CCDs at Liverpool

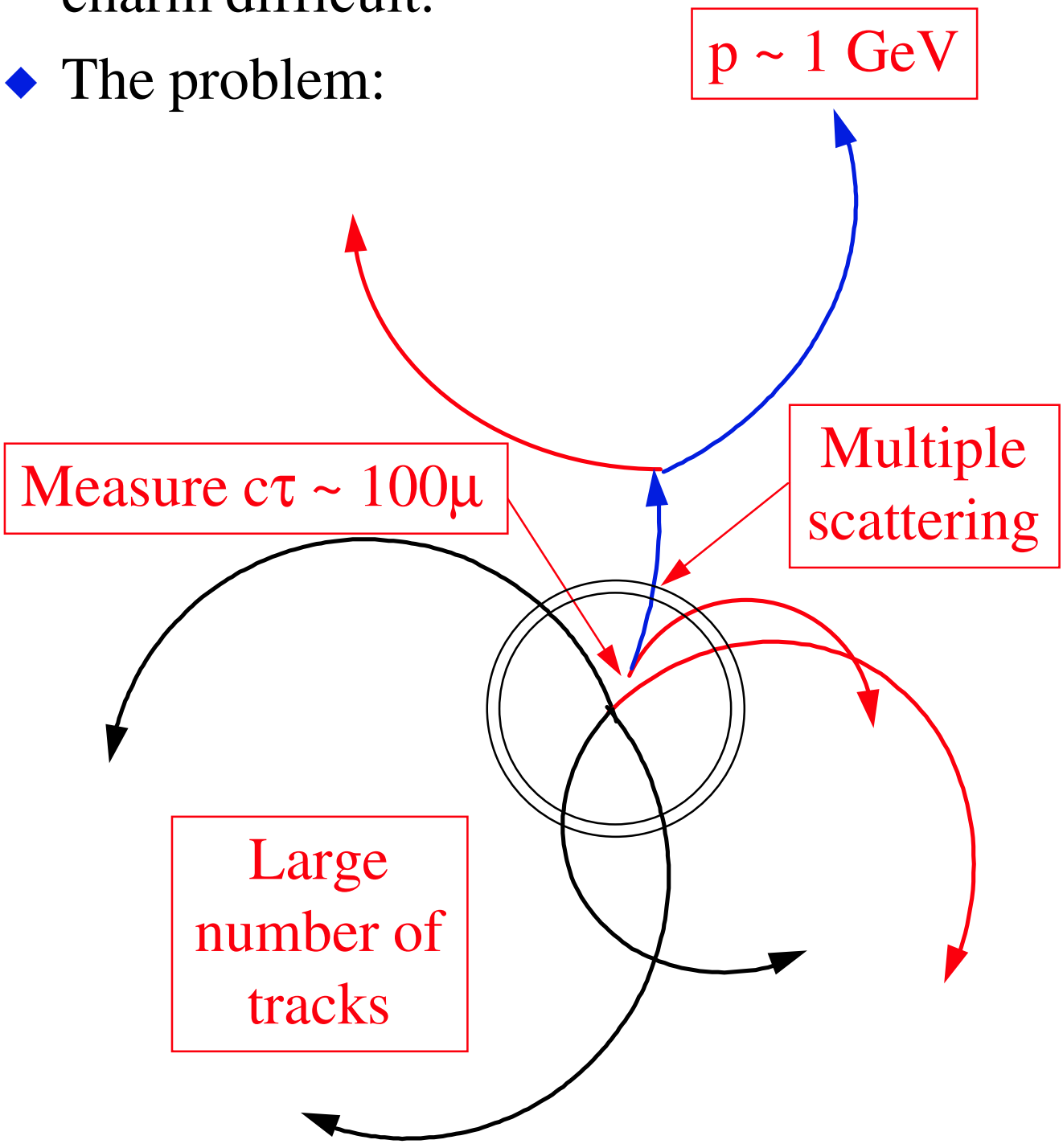
- Introduction
- Silicon and silicon detectors
- CCD construction and readout
- UK R&D on CCDs
- Liverpool research programme
- Summary

Introduction

- Many of topics of interest in HEP require high precision detectors.
- Two examples:
- Tagging b quarks likely to be essential for identification of Higgs' boson at the CDF or the LHC.
- If Higgs' boson is found, is this:
  - Confirmation of the Standard Model?
  - Evidence for SUSY?
- Look at ratio of decay widths to "u" and "d" type quarks (e.g. charm and beauty).
- Couplings to "u" suppressed, to "d" enhanced, over SM expectation in SUSY theories.
- Must tag efficiently c and b quarks, probably needs e^+e^- Linear Collider.

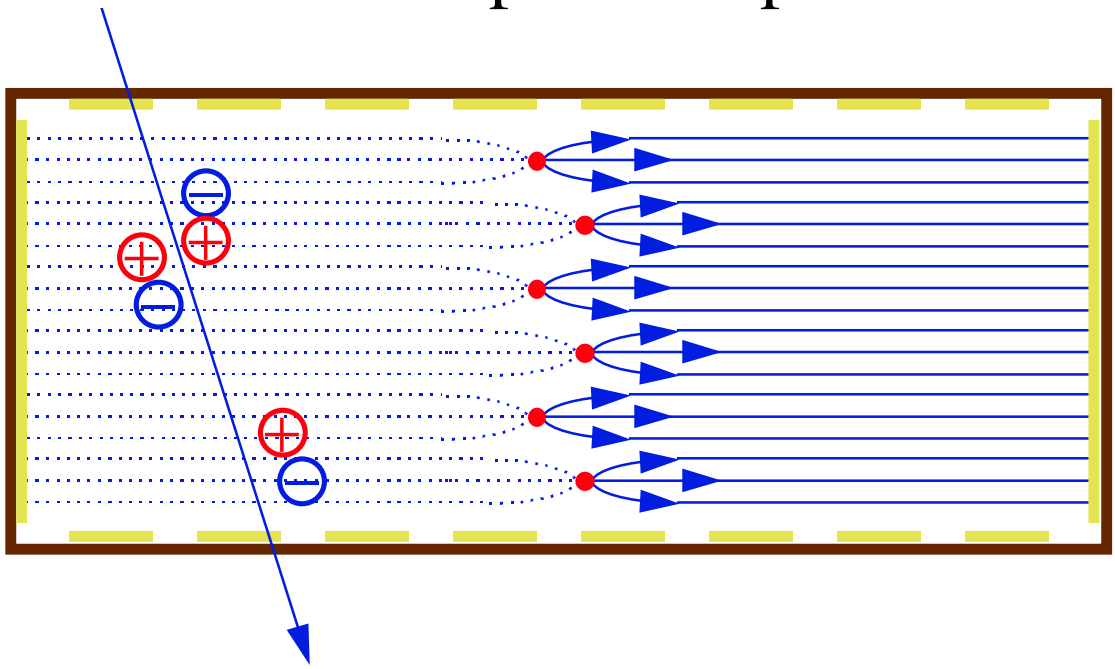
Introduction cont.

- In particular, efficient identification of charm difficult.
- The problem:



Introduction cont.

- Detectors for measurement of the paths taken by charged particles rely on the ionization those particles produce:



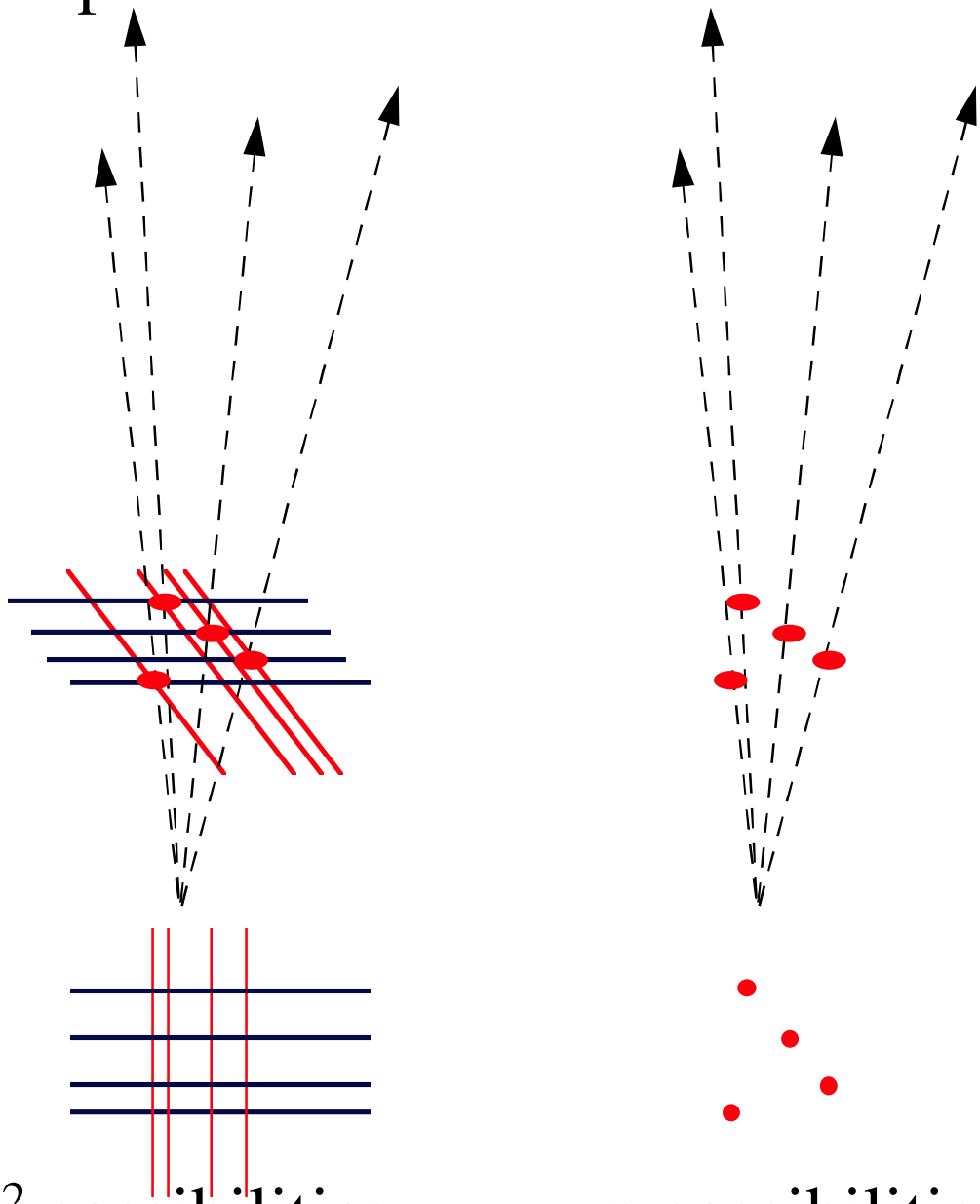
- Material in which ionization occurs can be gas, liquid or solid.
- Gasses good for covering large areas...
- ...but diffusion of drifting e^- means best possible resolution ~ few tens of μm, two track resolution typically ~ 1mm.
- Use a solid.

Introduction cont.

- Which solid?
- Need:
  - Low Z to minimize multiple scattering.
  - Lots of charge released by through going particle (small band gap).
  - Little free charge in absence of particles (large band gap).
  - Ability to accurately “machine”.
- Silicon is material which currently best fulfils above criteria.
- Alternatives include:
  - Diamond.
  - Gallium arsenide.
  -
  -

Introduction cont.

- Tracking performance drastically improved if 3D information can be used.

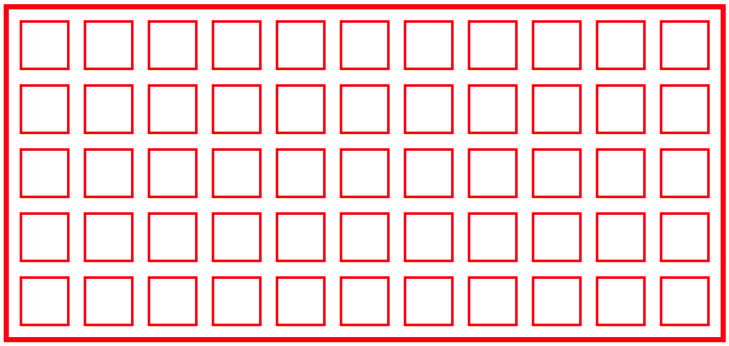


n^2 possibilities, resolve in pattern recognition

n possibilities, pattern recognition simplified

Introduction cont.

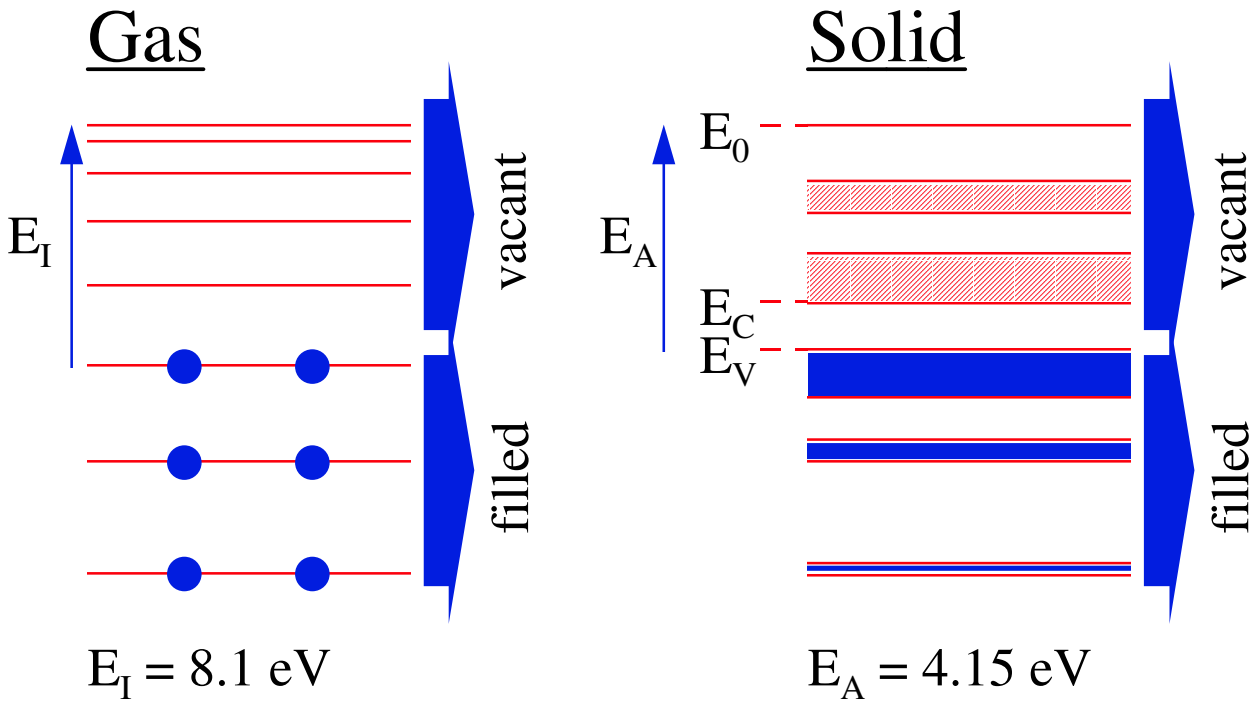
- Require silicon pixel detector.



- Options are:
  - Charge Coupled Device (CCD).
  - Active Pixel Sensor (APS).
- Have a quick look at:
  - How silicon detectors in general and CCDs in particular work.
  - Pros and cons of CCDs and APSs.
  - Where R&D needed on CCDs.
  - What we can do at Liverpool.

Silicon

- Energy levels in silicon atoms:



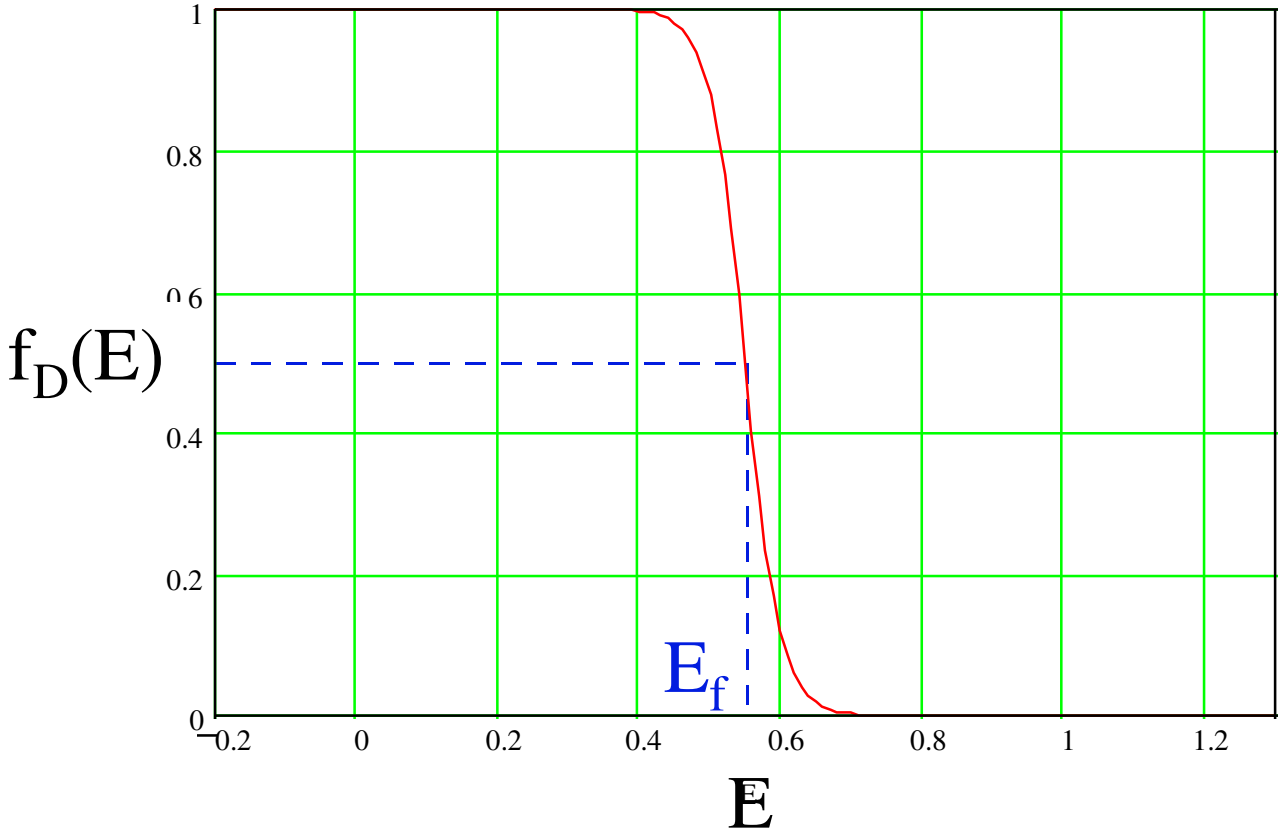
$E_I = 8.1$ eV $E_A = 4.15$ eV

- Electrons in valence band tightly bound to atoms.
- Electrons in conduction band free to move through crystal.
- If $E_C - E_V$ large, no free electrons, material is insulator.
- If E_C and E_V overlap, many free electrons, material is conductor.

Silicon cont.

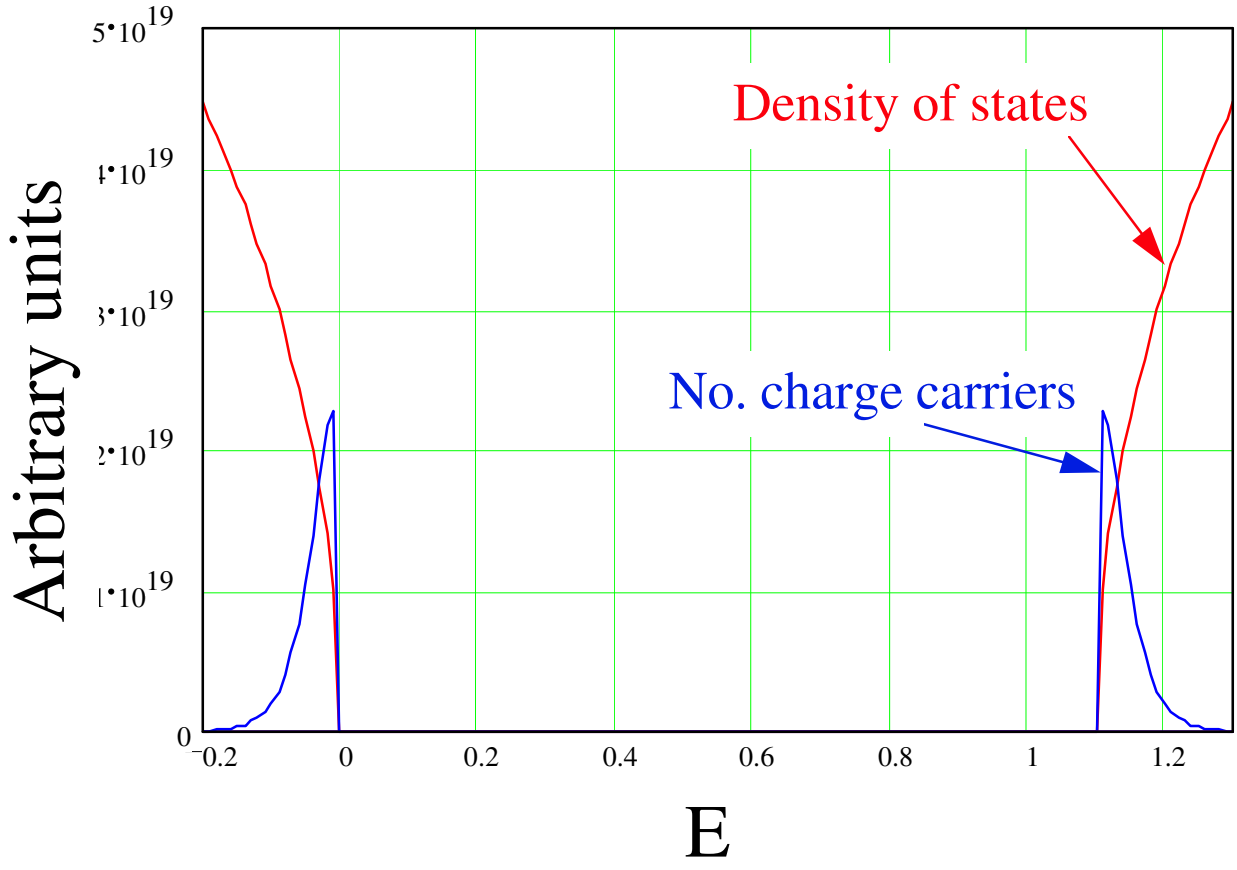
- If $E_C - E_V$ small (1.1 eV for Si), kT causes excitation of some valence electrons into conduction band, semi-conductor (room temp. kT = 0.026 eV).
- Prob. state of energy E occupied by e^- is:

$$f_D(E) = \frac{1}{1 + \exp\left[\frac{E - E_f}{kT}\right]}.$$



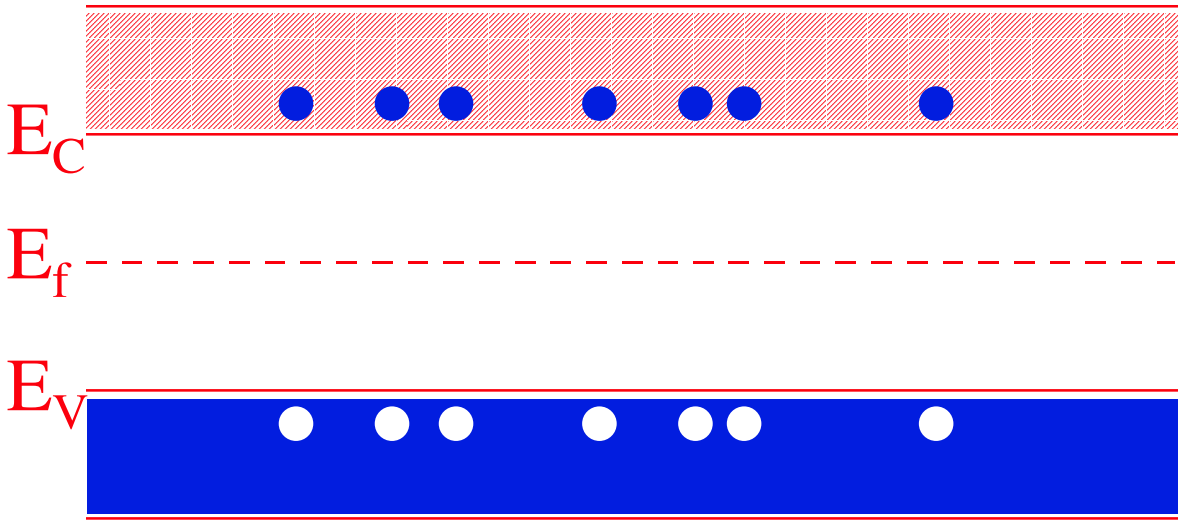
Silicon cont.

- Fermi level is energy at which occupation probability is half.
- Number of conduction electrons given by product of occupation probability and density of available states, g(E).



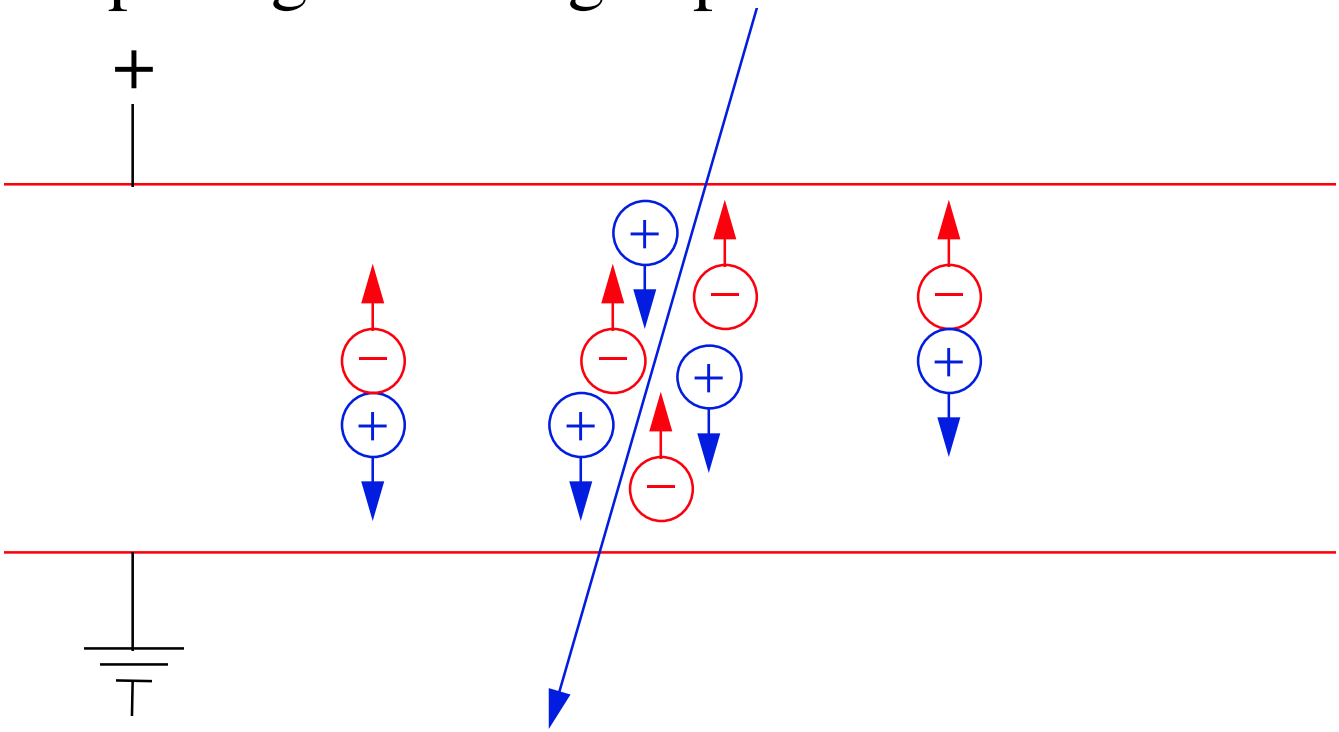
Silicon cont.

- At room temp. (kT = 0.026eV, $E_C - E_V = 1.1eV$), number of conduction electrons small for silicon.



Silicon detectors, take one.

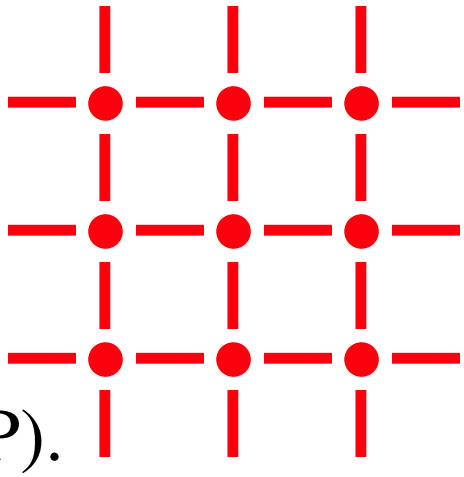
- Apply voltage across Si crystal.
- Observe increase in current due to passage of charged particle.



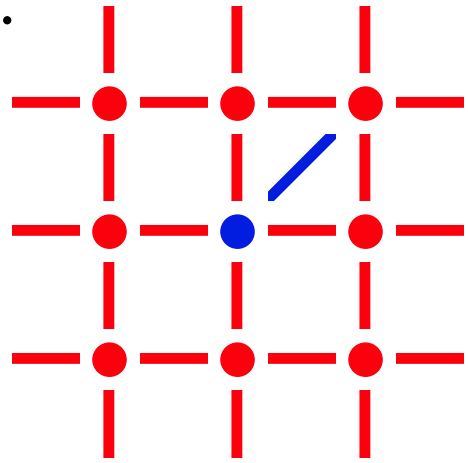
- Fails miserably:
  - Additional current due to charged particle too small.
  - Works for (some) insulators, e.g. diamond detectors.

Doped silicon

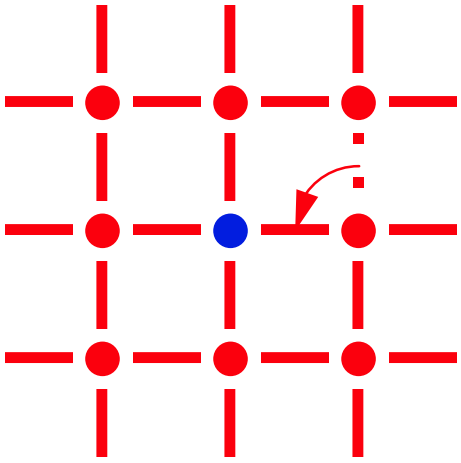
- Si atom in solid forms 4 covalent bonds with neighbours at equal space angles.



- Add pentavalent impurity (P).
  - 4 covalent bonds formed.
  - One electron left "dangling", relatively easily promoted into conduction band.
  - "n" type semi-conductor.

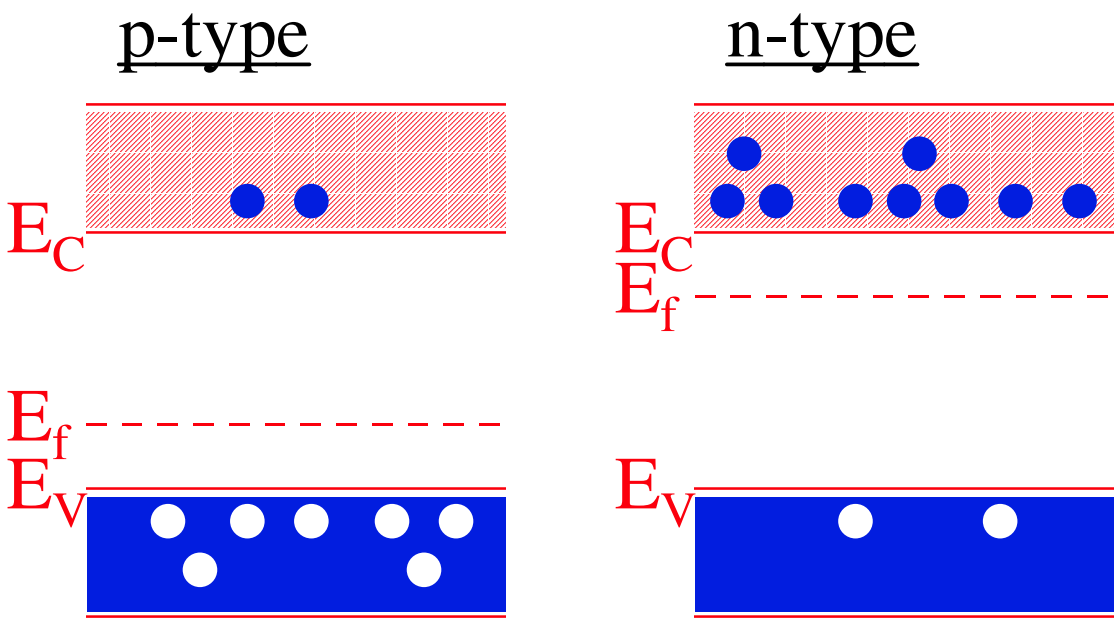


- Add trivalent impurity (B).
  - Missing covalent bond "mops up" adjacent electron creating hole.
  - "p" type semi-conductor.



Doped silicon cont.

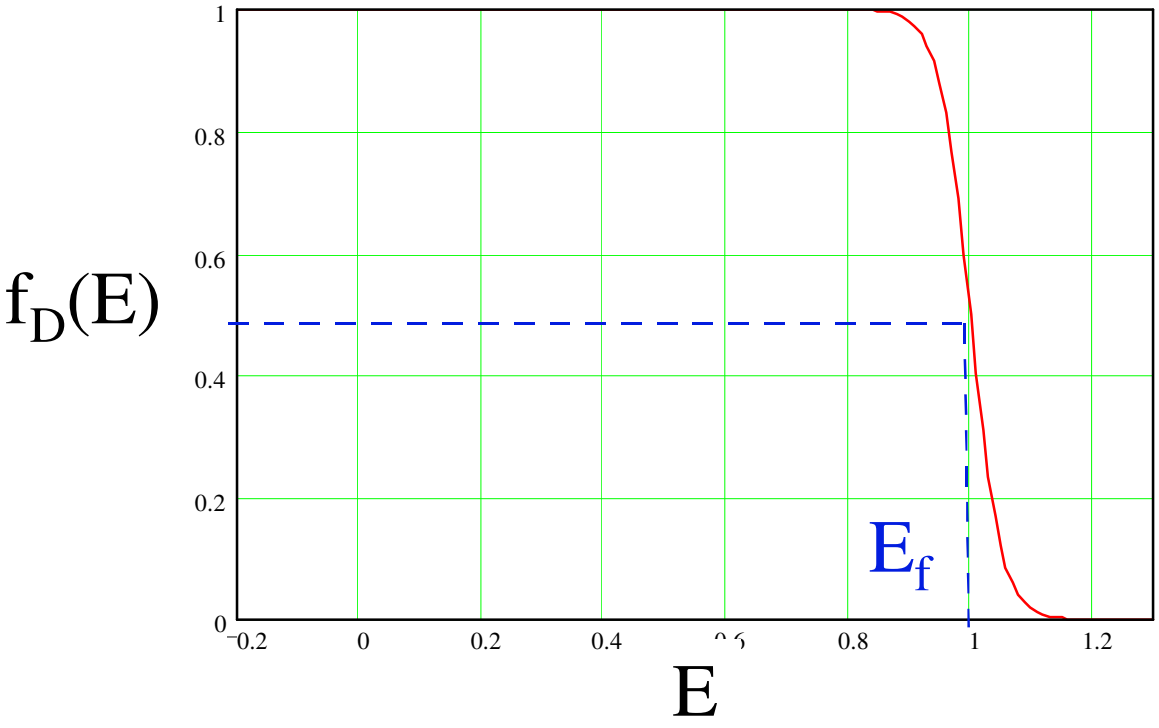
- Pentavalent doping (n-type Si) makes available lots of conduction electrons.
- Effectively move Fermi level up towards conduction band.
- Trivalent doping (p -type Si) makes available lots of conduction holes.
- Effectively move Fermi level down towards valence band.

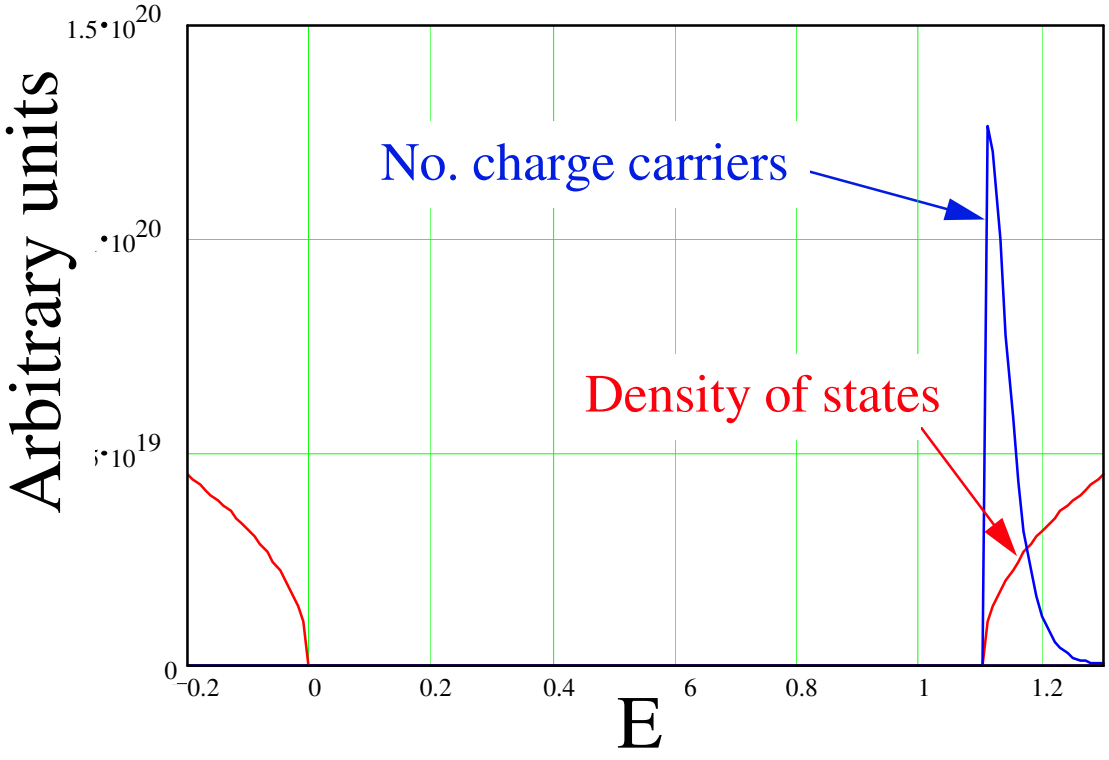


- What has this to do with detectors?

Doped silicon cont.

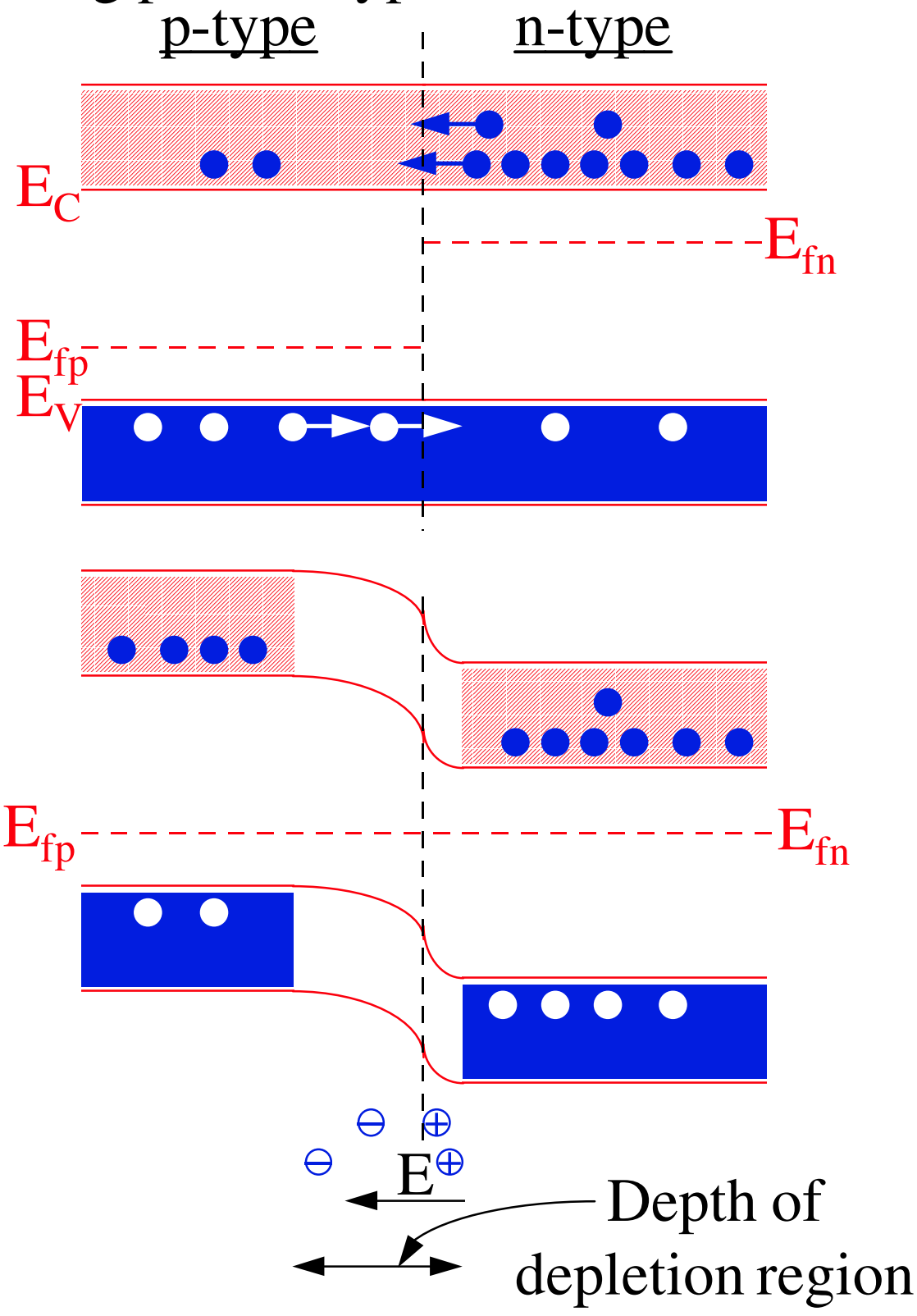
- For doped (n type) silicon:





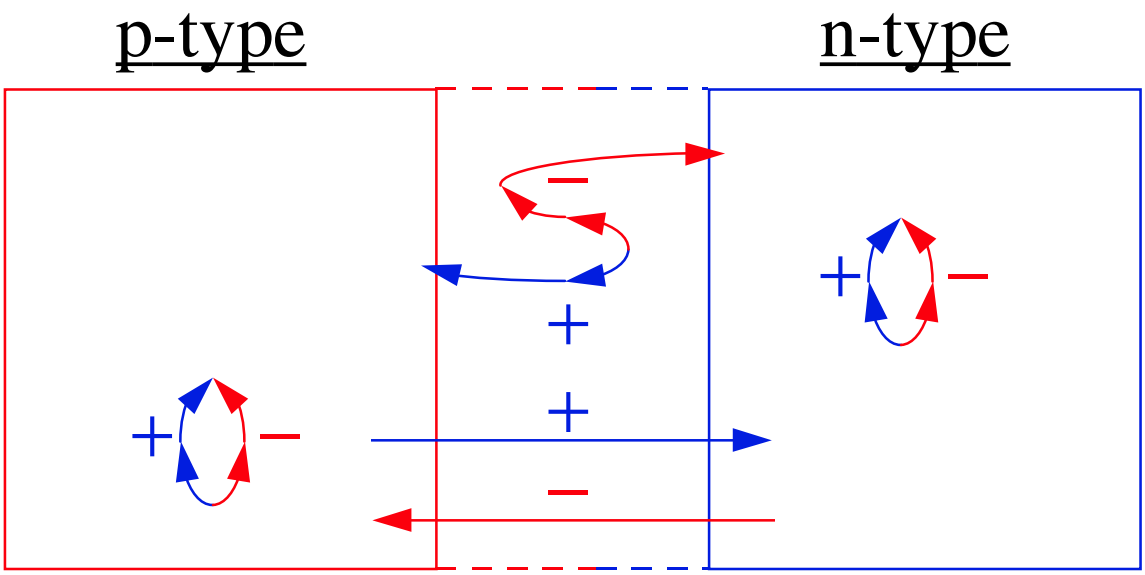
The pn junction

- Bring p and n-type Si into contact.

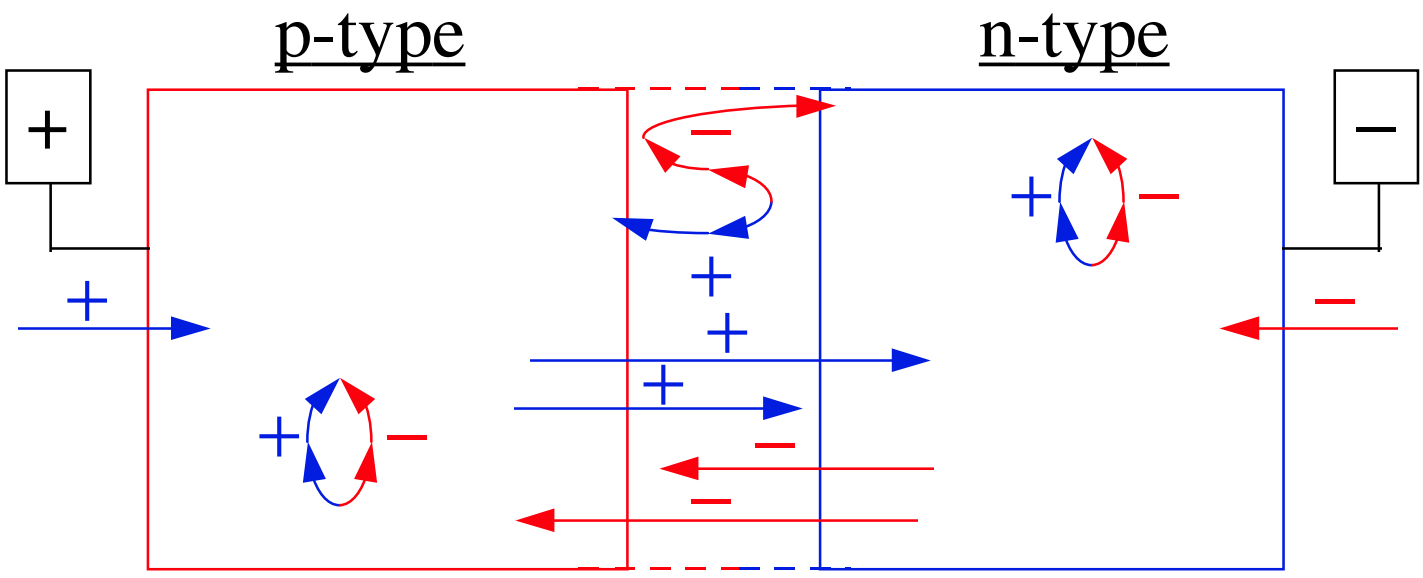


Dynamics of pn junction

- No applied voltage.

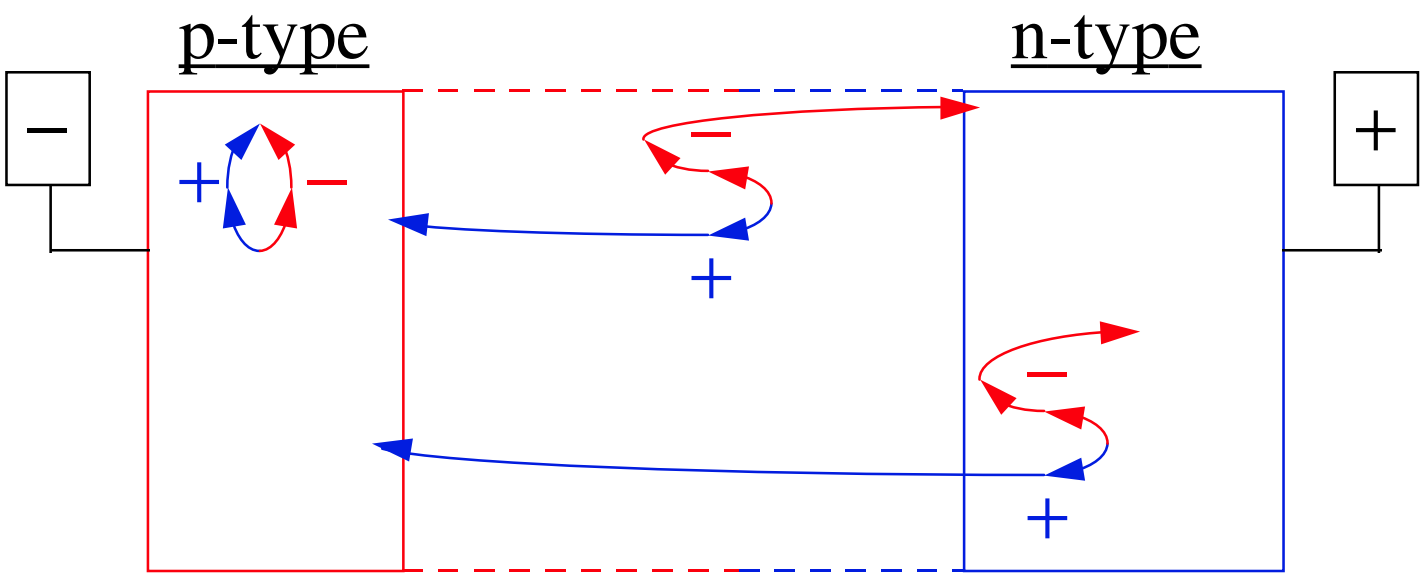


- Forward bias.



Dynamics of pn junction cont.

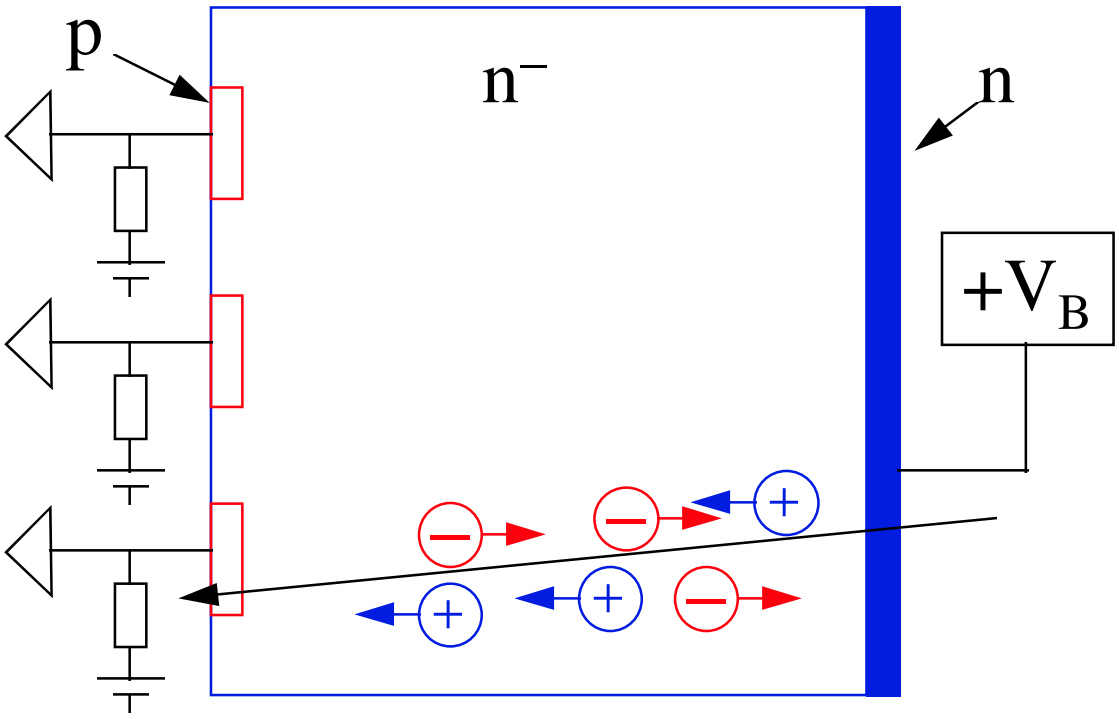
- Reverse bias.



- Use of reversed bias pn junction allows reduction of “noise” (thermally generated current) while maintaining size of charged particle signal.
- A silicon detector becomes feasible.

Silicon detectors, take two

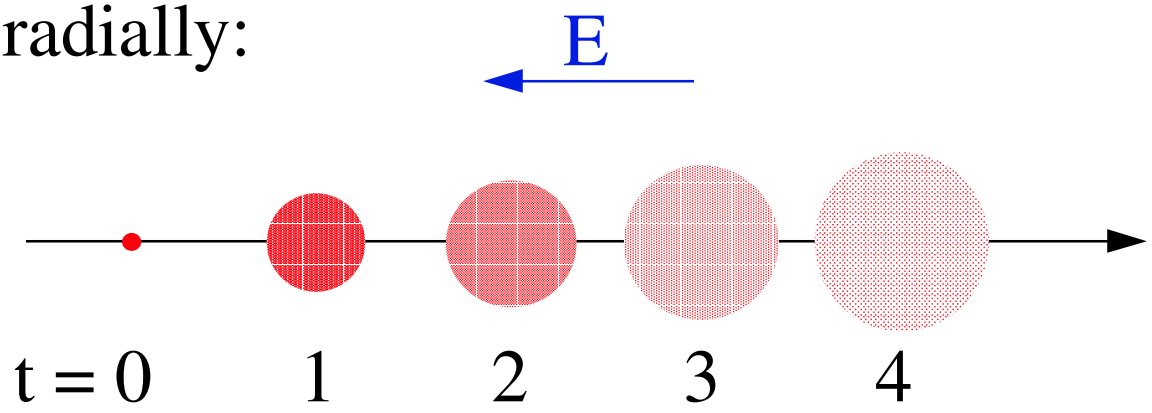
- APS/microstrip detector.



- Signal to noise ratio respectable.
- Position information from location of “hit” pixel/strip.
- Improve accuracy by centroid determination (measuring spread of charge over neighbouring pixels/strips).

Charge transport in silicon

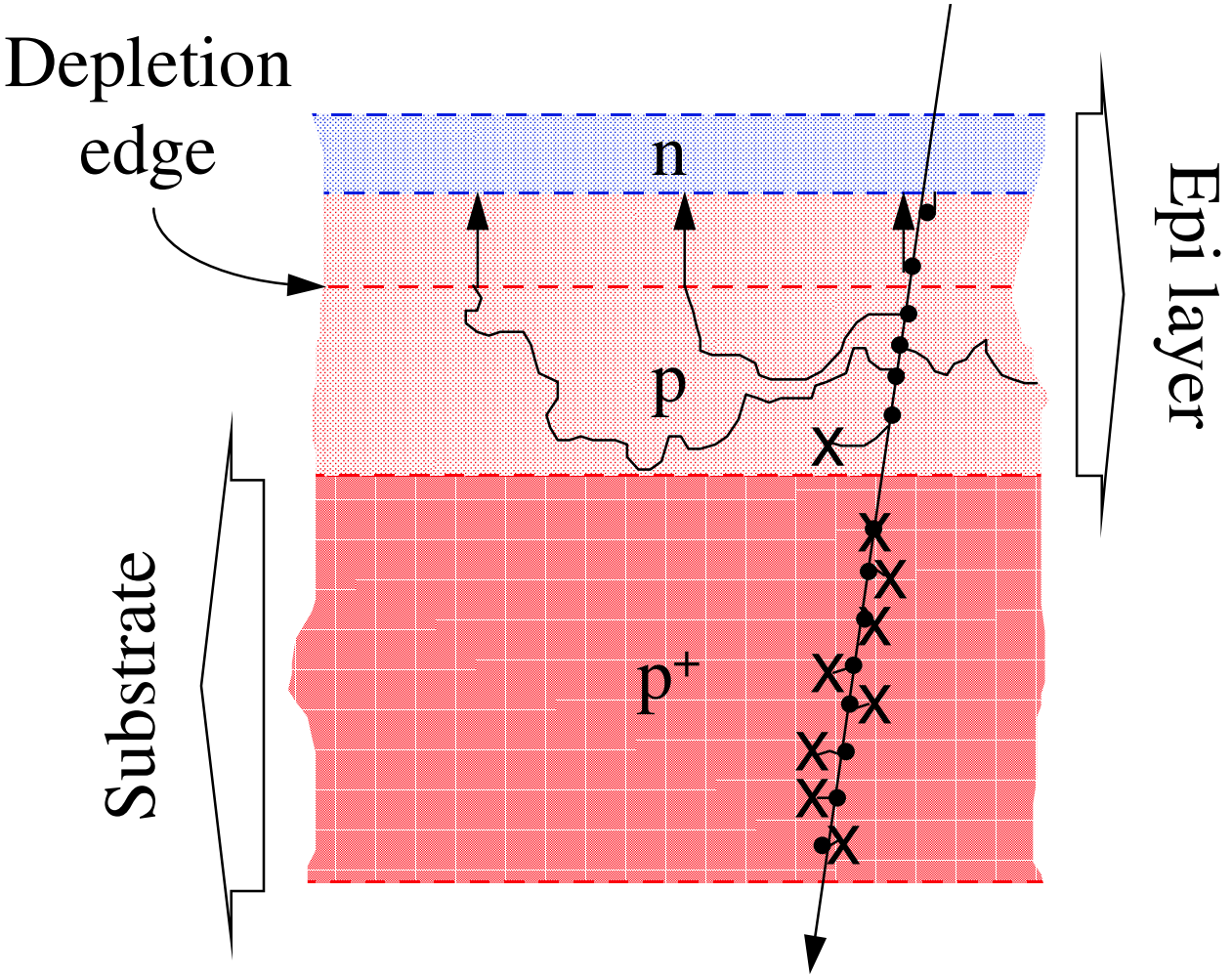
- Charge moving through silicon diffuses radially:



- For typical field and carrier mobility, charge radius 6µm after drifting 135µm.
- Requires lots of silicon to get good charge spread and hence allow centroid determination with respectable pixel sizes.
- Alternative charge spreading mechanism so far only applied to CCDs, but in principle applicable to APSs, microstrips...

The epitaxial layer

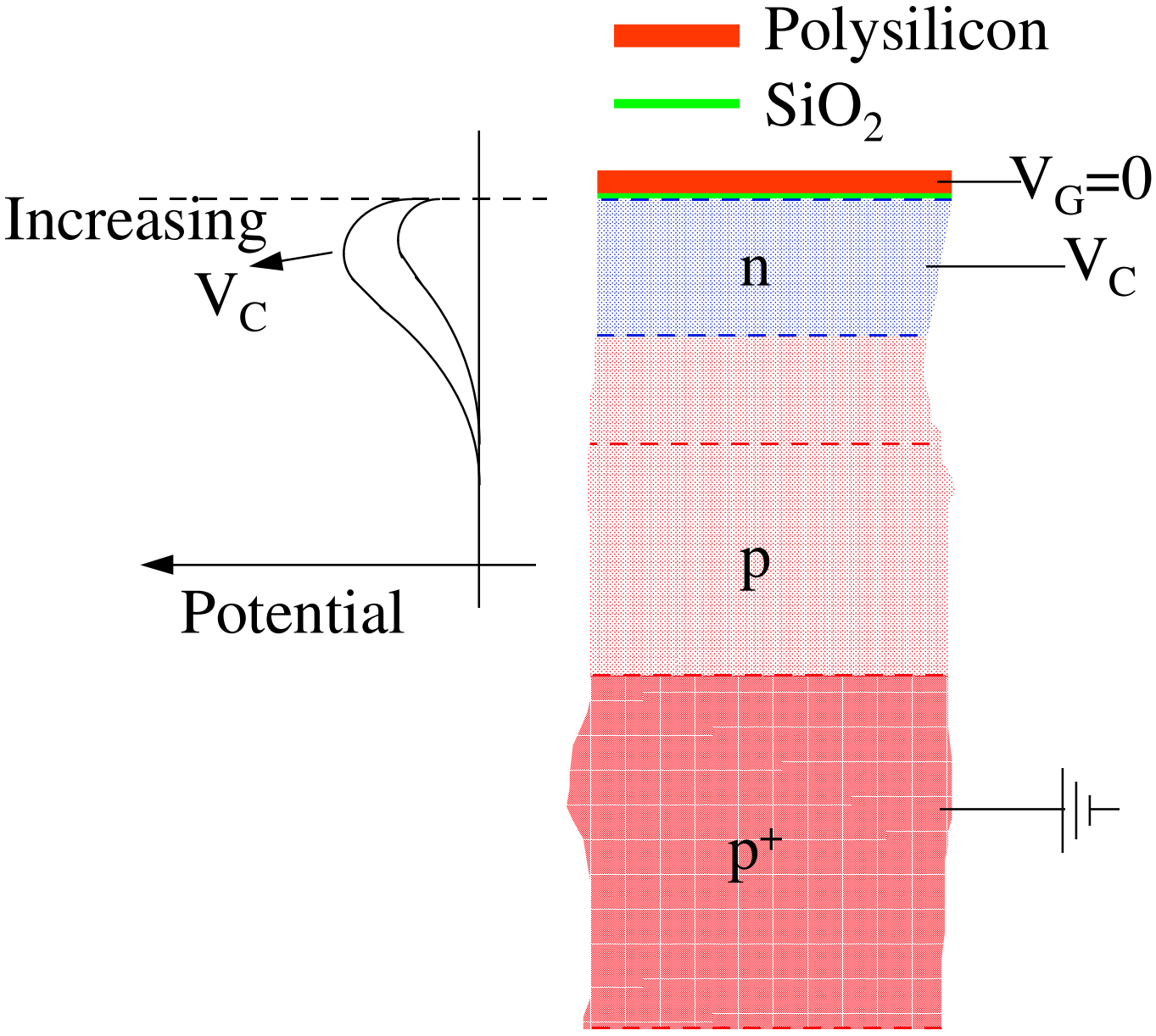
- Grow high ρ epitaxial layer on (relatively) low ρ silicon wafer.
- Implant “epi” layer to give:



- Allows charge to spread, hence centroid finding with thin detectors.
- Precision < 0.1μm achieved with 20x20μm^2 pixels.

CCD construction

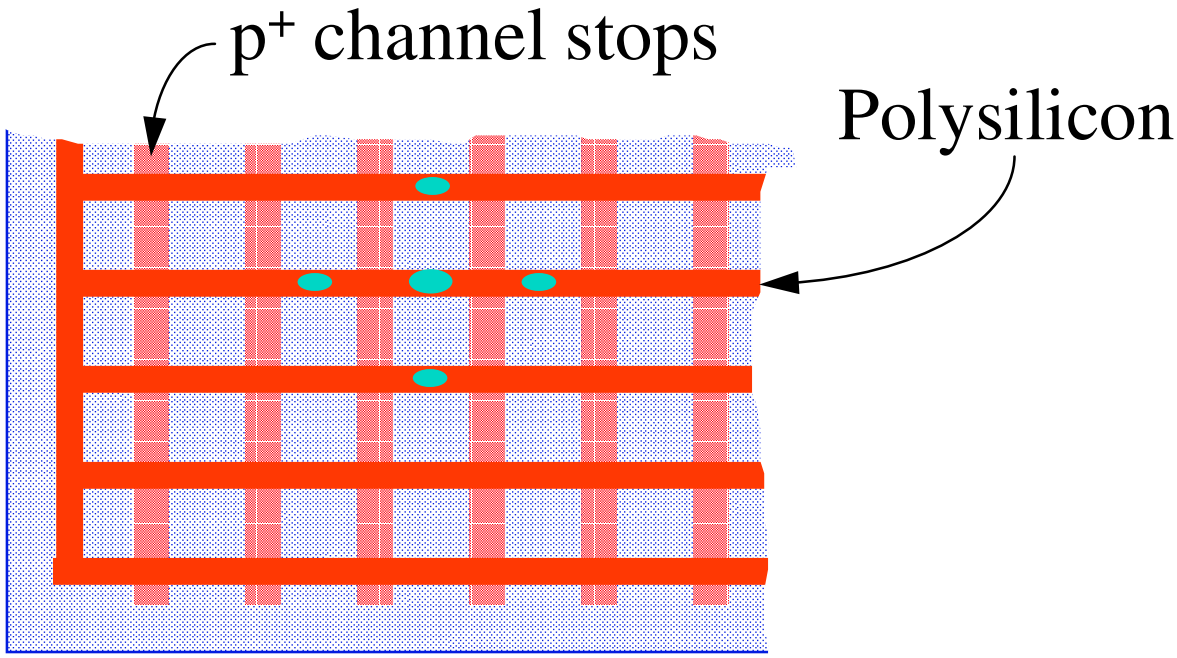
- Trapping electrons, first step:



- Electrons trapped inside “buried channel”.

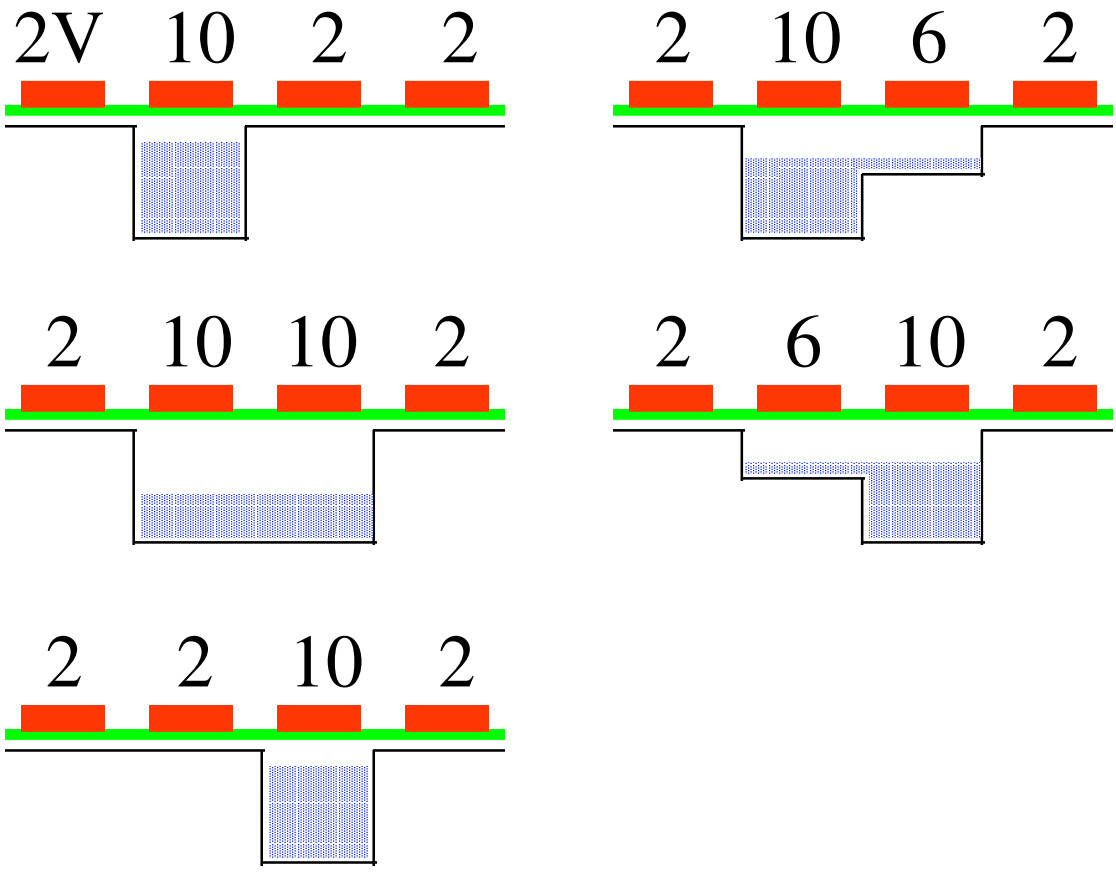
CCD construction cont.

- Trapping electrons, second step:



CCD readout

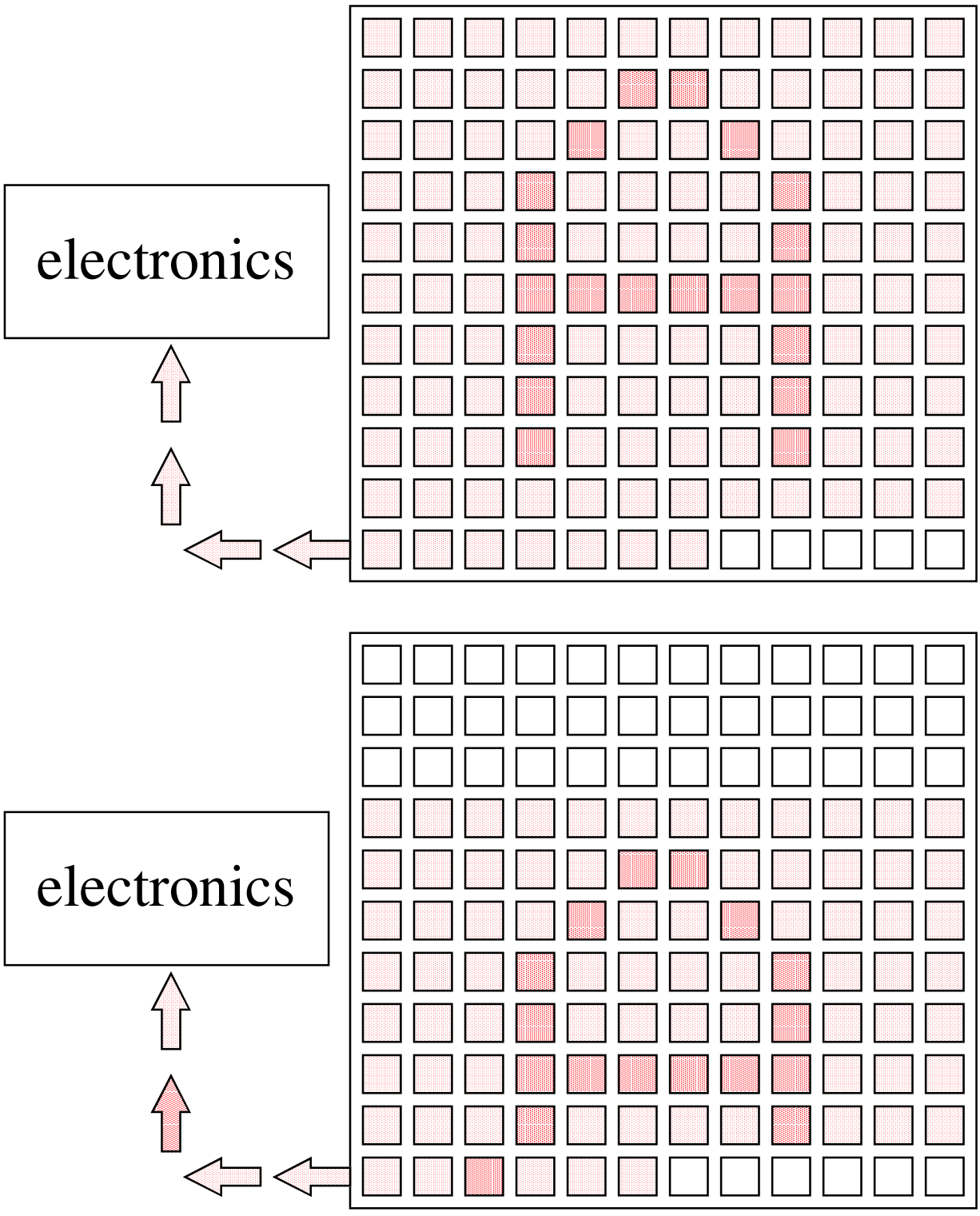
- Additional electrodes needed to transfer charge through CCD.
- Three phase system looks like:



- Use to shift rows down imaging (I) array.
- Use similar electrodes to shift charge across bottom of CCD, readout register (R register).

CCD readout cont.

- Schematic readout of CCD image:



CCD pros and cons

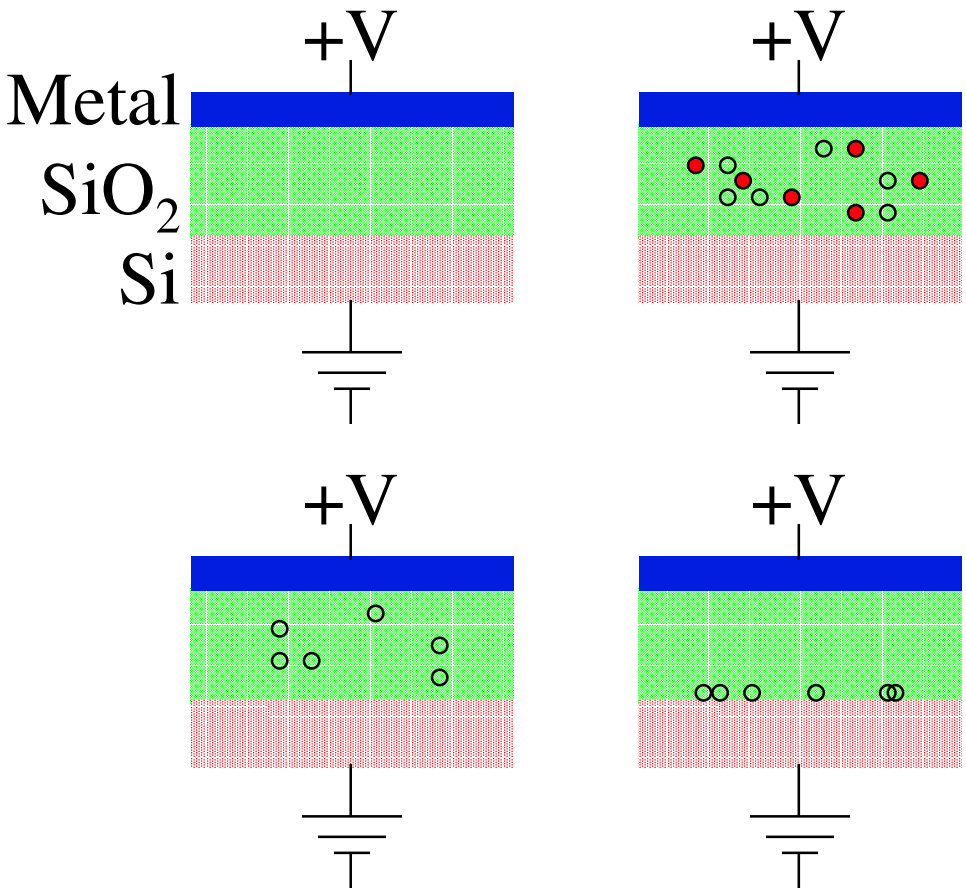
- The CCDs readout procedure is:
  - Its biggest strength; minimal amount of material associated with each pixel.
  - Its biggest weakness; readout slow and charge moves through ~ cm of silicon with concomitant risk of charge loss, particularly as silicon suffers radiation damage.
- Where readout speed at a premium and/or severe radiation damage likely, use APSs (ATLAS).
- Where can cope with slower readout and radiation levels tolerable, get better performance by using CCDs (e^+e^- linear collider).

UK R&D on CCDs

- Address two main problems of CCD based detectors:
- Readout speed - Aim to get readout of R register running at 50MHz. Note, have 50 MHz 10V drive pulses and are trying to measure ~ mVs! (RAL)
- Radiation damage - Carry out systematic studies of effects of radiation damage and how these can be ameliorated. (Liverpool)

Radiation damage, photons

- $E_\gamma > 10eV$, electron hole pairs created in SiO_2
- Some proportion (2% to 80%) trapped at Si/SiO^2 interface.
- Causes “flat band” voltage shifts.



Radiation damage, photons cont.

- $E_\gamma > 250keV$, photons can displace Si atoms from their lattice sites (need ~ 20eV to do this).
- Gives rise to point defects:
  - "Interstitials" - atoms stuck between lattice sites.
  - "Vacancies" - empty lattice sites.
- Former benign, latter move to form complex which introduces extra energy levels.
- Can trap electrons, or lead to increased thermal generation of e/hole pairs.

Radiation damage, protons

- 100 Si atoms displaced per mm at 1MeV, ~ 1 per mm at 1GeV.
- Non-ionizing energy loss (NIEL) much greater than for photons.
- In addition to point defects can cause damage clusters, i.e. disturb relatively large regions within the crystal.
- Large number of traps can be generated with many new energy levels.

Radiation damage, neutrons

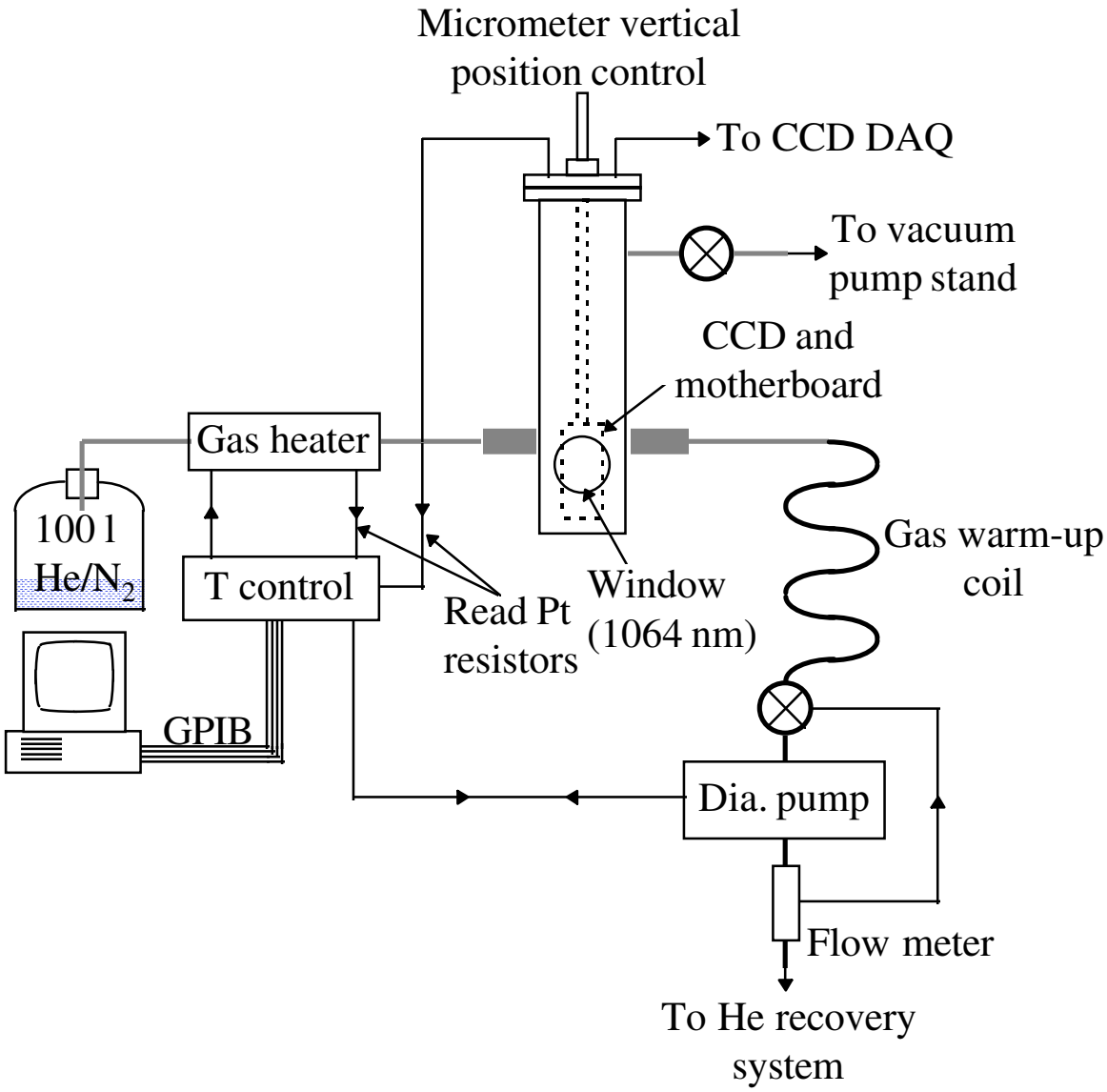
- Smaller cross-section for interaction with Si nucleus.
- Can induce nuclear disintegration, leading to large damage clusters - sizes up to few 10nm.
- Data on effects on CCDs sparse.

Coping with radiation damage

- Engineer to minimize effects of charges trapped at Si/SiO_2 interface (guard rings, choice of oxide thickness...)
- Reduce thermal generation of e/hole pairs by working at low temperature.
- Change typical trapping times and time within which charge released from traps by changing temperature.
- Some hints that very low temperature operation may produce improvements.

Liverpool tests

- Schematic of Liverpool test rig:



- Study charge transfer inefficiency as function of radiation species and dose.
- Look at behaviour at low temperature ($T \geq 40K$).

Summary

- CCDs are an interesting addition to armoury of charged particle detectors.
- There are gaps in our understanding of the effects of radiation on CCDs, particularly those due to neutrons and particularly at low temperatures.
- Liverpool aim to plug the gaps, with the goal of being major players in construction of LC vertex detector.
- In addition, potential applications in astrophysics, possible collaboration with JMU.