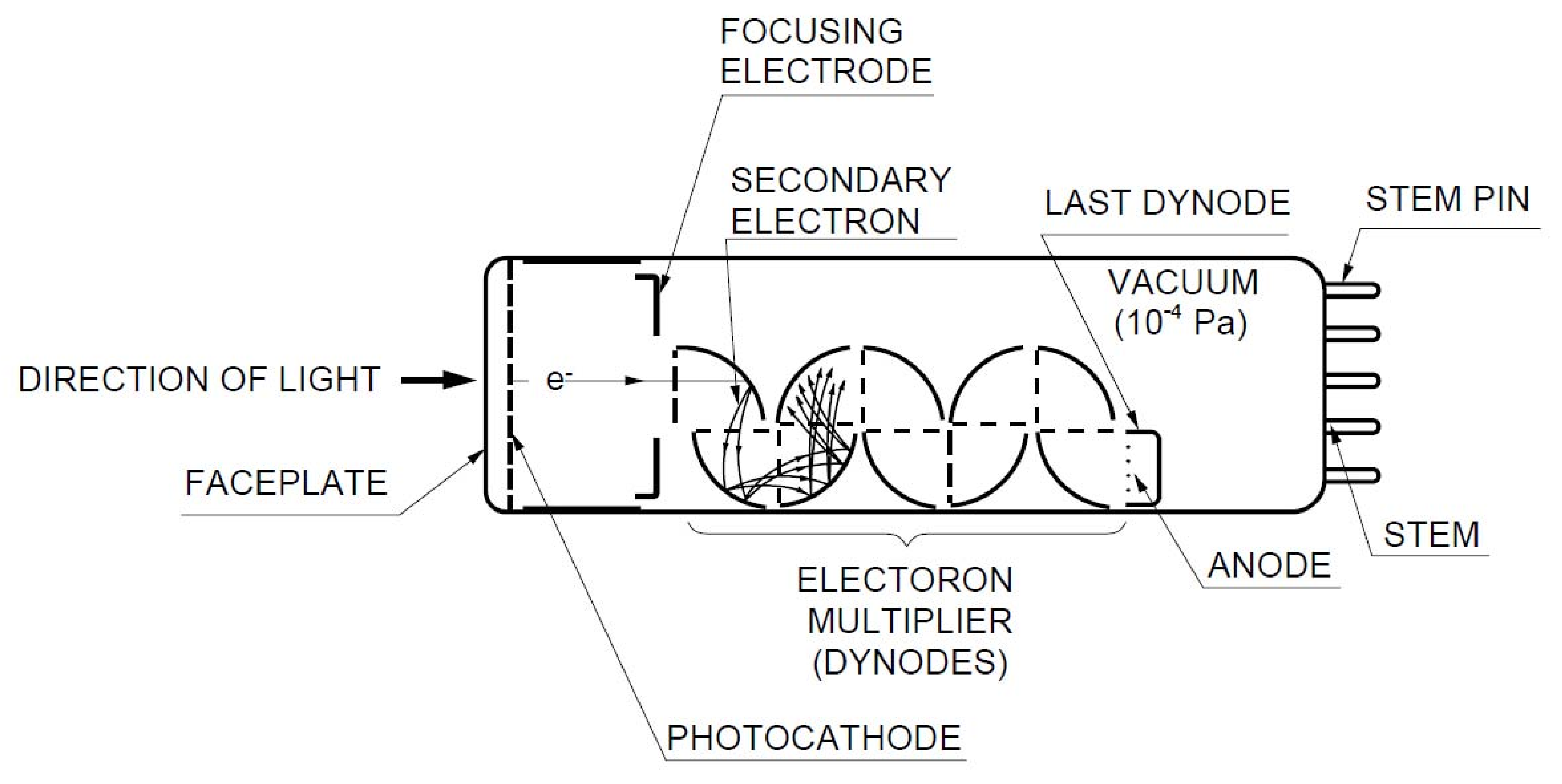
- Thermal time constant is a function of thermal conductance and heat capacity.
- Note that this time constant could become important for high speed operation.

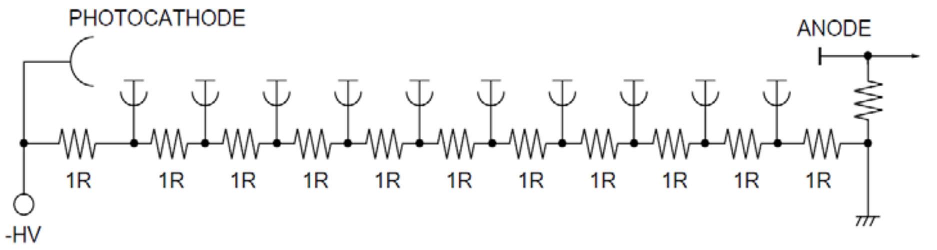
Photo-multiplier Tubes

Photo-multiplier Tubes (PMTs)

- PMTs convert individual photons into relatively large packets of charge through an avalanche process that relies upon the photoelectric effect.
- The incoming photon must have sufficient energy to generate charge with energy that exceeds the “work function,” i.e. enough energy to be able to leave the material. This is called the “photoelectric effect.”
- Semiconductors are usually used for the absorbing material, as they are less reflective than conductors.
- PMTs have only one element, i.e. they are not imagers.
- PMTs offer high sensitivity and fast response times (a few ns).

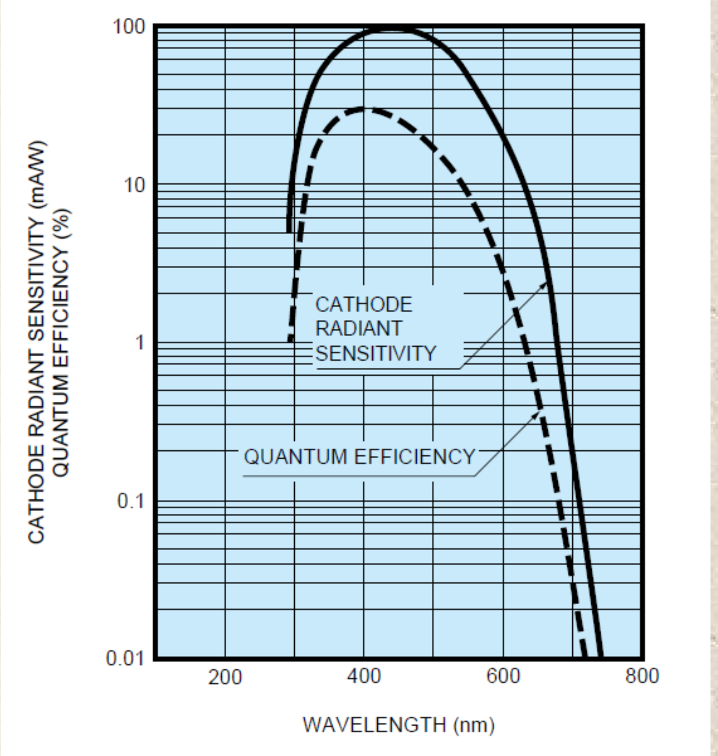
PMT Cross-section and Schematic

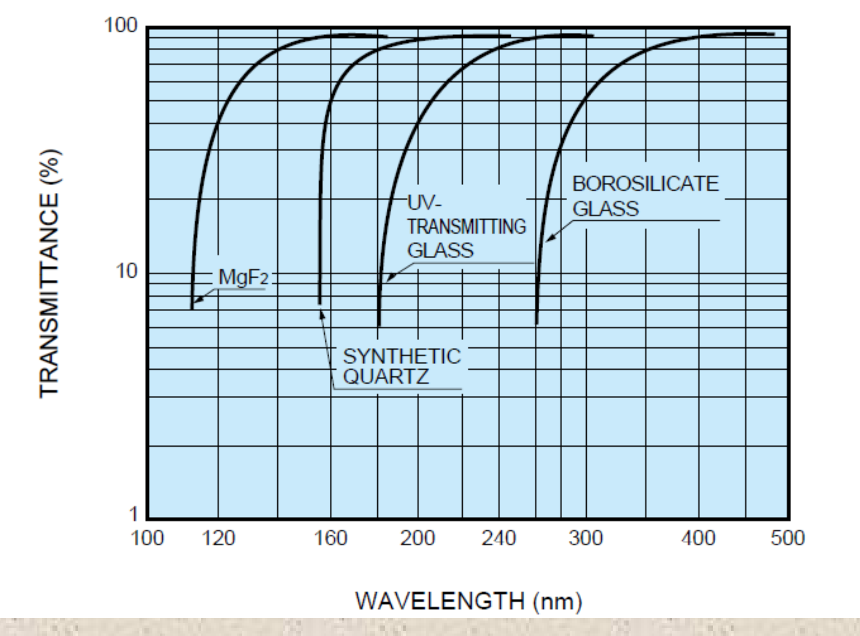




PMT Response

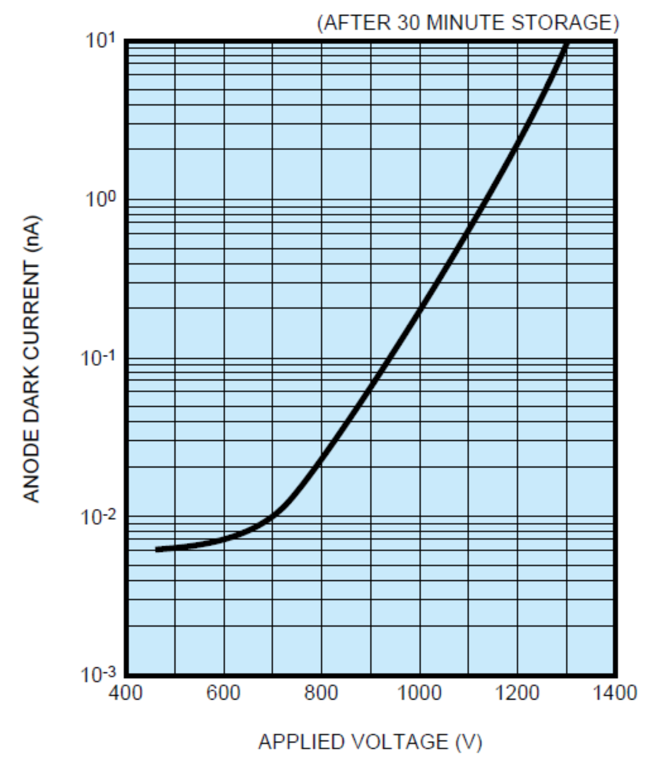
- PMT response is dependent on quantum efficiency of photocathode material and transmission of window.

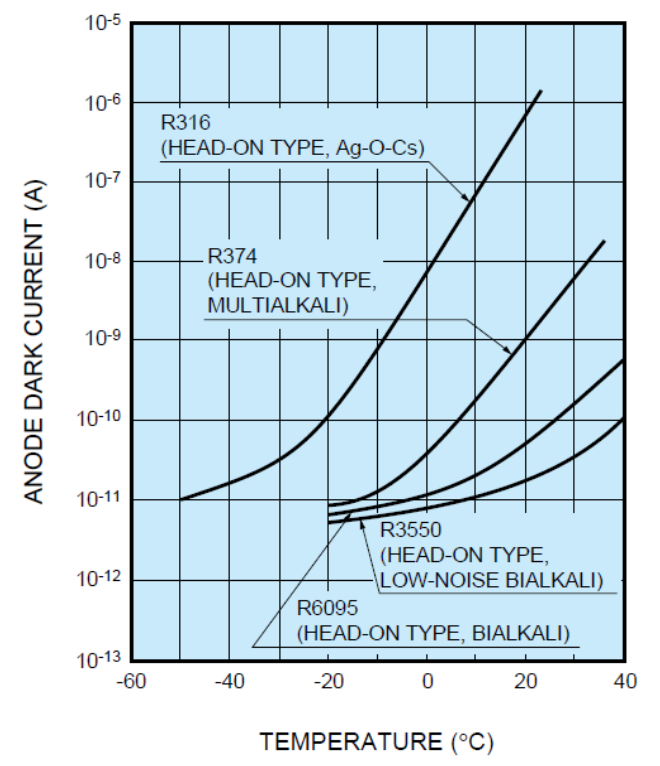




PMT Dark Current

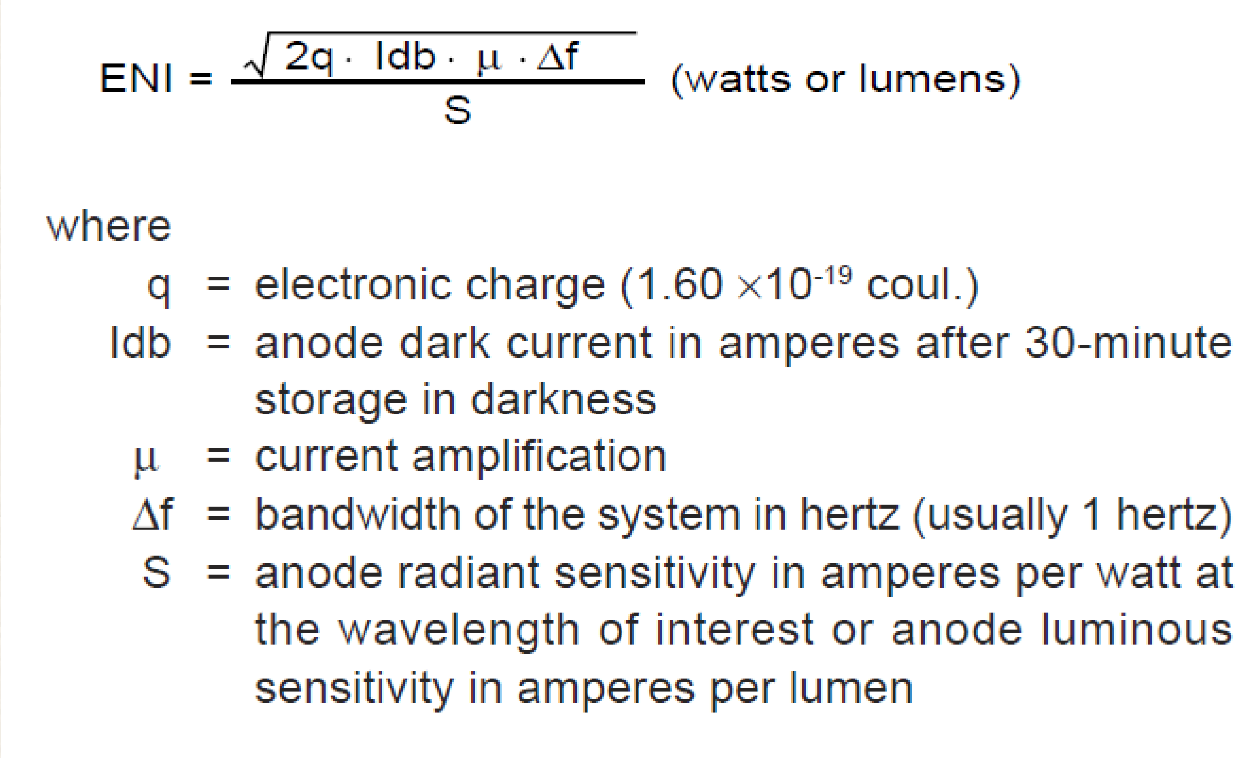
- PMT dark current is a function of cathode voltage and temperature.





PMT Sensitivity

- PMT sensitivity is often expressed as the minimum source flux to generate a signal that has at least SNR=1. This is sometimes called the “equivalent noise input” (ENI).



$$\mathrm{ENI} = \frac{\sqrt{2q \cdot \mathrm{Idb} \cdot \mu \cdot \Delta f}}{S} \quad \text{(watts or lumens)}$$

where

q = electronic charge (1.60×10^{-19} coul.)

Idb = anode dark current in amperes after 30-minute storage in darkness

μ = current amplification

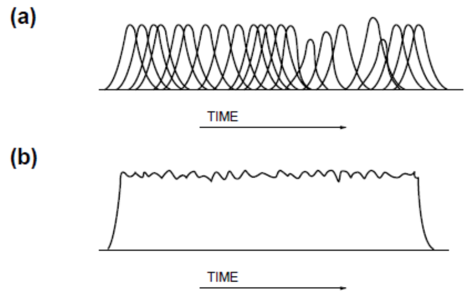
Δf = bandwidth of the system in hertz (usually 1 hertz)

S = anode radiant sensitivity in amperes per watt at the wavelength of interest or anode luminous sensitivity in amperes per lumen

PMTs and Single Photon Counting

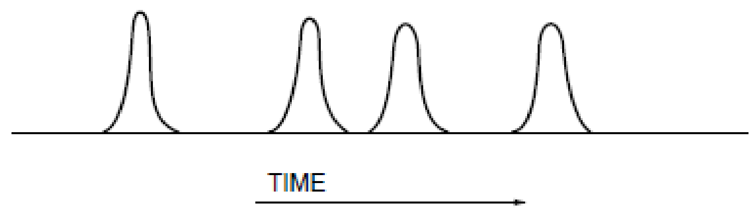
- In a typical application, the individual charge packets are indistinguishable, and the PMT generates a steady "direct current" (DC) level.

Figure 25: Overlapping Output Pulses



- In low light conditions, each individual charge packet can be discerned. This enables photon counting and zero read noise.

Figure 26: Discrete Output Pulses (Single Photon Event)



PMTs and High Energy Detection

- It is possible to use a PMT to effectively detect high energy photons by using scintillator material.
- The scintillator absorbs the high energy photon and subsequently emits photons of lower energy that are in the energy range of detection by the PMT.
- This configuration can be used to measure energy.

Figure 29: Diagram of Scintillation Detector

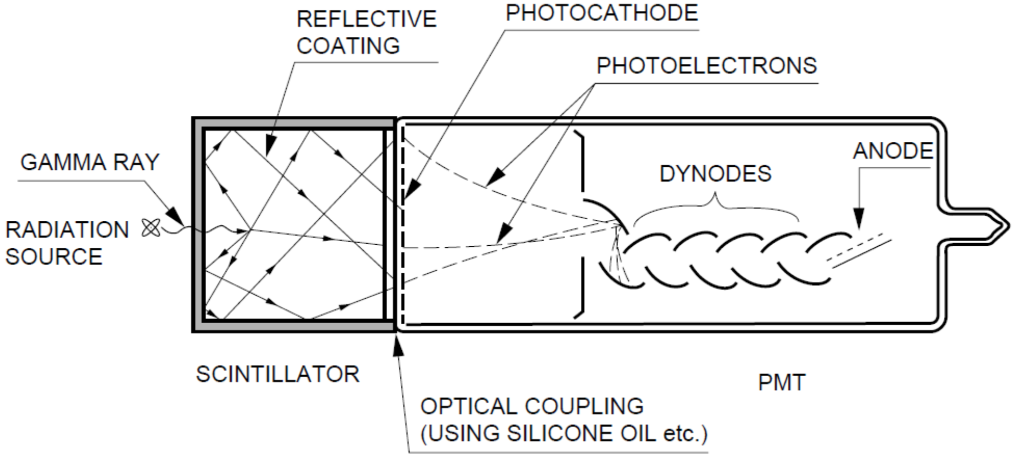
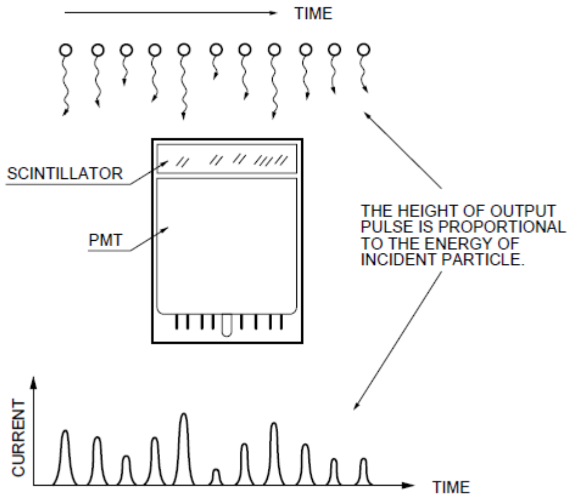


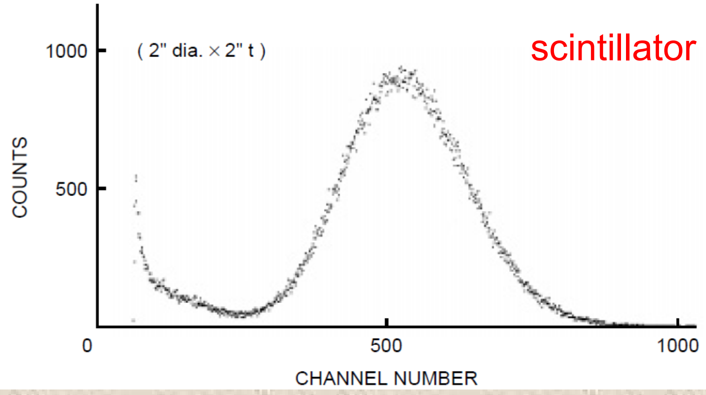
Figure 30: Incident Particles and PMT Output



PMTs and Energy Resolution

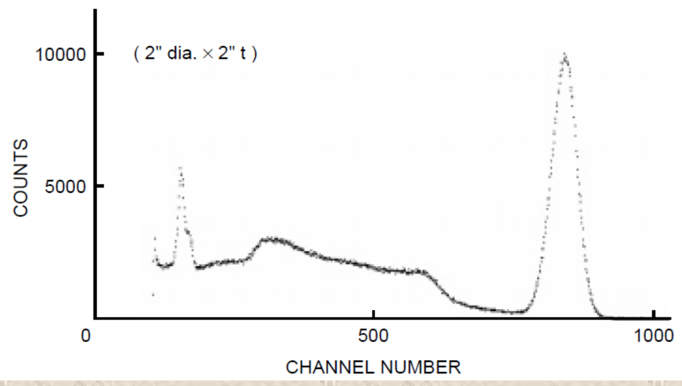
- Scintillator material will emit a number of photons that is proportional to the input energy of the high energy photon.

^{55}Fe+NaI (Tl)

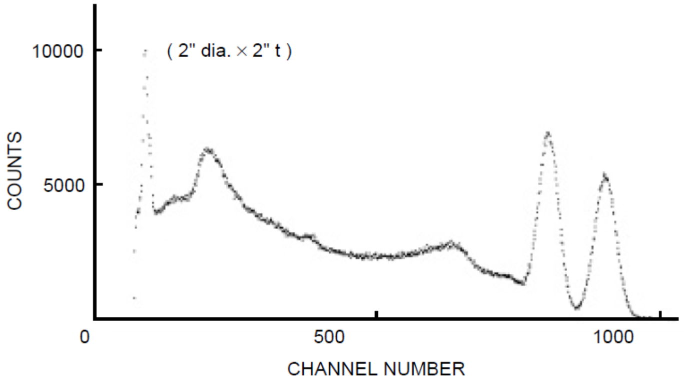


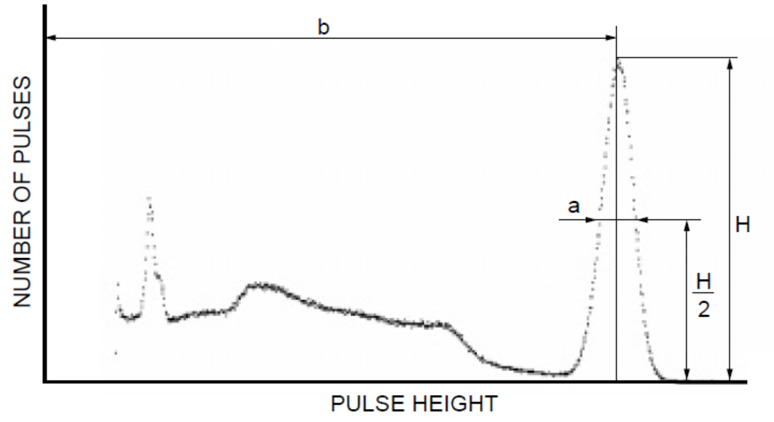
scintillator

^{137}Cs+NaI (Tl)



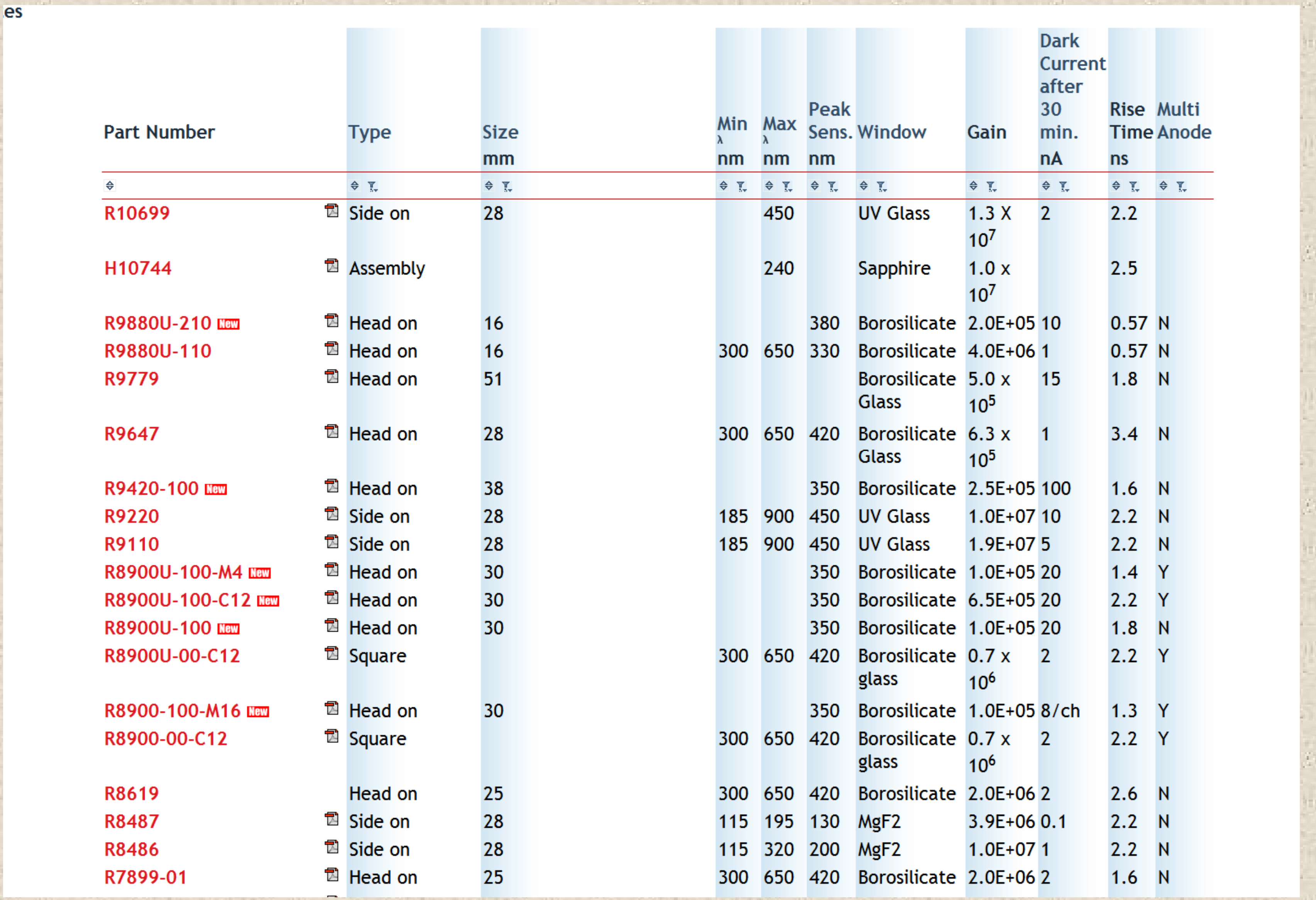
^{60}Co+NaI (Tl)





radioactive material

PMTs Examples (Hamamatsu)

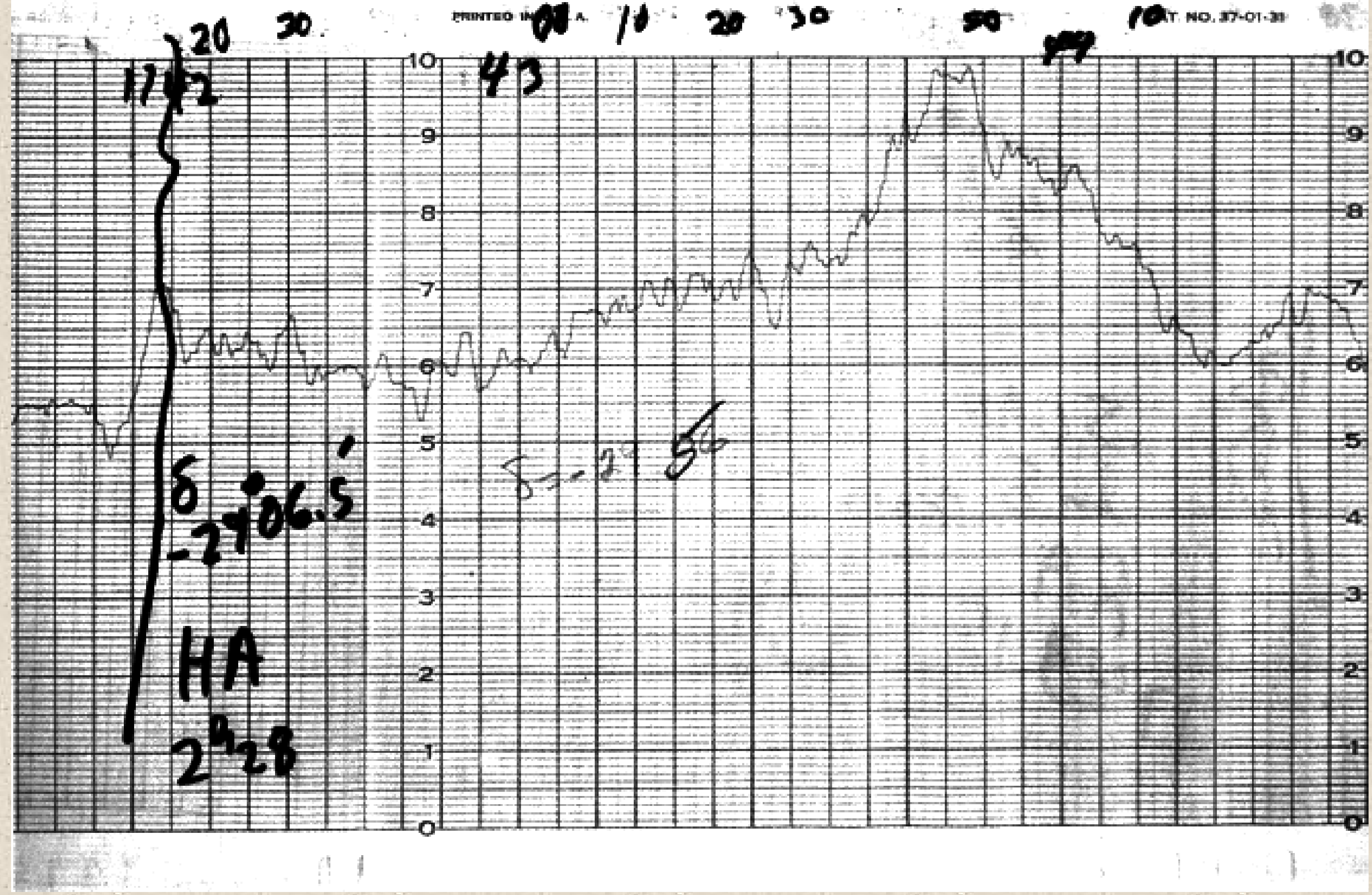


es

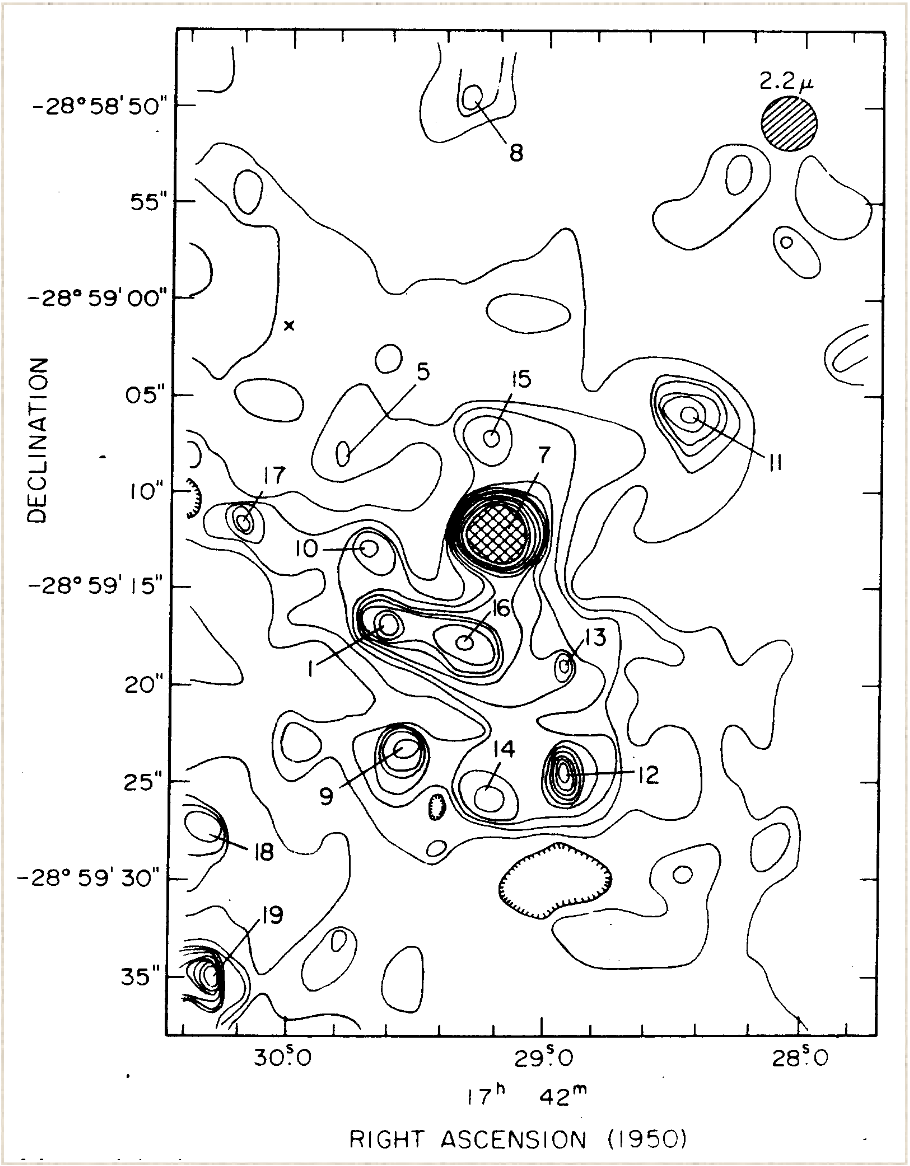
Part Number	Type	Size mm	Min λ nm	Max λ nm	Peak Sens. nm	Window	Gain	Dark Current after 30 min. nA	Rise Time ns	Multi Anode
R10699	Side on	28		450		UV Glass	1.3 X 10^7	2	2.2	
H10744	Assembly			240		Sapphire	1.0 x 10^7		2.5	
R9880U-210 New	Head on	16			380	Borosilicate	2.0E+05	10	0.57	N
R9880U-110	Head on	16	300	650	330	Borosilicate	4.0E+06	1	0.57	N
R9779	Head on	51				Borosilicate Glass	5.0 x 10^5	15	1.8	N
R9647	Head on	28	300	650	420	Borosilicate Glass	6.3 x 10^5	1	3.4	N
R9420-100 New	Head on	38			350	Borosilicate	2.5E+05	100	1.6	N
R9220	Side on	28	185	900	450	UV Glass	1.0E+07	10	2.2	N
R9110	Side on	28	185	900	450	UV Glass	1.9E+07	5	2.2	N
R8900U-100-M4 New	Head on	30			350	Borosilicate	1.0E+05	20	1.4	Y
R8900U-100-C12 New	Head on	30			350	Borosilicate	6.5E+05	20	2.2	Y
R8900U-100 New	Head on	30			350	Borosilicate	1.0E+05	20	1.8	N
R8900U-00-C12	Square		300	650	420	Borosilicate glass	0.7 x 10^6	2	2.2	Y
R8900-100-M16 New	Head on	30			350	Borosilicate	1.0E+05	8/ch	1.3	Y
R8900-00-C12	Square		300	650	420	Borosilicate glass	0.7 x 10^6	2	2.2	Y
R8619	Head on	25	300	650	420	Borosilicate	2.0E+06	2	2.6	N
R8487	Side on	28	115	195	130	MgF2	3.9E+06	0.1	2.2	N
R8486	Side on	28	115	320	200	MgF2	1.0E+07	1	2.2	N
R7899-01	Head on	25	300	650	420	Borosilicate	2.0E+06	2	1.6	N

Applications

The Galactic Center: Discovery Strip Chart

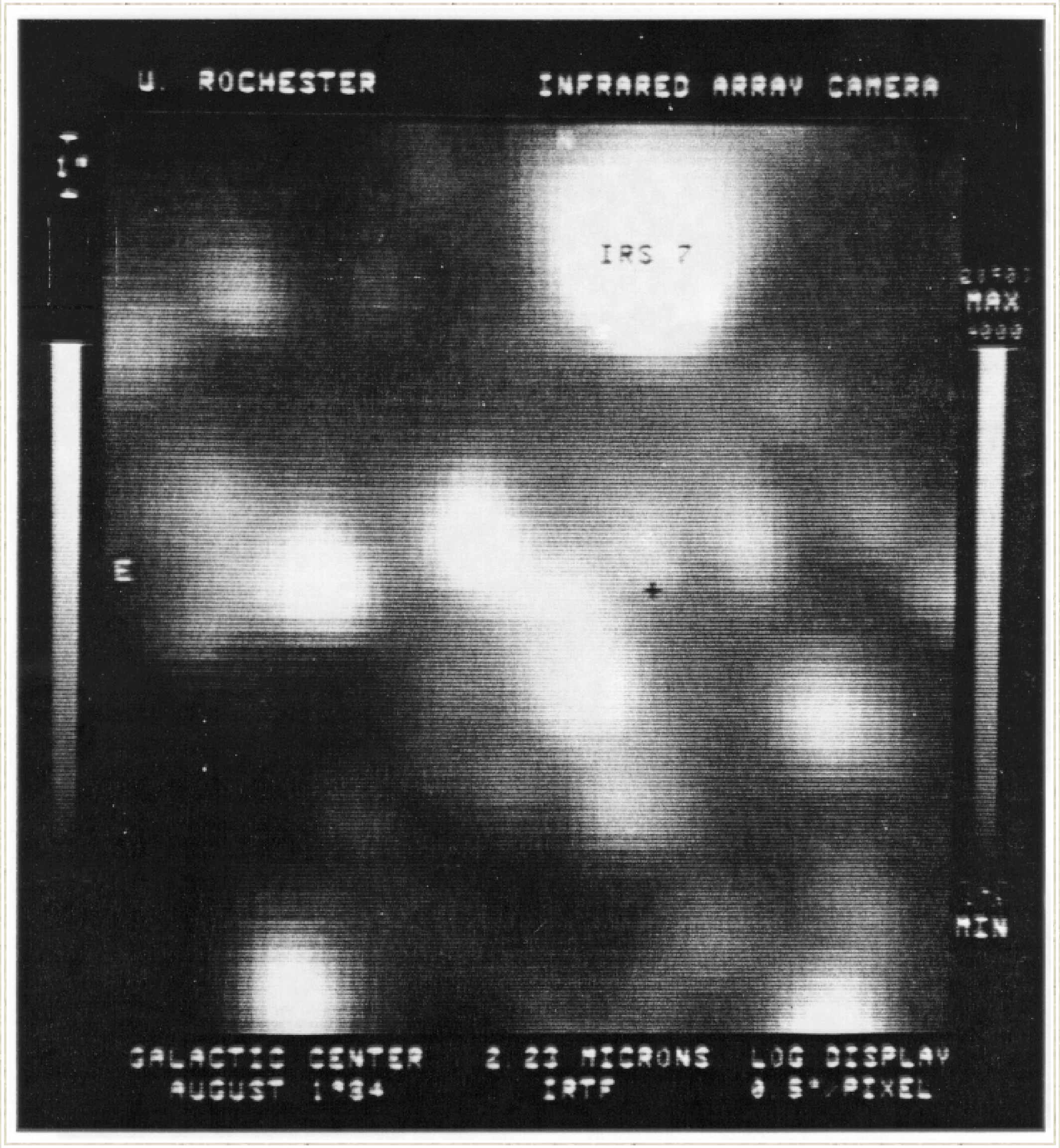


The Galactic Center: PbS Bolometer



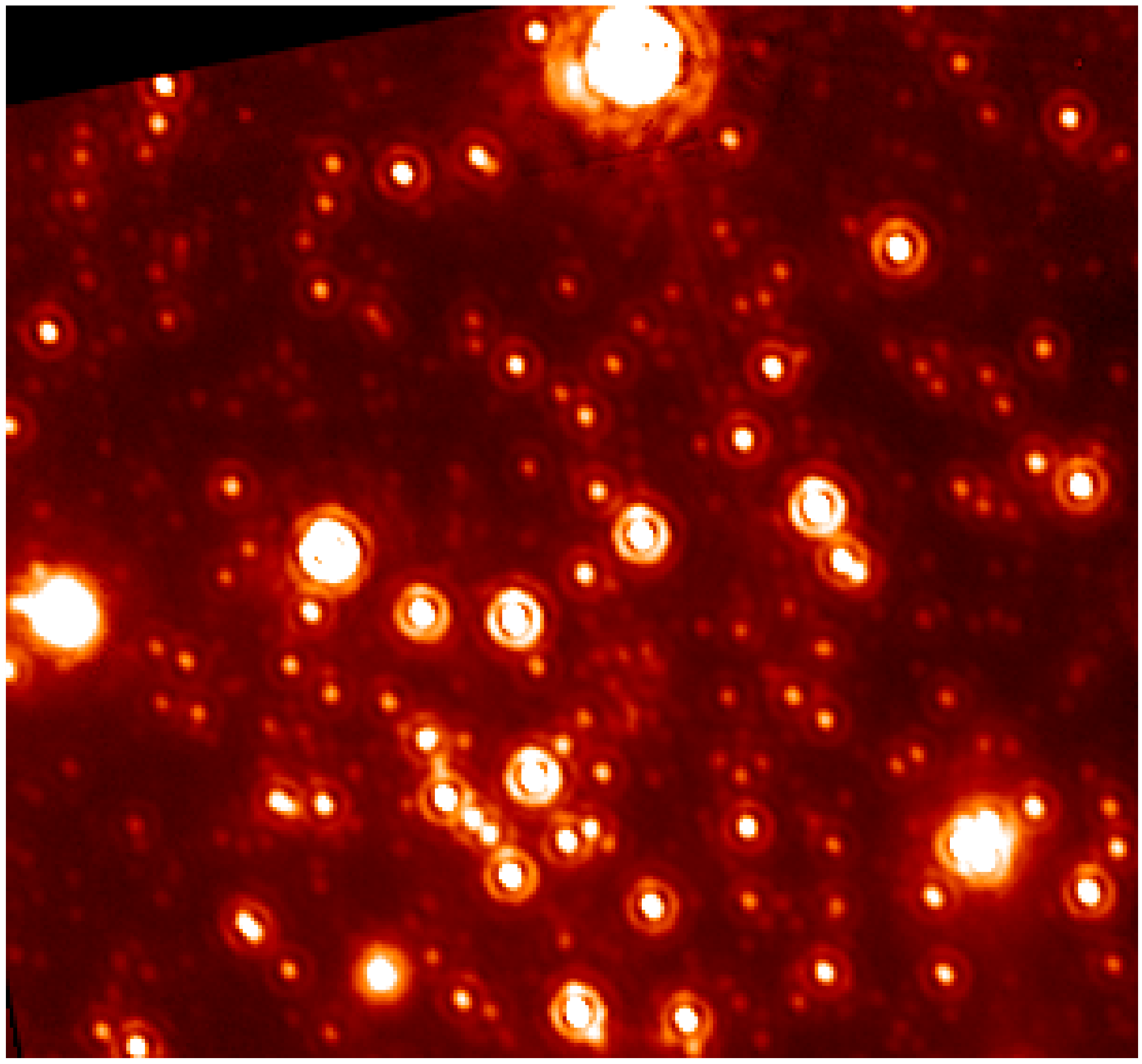
Becklin and Neugebauer, 1975

The Galactic Center: InSb Photodiode Array



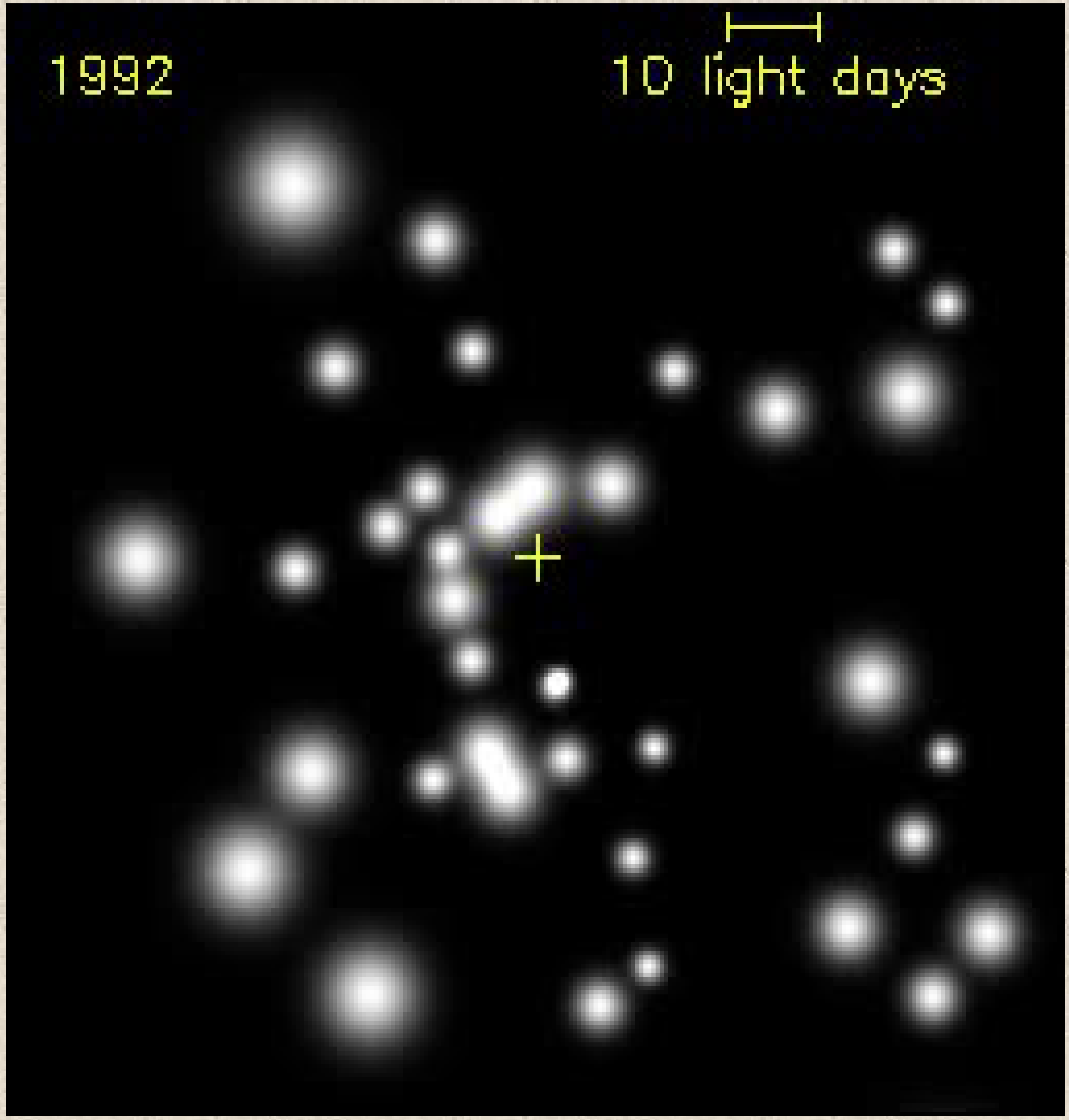
Forrest et al., 1986

The Galactic Center: HgCdTe Photodiode Array



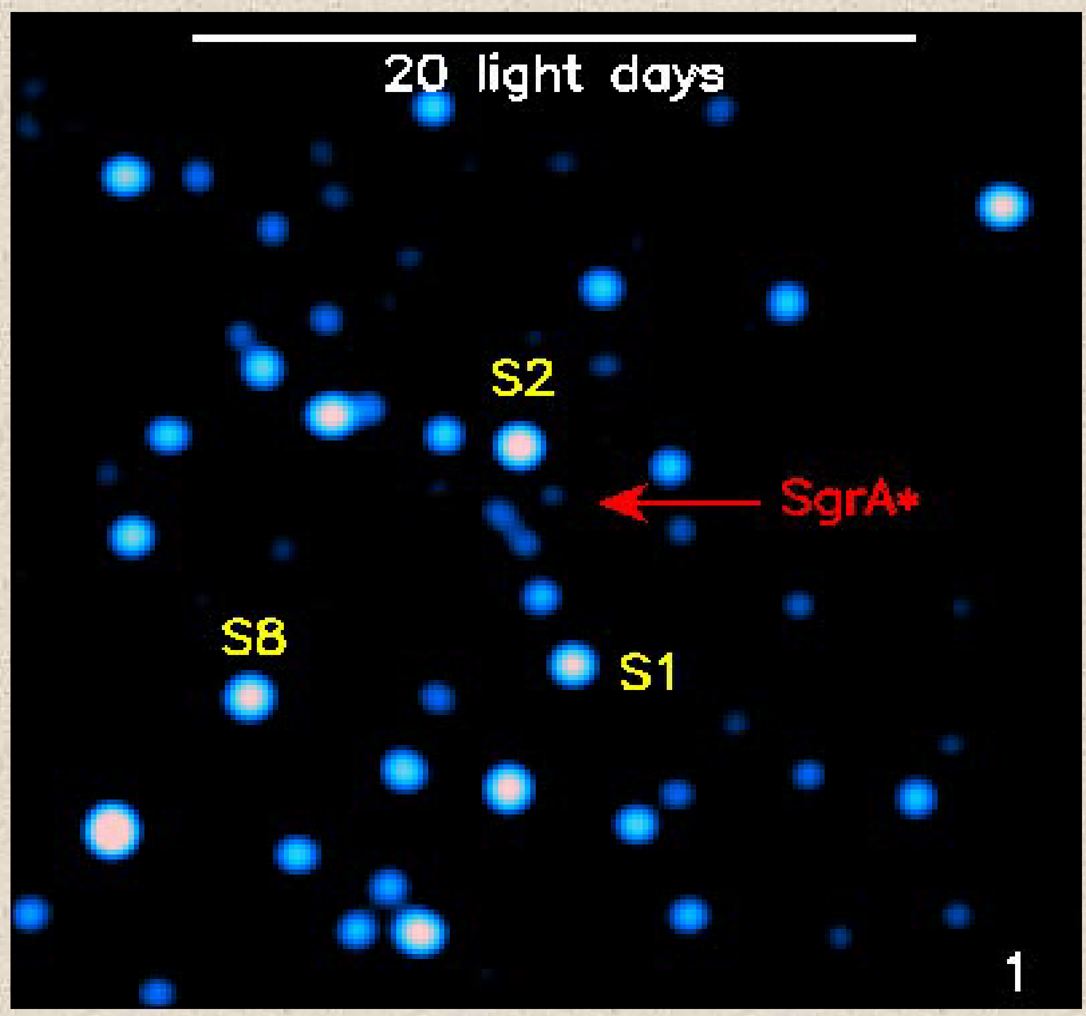
Rigaut et al., 1998

The Galactic Center: Evidence of Black Hole



Zeroing in on a Massive Black Hole…

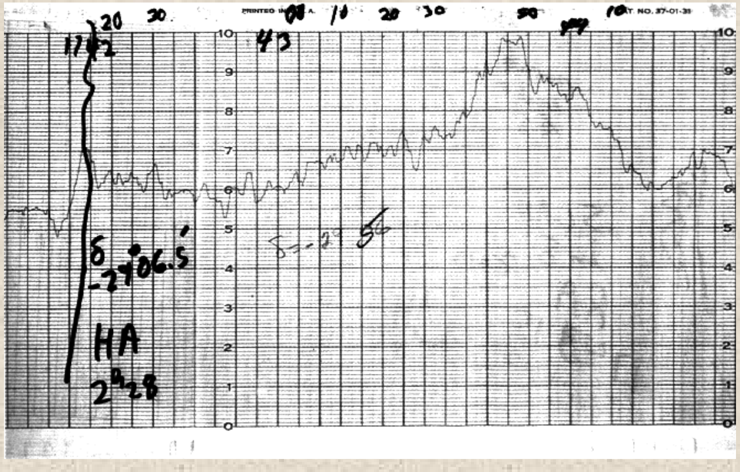
The Galactic Center: Black Hole



Infrared Flares and Black Hole Feeding

The 25 Year "Evolution" of the Galactic Center…

- Our basic understanding of key areas in astronomy is clearly a function of current technology
- What took us perhaps 25 years to achieve before, may only take ~10 years with the rapid acceleration of technology available to astronomers
- Advancements in science detectors have made this all possible…



25 yrs