

**Energetic particles and their detection in situ  
(particle detectors)  
Part II**

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# Simple particle detectors

## **Gas-filled counters**

Geiger tube

Ionization chambers

Proportional counters

## **Channeltron**

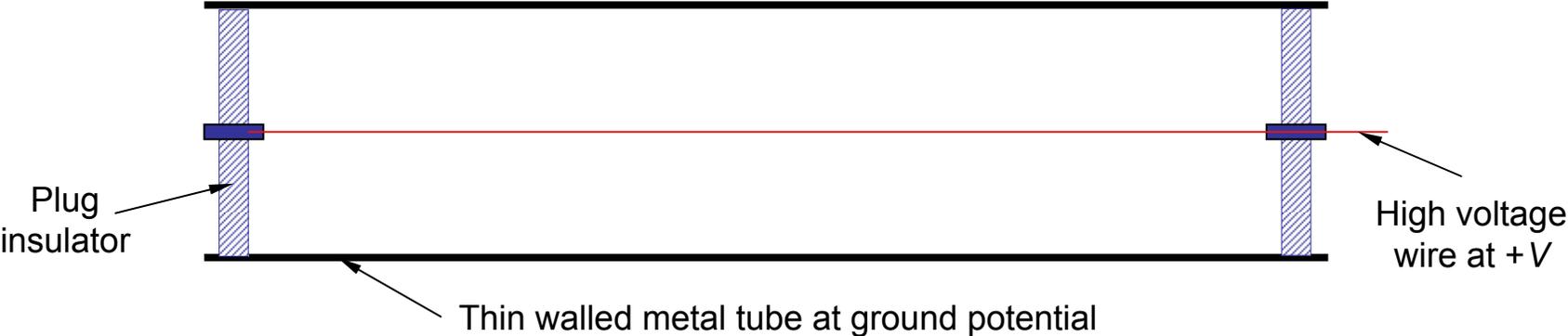
## **Microchannel Plate**

## **Solid-state detector**

## **Scintillation detector**

# Gas-filled counters

## Geiger tube

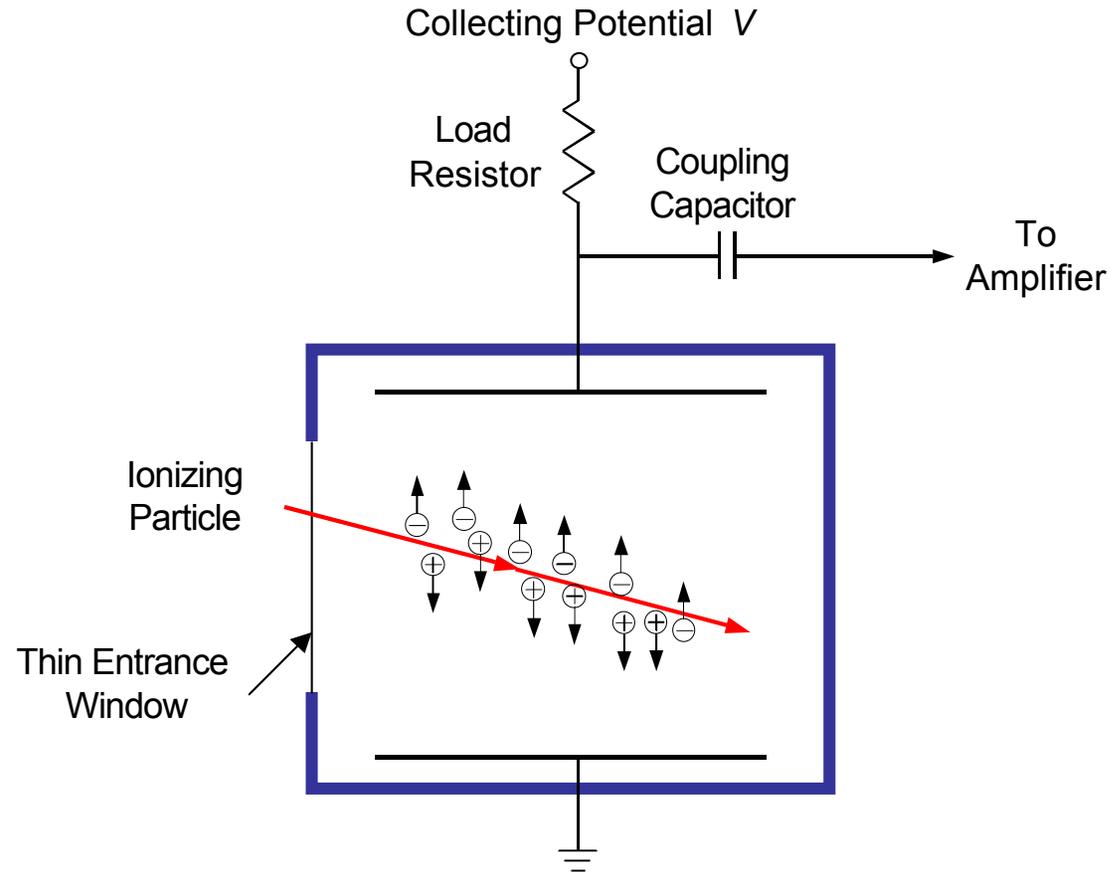


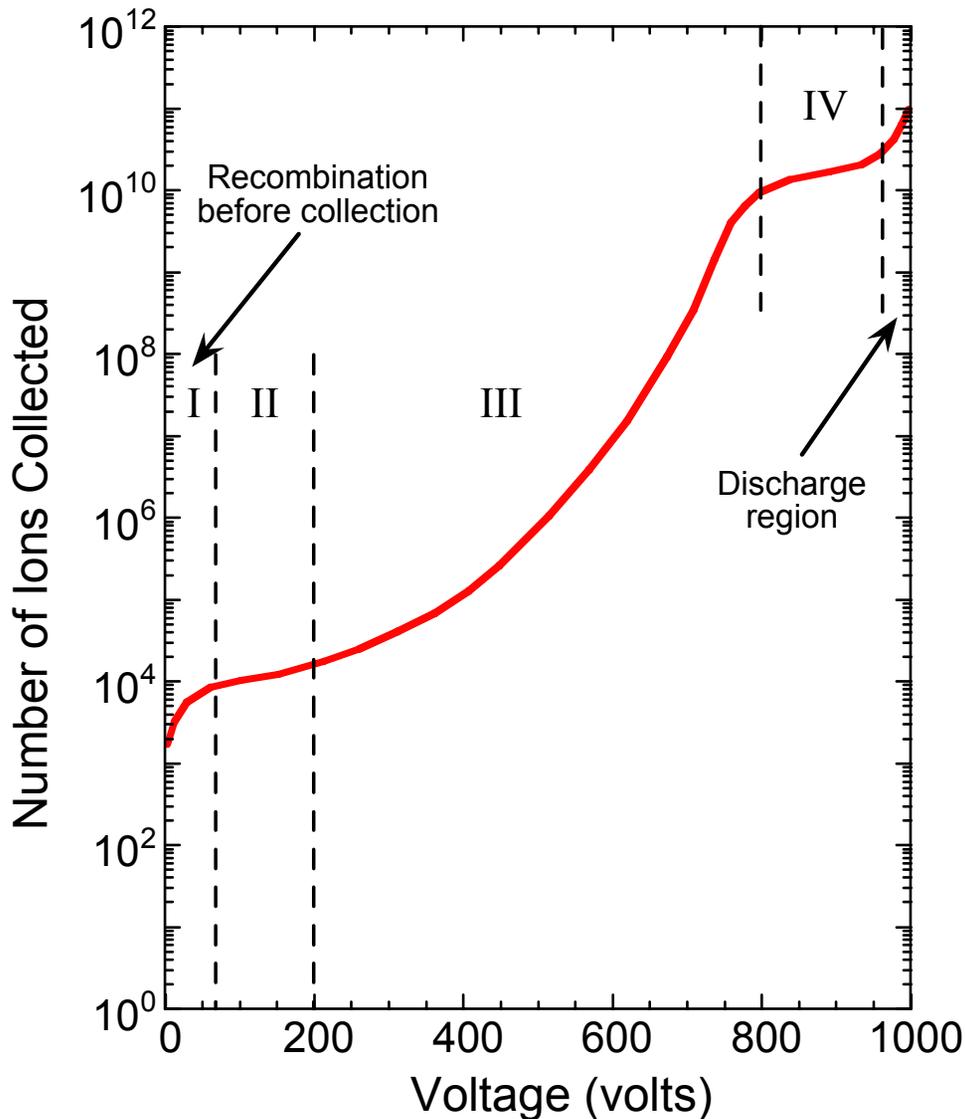
# Ionization chambers and Proportional counters

A particle passing through a gas-filled counter will ionize the gas along its path

The applied voltage  $V$  between the electrodes will sweep the positive and negative charges toward the respective electrodes causing a charge  $Q$  to appear on the capacitor.

The charge  $Q$  collected (amplitude of pulse) depends on voltage  $V$





**Region I** *no pulses produced*

recombination of charges takes place before they can drift apart and be collected, and no pulses are produced.

**Region II** *ionization chamber region.*

loss of ions due to recombination becomes small and the charge collected  $Q = N \cdot e$ , where  $N$  is the number electron-ion pairs produce by the incident energetic particle.

**Region III** *proportional counter region*

$Q$  is increased by a factor of  $M$  through gas multiplication. Electrons released in the primary ionization will produce additional ionization and thus add to the total charge.  $M$  is independent of the initial ionization at the onset of region III

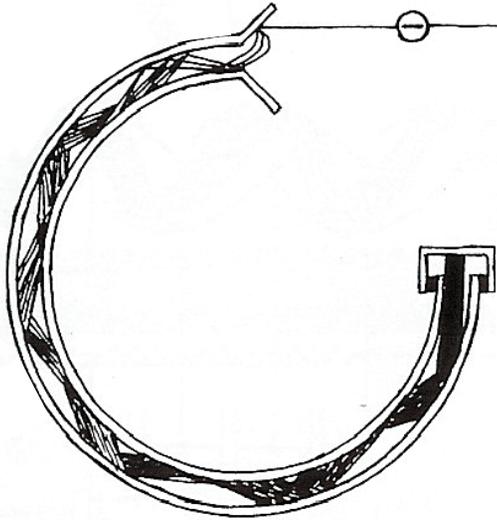
**Amount of deposited energy is recorded**

**Region IV** *Geiger region*

$Q$  is completely independent of the initial ionization, but governed by the characteristics of the filling gas and electronics.

# Channeltron

*channel electron multiplier (CEM)*



The CEM is a small, curved glass tube, ~1 mm inside diameter and several cm long

Inside surface is treated to have

- high resistivity
- large secondary electron yield
- stability when exposed to air

A simple and compact device that detects ~0.1 to ~100 keV ions and electrons

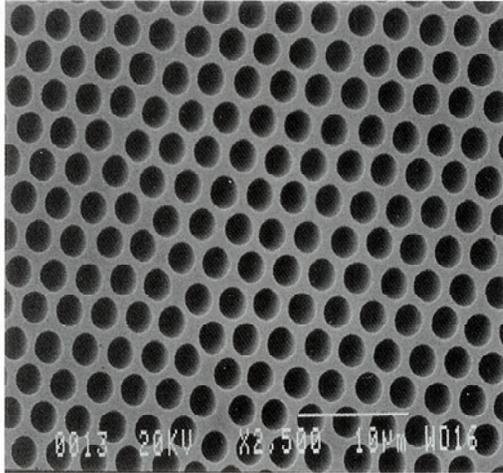
When several kilovolts are applied from one end to the other, a single electron produced at the low potential end will be accelerated down the tube and, at every collision with the tube wall, will produce several secondary electrons that continue that process

CEMs are curved to prevent *ion feedback* caused by cascading electrons that ionize some of the residual gas inside the device toward the high potential end of the devices

Positive ions are thus prevented from being accelerated toward the low potential input, where they could initiate a new cascade

For a fixed voltage, the gain ( $10^6$  to  $> 10^8$ ) depends on *length to diameter* ratio which sets the number of secondary electron multiplications

# Microchannel Plate (MCP)



An array of microscopic glass tubes (12 to 25  $\mu\text{m}$  spacing), hexagonally packed and sliced to thin (0.5 to 1.0 mm thick) wafers

Microchannel length to diameter ( $l/d$ ) ratios range from 40:1 to 80:1

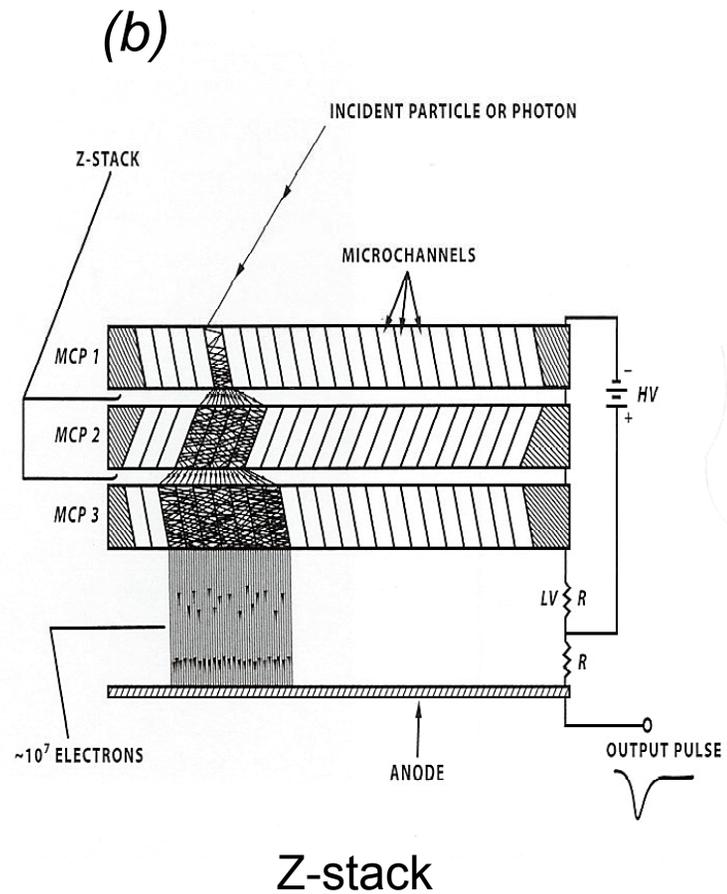
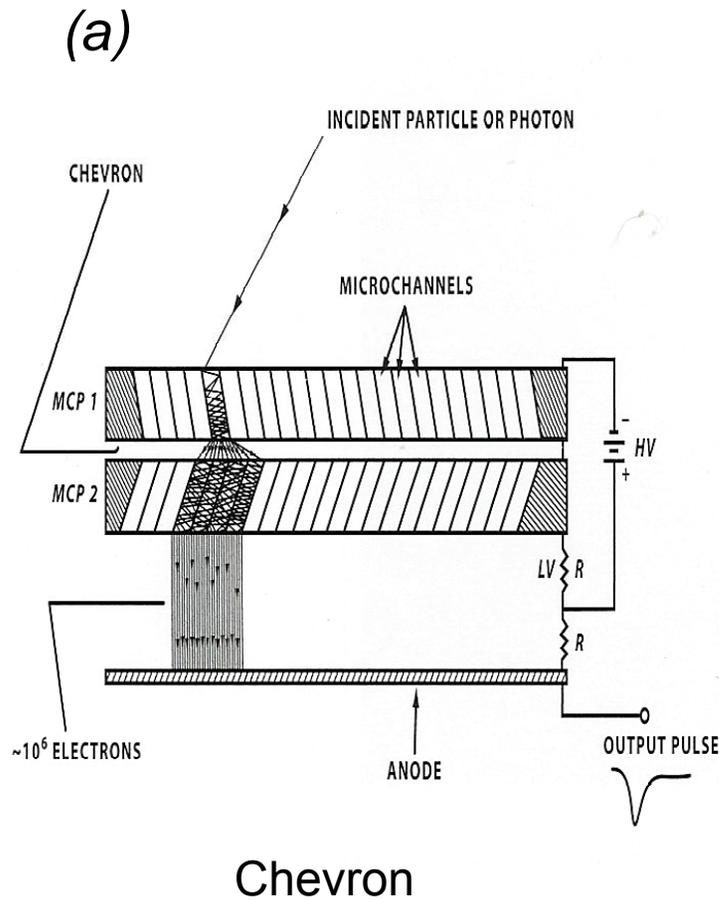
Wafers are treated at high (250-450°C) temperature in a hydrogen atmosphere to produce a resistive coating along the micro channels, and the top and bottom surfaces are metallized

Compact particle or photon detectors with a high signal to noise ratio allowing individual event counting

Low background rates ( $<1 \text{ cm}^{-2} \text{ s}^{-1}$ )

Are often used as position sensing devices

As in CEMs, electron multiplication MCPs is produced by voltage bias across a resistive glass tube that generates an electron cascade through secondary electron production

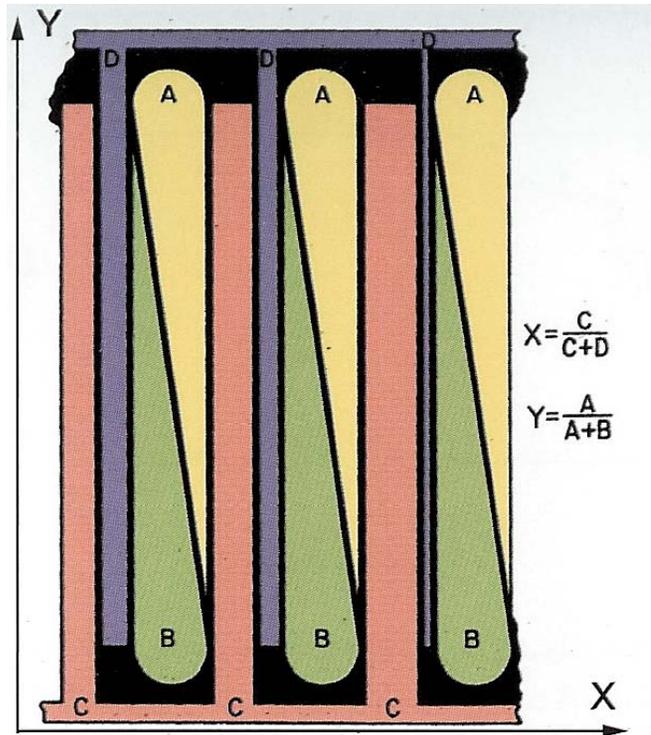


MCP wafers are sliced at a small (8-12°) bias angle relative to the microchannel axis

They are stacked in pairs (Chevron configuration) or in triplets (Z-stack), with adjacent wafers having opposite bias angles to prevent ion feedback

Typical bias voltages are  $\sim 1$  kV per plate and typical gains are  $\sim 1000$  per plate.

## Position sensing anodes



Charge pulses from MCPs may be recorded using

One or more discrete anodes (each with its own preamplifier) to count up to  $10^8$  counts/second

Resistive or delay line or **wedge and strip** anodes provide excellent x-y position resolution at the expense of lower maximum count rates

# Solid state detectors (SSDs)

*Surface barrier, Ion implant and Lithium drift detectors*

SSDs are solid-state ionization counters with an electric field is set up within a semiconductor crystal by a voltage applied across opposite faces of the crystal

Particles (or energetic photons) penetrating the crystal produces secondary electrons which, in turn, produce further ionization in the crystal until no electron has enough energy left to ionize the atoms in the crystal any further

The electric field inside the crystal sweeps out the liberated charges, their number being proportional to the energy lost by the primary particle

Advantages of SSDs compared to proportional counters

- far more effective in stopping particles, and hence absorbing their energy
- measurement of the incident particle energy is more precise (because it takes on average less energy for the production of an electron-hole pair)

Disadvantages of SSDs compared to proportional counters

- their sensitive area is limited both because of crystal size and capacitance that affects amplifier noise
- some of the energy of the primary particle goes into nuclear collisions resulting in a *total energy defect* for measuring the energy lost by (low energy) particles

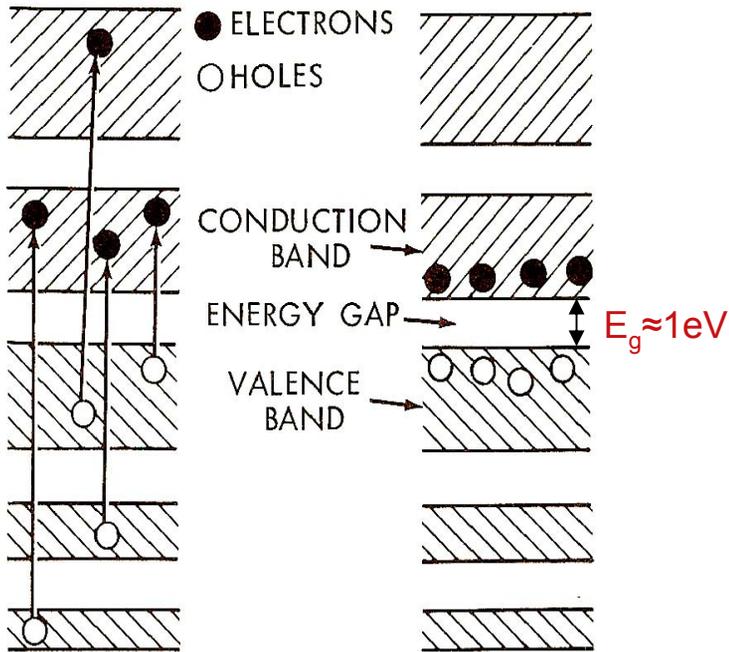


### *Special properties of semiconductor material required for fabrication of SSDs*

- The resistivity of the material must be high enough to support the required electric field without creating an excessive leakage current
- The charge carriers must have a high mobility in the crystal in order to be collected in a reasonably short time
- The trapping rate for the carriers must be low in order to maintain a high efficiency for charge collection and to reduce space-charge buildup within the crystal
- The average energy required to produce an electron-ion pair must be low, in order to give better energy resolution
- The crystal must be uniform and its properties stable over prolonged time periods

For room-temperature operation only silicon can be used for fabrication of SSDs

## *Production of electron-hole (n-p) pairs in an ideal (intrinsic) semiconductor*



(a) INITIAL CONDITIONS WITH HIGHLY EXCITED STATES

(b) RESIDUAL EXCITATION AFTER ABOUT  $10^{-12}$  SEC

- Thermal excitation,  $n = p \approx 10^{19} \exp(-E_g/2kT) \approx 2 \cdot 10^{10} \text{ cm}^{-3}$  at room temperature
- Energetic particle passing through the crystal
  - loses energy by ionization thus lifting electrons from the valence band or deeper-lying electronic bands to the conduction band or higher-lying unoccupied bands
  - the highly excited states quickly ( $\sim 10^{-12} \text{ s}$ ) decay until the electrons are near the bottom of the conduction band and the holes are near the top of the valence band
  - decay of these highly excited states produces additional electron-hole pairs
- For every 3.6 eV a particle loses in the crystal, one electron-hole pair is produced

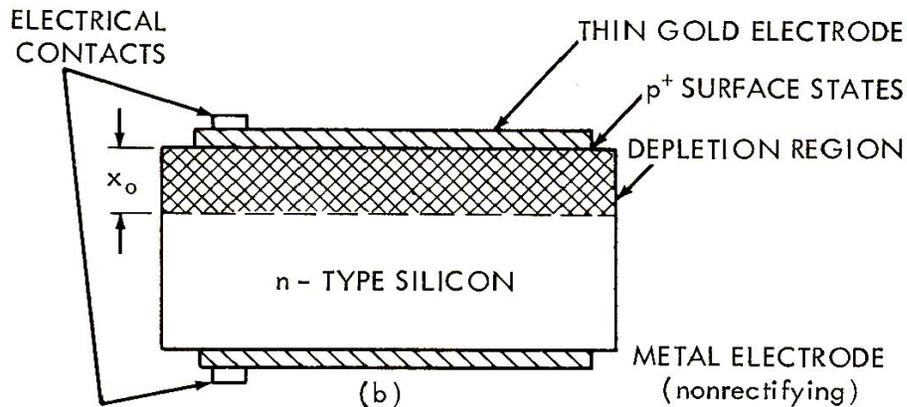
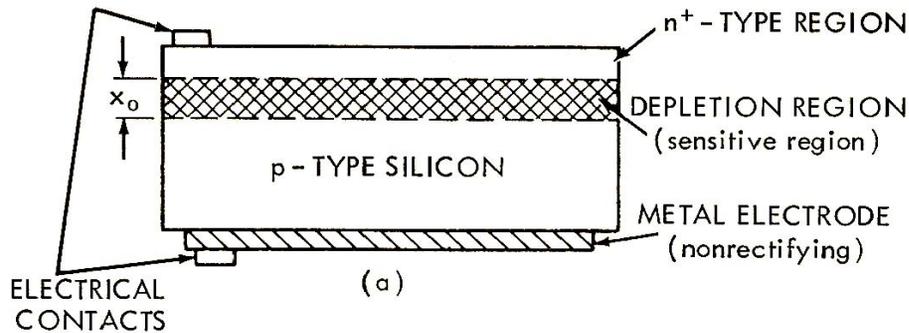
## *n- and p-type semiconductors*

- intrinsic silicon cannot be grown at present
  - even small amounts of impurity atoms produce energy levels in the forbidden gap and contribute additional charge carriers
  - impurity atoms can supply either additional electrons (donor impurities) or additional holes (acceptor impurities)
  - both types of impurity may be present in the same crystal at the same time
  - donors have energy levels in the forbidden zone near the conduction band, acceptors near the valence band
  - the number of free carriers is large because the energy gap between impurity levels and the conduction (valence) band is small
  - these extra carriers add significantly to the conductivity of the material.
- Semiconductor material is classified as either *n-type* or *p-type* depending on whether it contains more donor or more acceptor impurities
- The crystal behaves like an intrinsic semiconductor if the number of donors,  $N_D$  is equal to the number of acceptors,  $N_A$
- Making  $N_D \approx N_A$  by doping or *compensating* it with the appropriate impurity increases the resistivity of the crystal
- Compensation also increases the number of traps that reduce collection efficiency and carrier lifetime and enhance the buildup of space charge

## *p-n junction*

- When p-type and n-type semiconductors are brought into electrical contact, electrons from the n material diffuse into the p material while the holes diffuse the other way, until a new equilibrium condition is established.
- A *depletion region*,  $x_o$ , a region that contains no free carriers, is established at the interface
- The depletion region can be increased (to  $\sim 1$  mm) by applying a reverse bias across the junction
- The electric field produced by the applied voltage  $V_a$  ( $\sim 100$  to  $\sim 500$  volts) pulls out additional free carriers from the depletion region until a new equilibrium is established

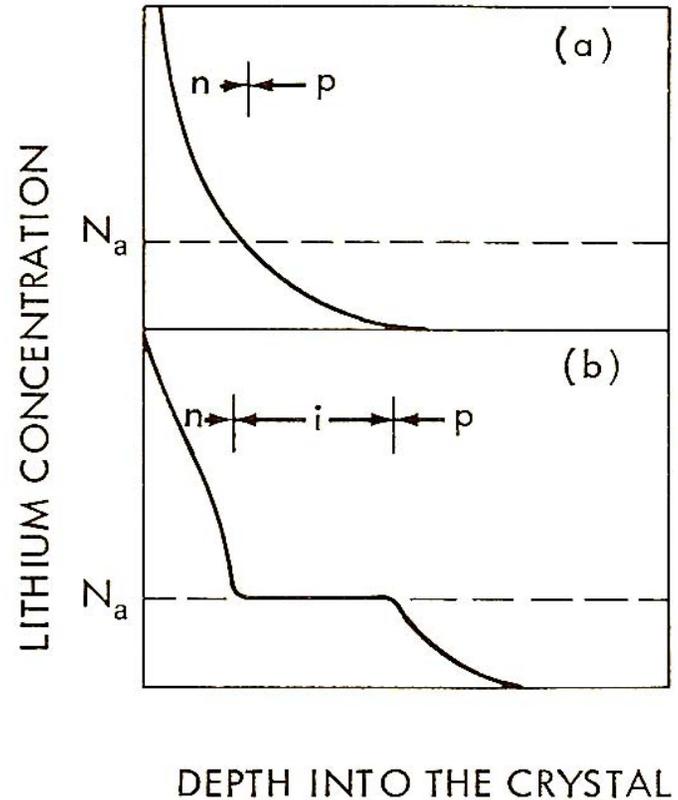
# Diffused-Junction, Surface-Barrier and Ion Implant Detectors



- The p-n junction in the *diffused-junction detector* is formed by diffusing a donor impurity (e.g. phosphorus) to a shallow depth into one face of a high-purity p-type silicon slice
  - this face becomes heavily doped n<sup>+</sup>-type material with a high donor concentration
  - a p<sup>+</sup>-n junction can be made by diffusing an acceptor impurity
- A *surface-barrier* detector is made using high-resistivity n-type material
  - One face of the crystal is chemically etched and then exposed to air (oxygen)
  - surface states, formed by spontaneous oxidation, induce a high density of holes to form a very thin p<sup>+</sup> layer
- *Ion implant* detectors are also made from high-resistivity n-type silicon with a very thin p<sup>+</sup> layer formed by implantation of ions
- Electrical contacts are made by evaporating gold onto both surfaces.

# Lithium-Drifted Detectors

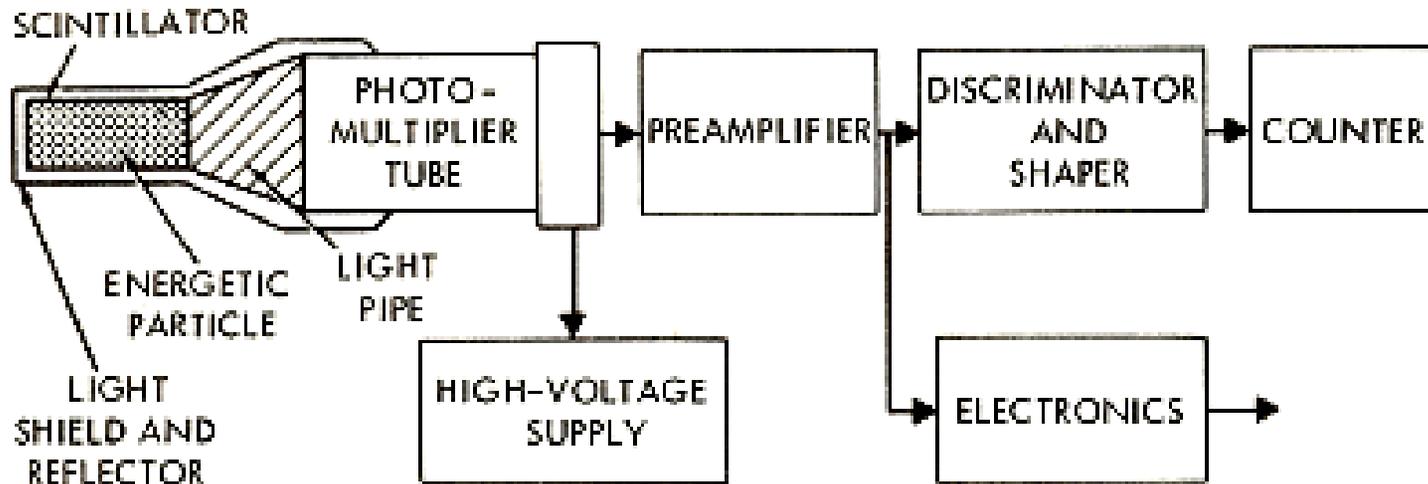
- Lithium compensation is used to obtain depletion depths larger than 1 mm at moderate bias voltages
- Lithium, donor interstitial impurity, is applied by evaporation to one face of a heated (300-500°C) slice p-type silicon
- Lithium ions diffuse into the crystal to a depth of ~0.1 mm, forming a highly doped n<sup>+</sup> region
- Reverse-biasing the junction (with the crystal still at a constant high temperature)
  - lithium ions drift and redistribute themselves so that the Li<sup>+</sup> concentration is exactly equal to the acceptor concentration of the p material
  - donor (Li) and acceptor (usually boron) impurities completely compensate each other producing an effective intrinsic region between the p and n<sup>+</sup> material.
  - drifting is continued until nearly all the p material is compensated for, most of the remaining p layer removed by lapping and finally chemically etched to form a thin surface-barrier p<sup>+</sup> layer.



- Nearly windowless lithium-drifted detectors with depletion depths of ~ cm that operated at moderate (20-50 volts) voltages and are more stable against breakdown have been produced

# Scintillation Detector

- An energetic particle passing through a *scintillator* material excites atoms that then emit light as they decay to their ground states
- The light is then converted to an electrical signal that is amplified and recorded
- The scintillation material may be a solid, a liquid, or even a gas and the device converting light into an electrical signal is generally a photomultiplier tube, although in some applications photo-diodes (essentially thin window SSDs) are used

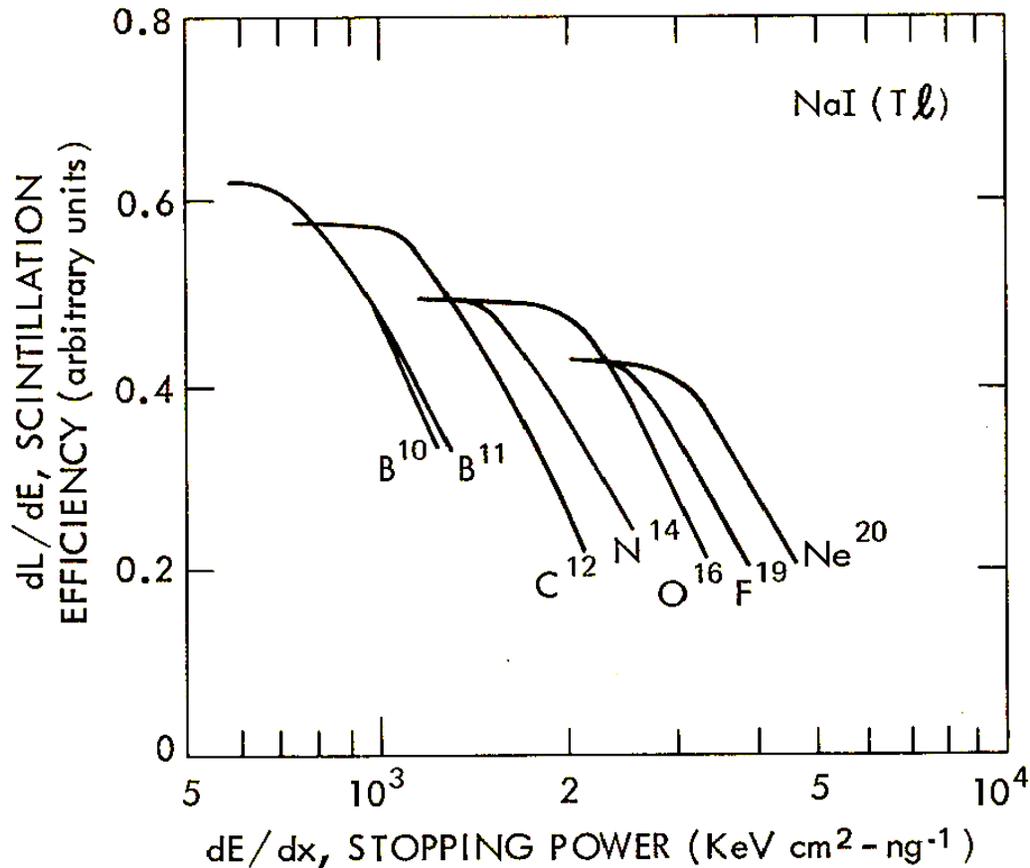


- Solid scintillation detectors (scintillators) have several advantages over gas counters and even solid-state detectors
  - energetic particles may be stopped in a relatively small volume of the detector because of the high (electron) density of the detector
  - the thickness of solid scintillators can be as large as  $\sim 10$  cm, allowing total energy measurements of several hundred MeV/nucleon particles
  - a fast response allows operation at much higher counting rates than is possible for gas counters
- Their main disadvantages are
  - complicated light collection and conversion to electrical signals
  - higher energy (50 to 300 eV compared to 3.6 eV in silicon SSDs) to produce one photoelectron
  - use of photomultiplier tubes and high voltages

- The amount of charge  $Q$  produced at the photomultiplier tube output given by

$$Q = \Delta E(\eta\omega\theta\mu K/E_{ph}) \cdot e$$

- $\eta$  is the small fraction of the energy,  $\Delta E$ , lost by the energetic particle that is converted into light, which is characterized by some spectral distribution with  $E_{ph}$ , the average energy of the emitted photons.
  - $\omega$  is the optical efficiency (number of photons that reach the photocathode)
  - $\theta$  is the probability of ejection of an electron from the photocathode by a photon
  - $\mu (< 1)$  is the efficiency of the photoelectrons reach the first dynode
  - $K$  is the multiplication factor due to the secondary emission cascade in the photomultiplier tube
  - $e$  is the charge of an electron
- Two types of scintillators are used
    - *organic scintillator* material consists of aromatic hydrocarbons whose molecules contain benzene-ring structures along with various nonaromatic substitutions (e.g. anthracene and stilbene crystals)
    - *inorganic* scintillators are crystals of inorganic salts (e.g. alkali halides) containing small amounts of impurities as activators for light emission
  - The desirable properties of a good scintillator are
    - high conversion efficiency  $\eta$
    - high transparency to its fluorescent radiation
    - short decay times for fluorescent radiation
    - spectral distribution consistent with the responses of available photosensitive devices.



- The dependence of *conversion efficiency* on particle type is best expressed in terms of the light output per unit energy lost,  $dL/dE$ , as a function of the stopping power  $dE/dx$  of the particle
- In organic scintillators the reduction of the conversion efficiency for *heavy particles* is due to the relatively large fraction of non-radiating transitions that occur from states excited by low-energy electrons ( $\delta$ -rays) produced by the energetic particle
- In the inorganic scintillator, the reduction in conversion efficiency is probably due to a saturation of the activator sites along the track of a heavily ionizing particle