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Silicon Detectors and Readout Electronics

Peter Fischer, ziti, Universität Heidelberg

Content of the Lecture (sorted by subject)

- Introduction:
  - Applications of silicon detectors
  - Requirements, measured quantities
  - Interaction of particles & photons in silicon
- Detectors
  - pn diode and more general structures
  - Signal induction and spatial resolution
  - Detector Types (strips, pixels, CCDs, MAPS, APDs, SiPMs,...)
  - Manufacturing technology
  - Radiation damage
- Readout Electronics
  - Principle (charge amplifier, shapers)
  - Amplifiers (transistor level), Noise
  - Readout architectures, Trigger,…
- Sample Applications & Projects

Literature

- Semiconductor Devices
  - S. M. Sze, Wiley, ISBN 0471874248
- Semiconductor Radiation Detectors
  - G. Lutz, Springer, ISBN 3540648593
- Semiconductor Detector Systems
  - H. Spieler, Oxford Science Publications, ISBN 9780198527848
- Pixel Detectors
  - Rossi/Fischer/Rohe/Wermes, Springer, ISBN 3540283323
- Einführung in die Halbleiter Schaltungstechnik
  - H. Göbel, Springer, ISBN 3540234454
    (With a CD with many nice Applets)

Organization

- Lecture:
  - Wednesday, 11:15, here
  - Slides will be on ‘uebungen’ web site or public site (tbd)
- Exercises:
  - Wednesday, starting in ~ 2 weeks
  - Held by me
- CP:
  - 6, (accepted for MSc Physics and MSc Computer Engineering)
- Examination:
  - Oral examination, date can be agreed

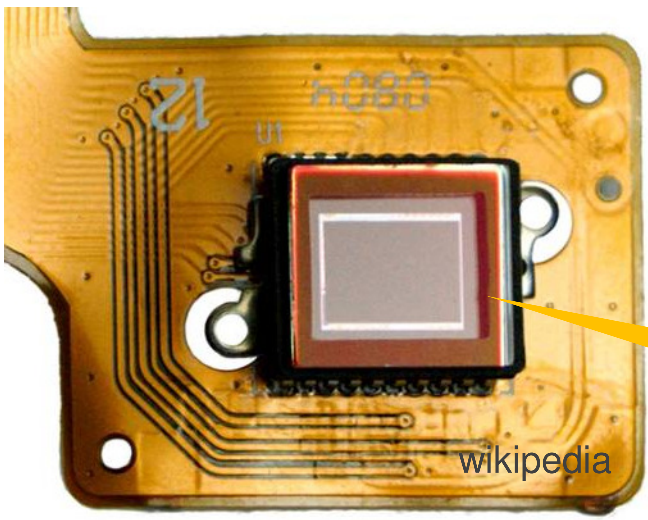
Introduction / Motivation

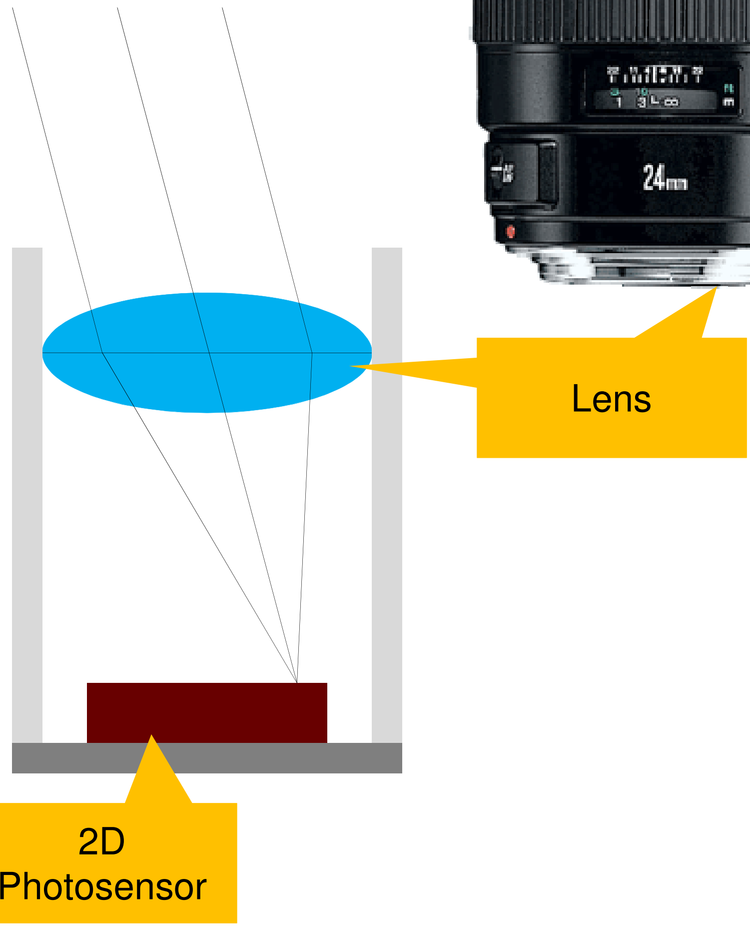
Cameras for the Invisible

Content

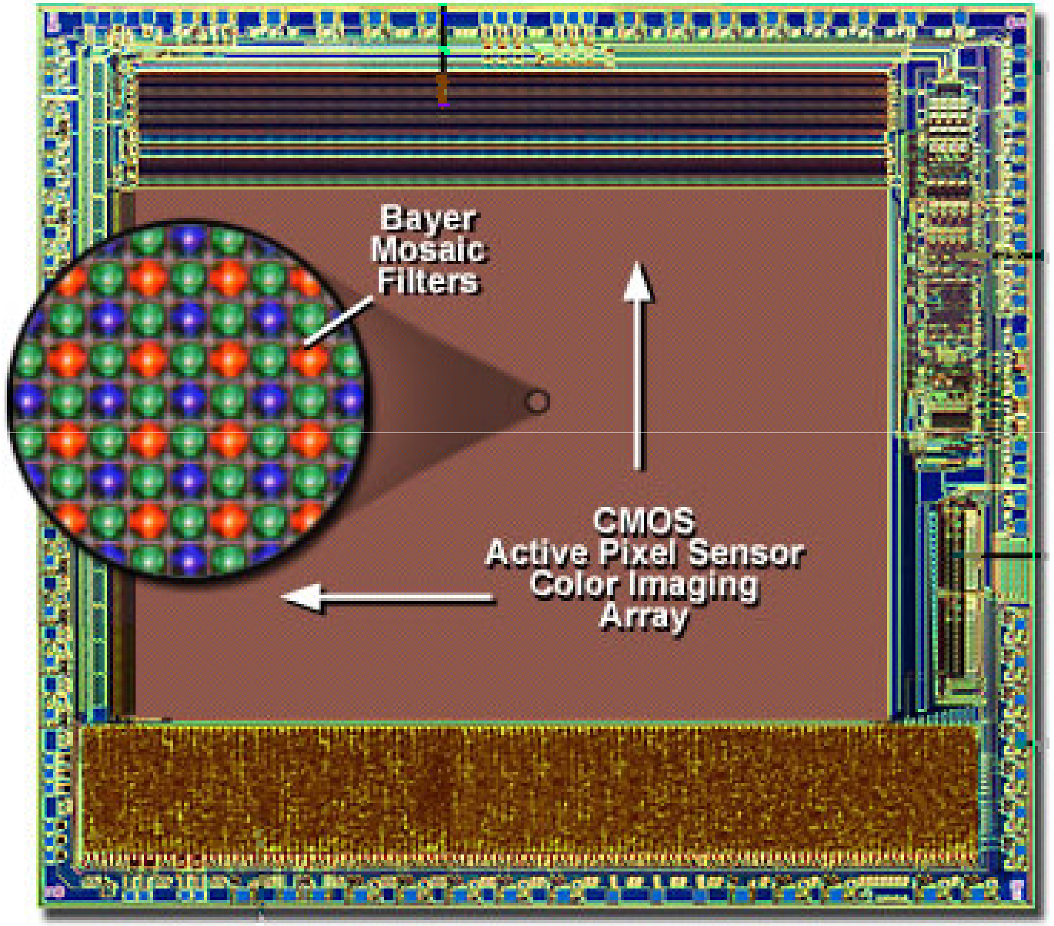
- The ‚normal' digital camera
- Basics:
  - Photons & other Particles
  - What do they do in silicon?
  - How does a silicon detector look like?
- Some types:
  - Pixel
  - CCDs
  - DEPFET
  - others…
- Applications:
  - Astronomy, Medicine, Material Science, Biology, Physics,…

What‘s in a normal camera?

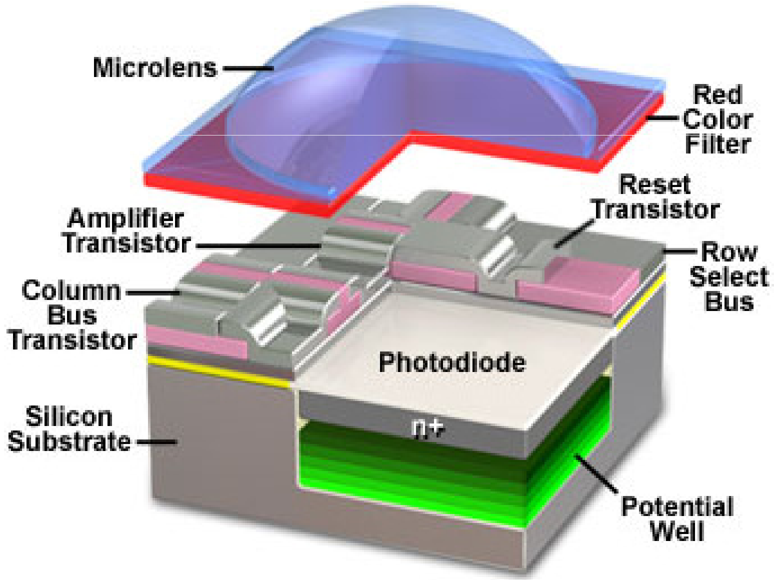




The ‚CMOS' Photo Sensor

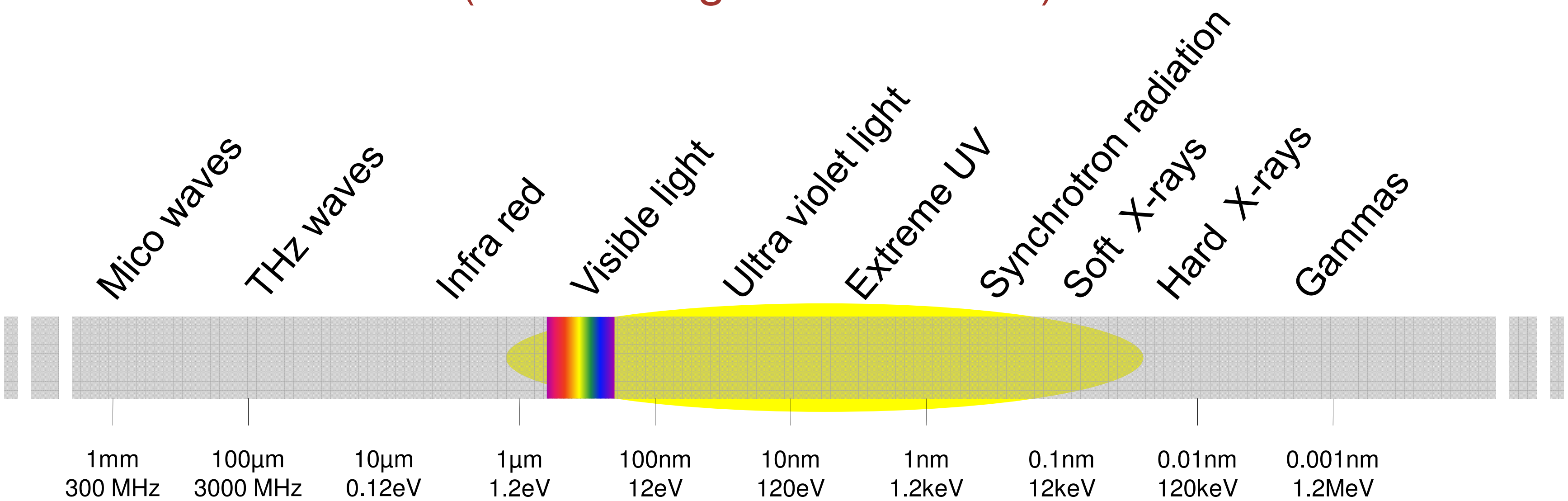


http://micro.magnet.fsu.edu/primer/digitalimaging/cmosimagesensors.html



Types of Radiation

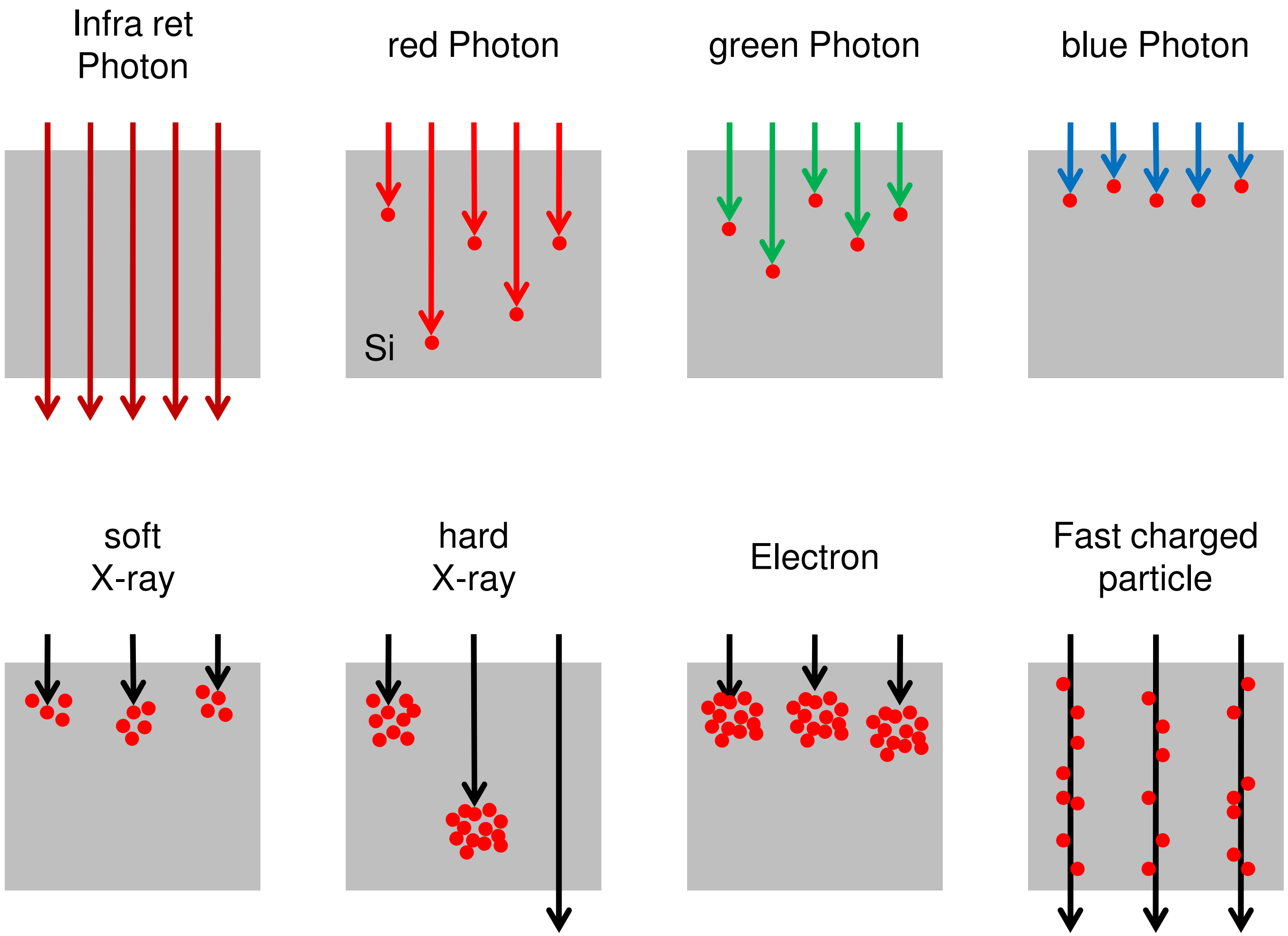
- Photons (electromagnetic radiation)



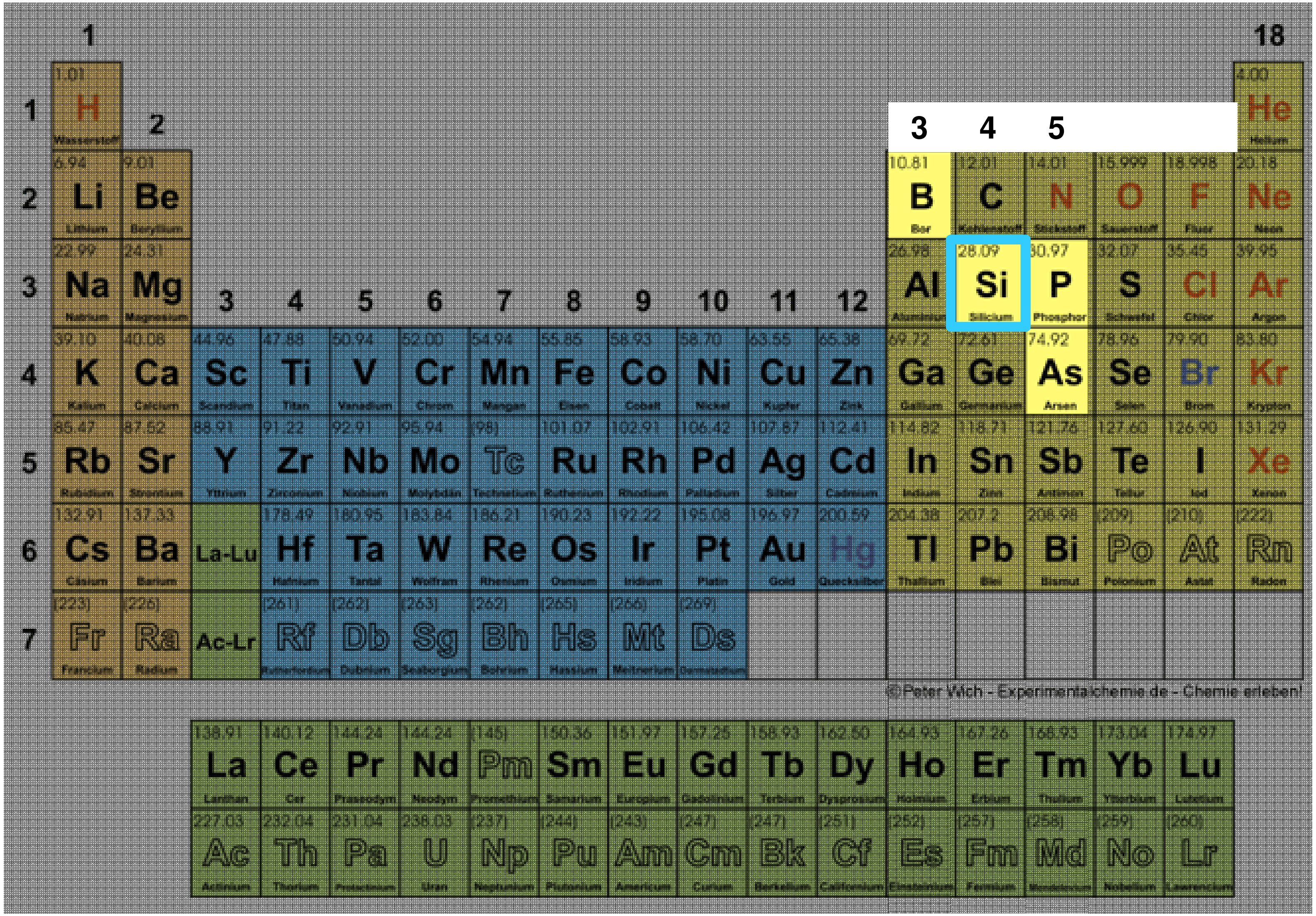
- Electrons (radioactive decays, electron microscope)
- Fast charged particles (physics, cosmic rays)
- Ions, neutrons, neutrinos,…

Radiation in Silicon

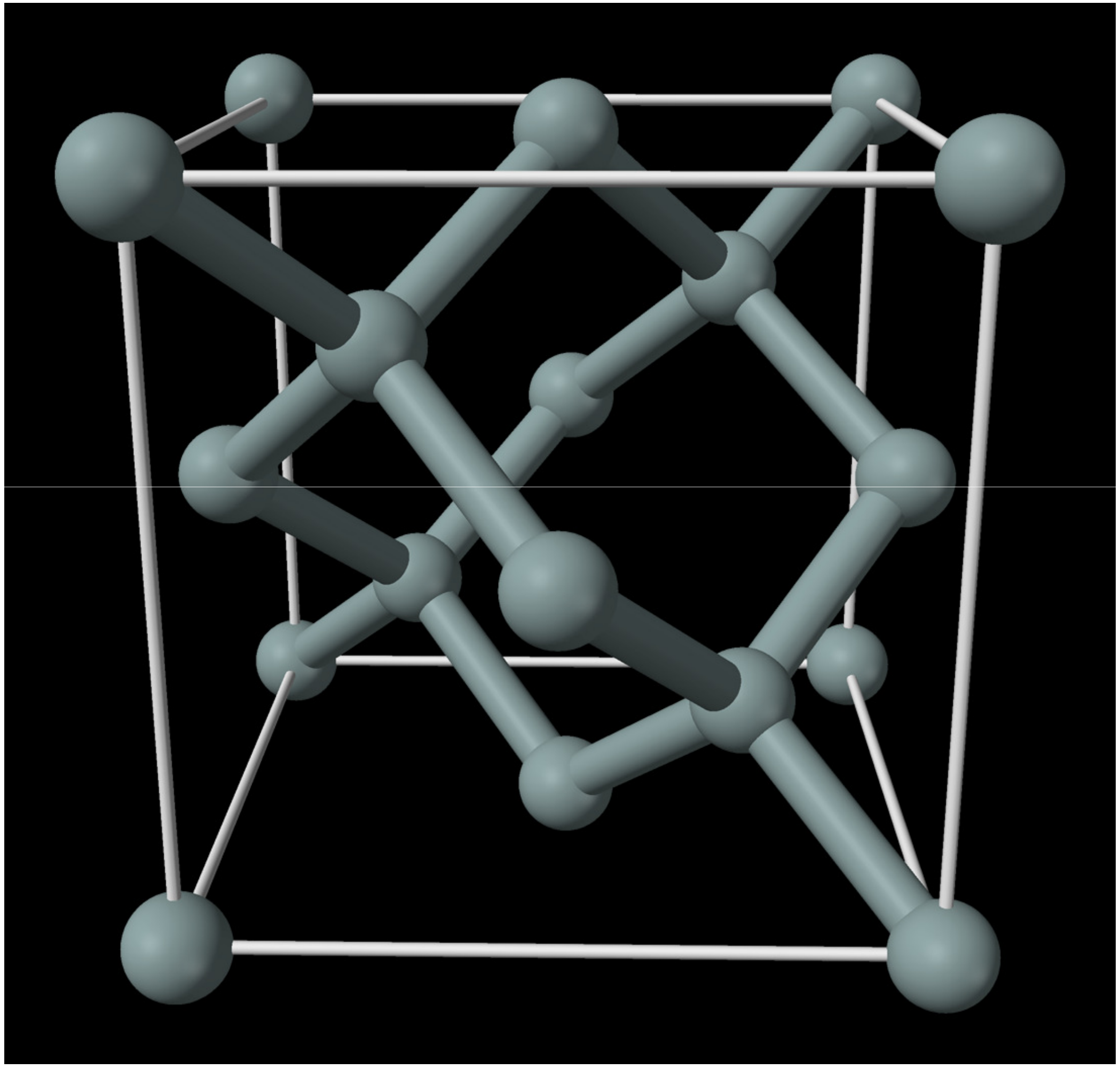
- Atoms are ionized (electrons • are knocked off the shell)



Silicon


1 18
2
3 4 5
H He
Li Be B C N O F Ne
Na Mg 3 4 5 6 7 8 9 10 11 12 Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba La-Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Ac-Lr Rf Db Sg Bh Hs Mt Ds
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
28.09
Silicium
©Peter Wich - Experimentalchemie.de - Chemie erleben!

Silicon Crystal



Face centered
Cubic lattice

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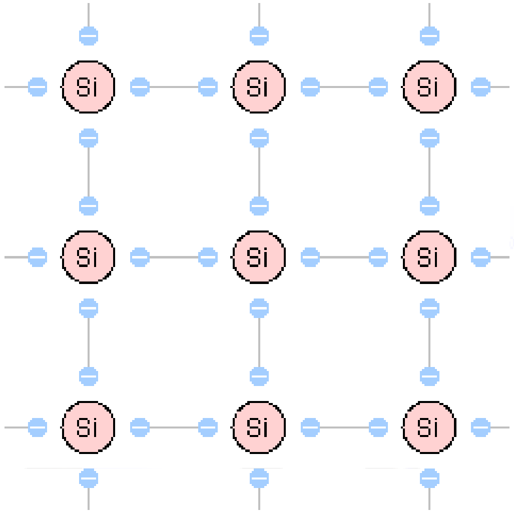
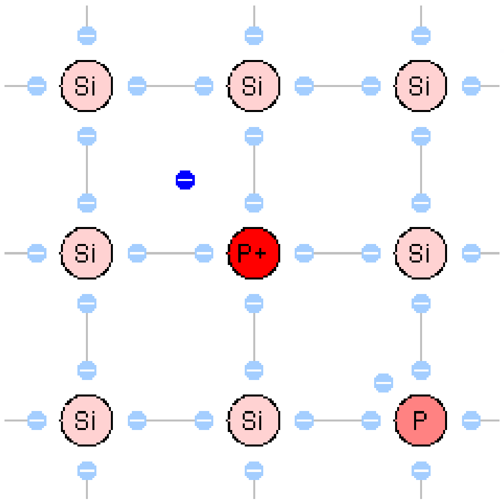
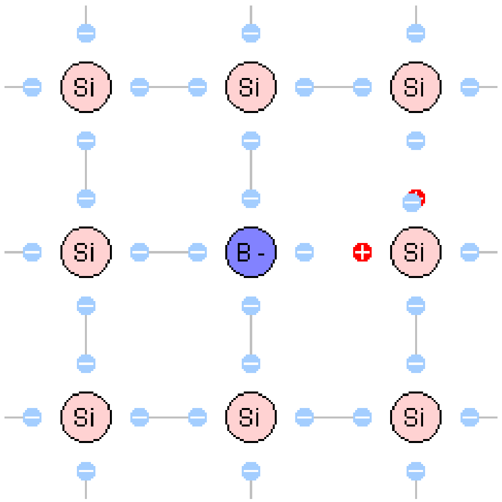
Silicon: Crystal & Doping



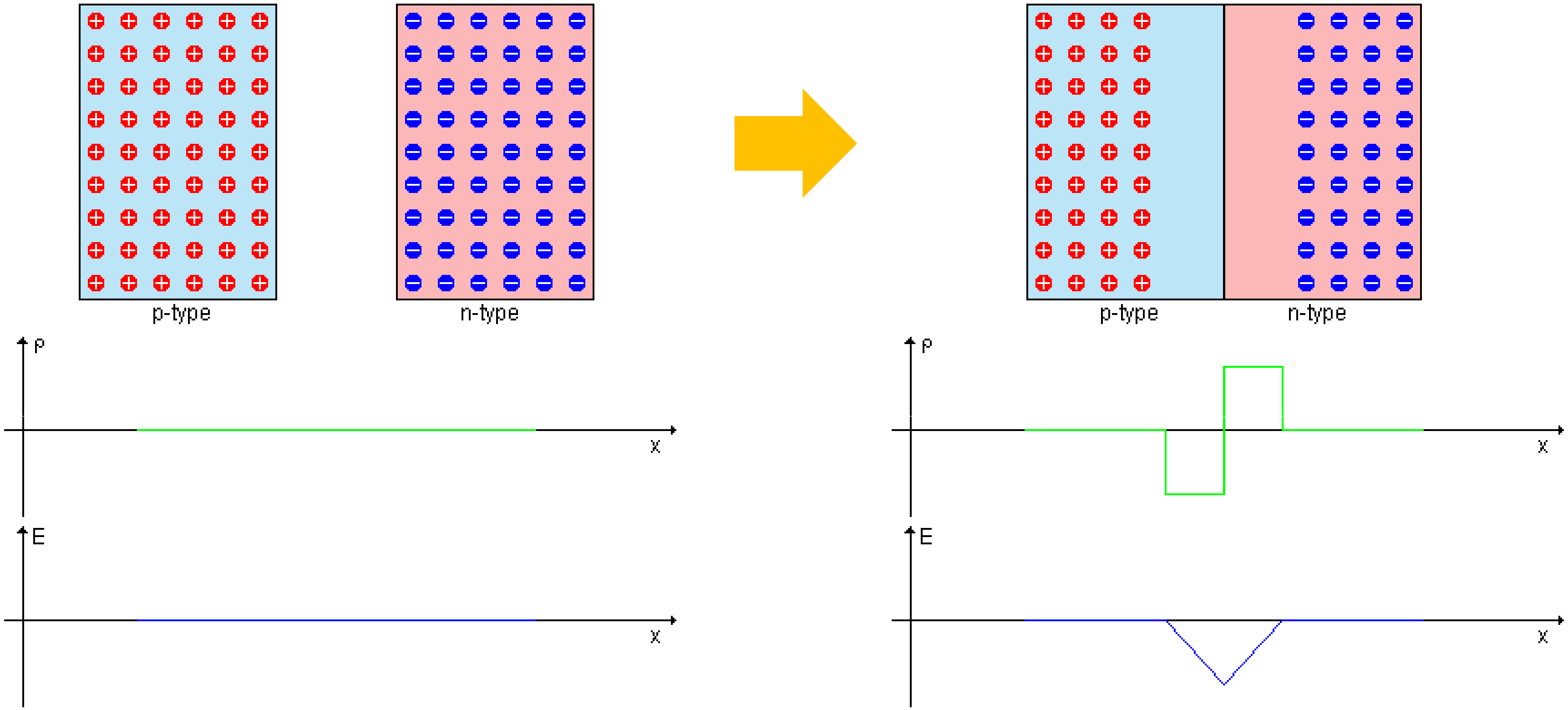
doping with
5-valued atoms:
- **N-conductor**
- Donators **positive**



doping with
3-valued atoms:
- **P-conductor**
- Acceptors **negative**



The pn-junction (diode)



- A **depletion zone** with no charge carriers is created
- There is an **electric field**

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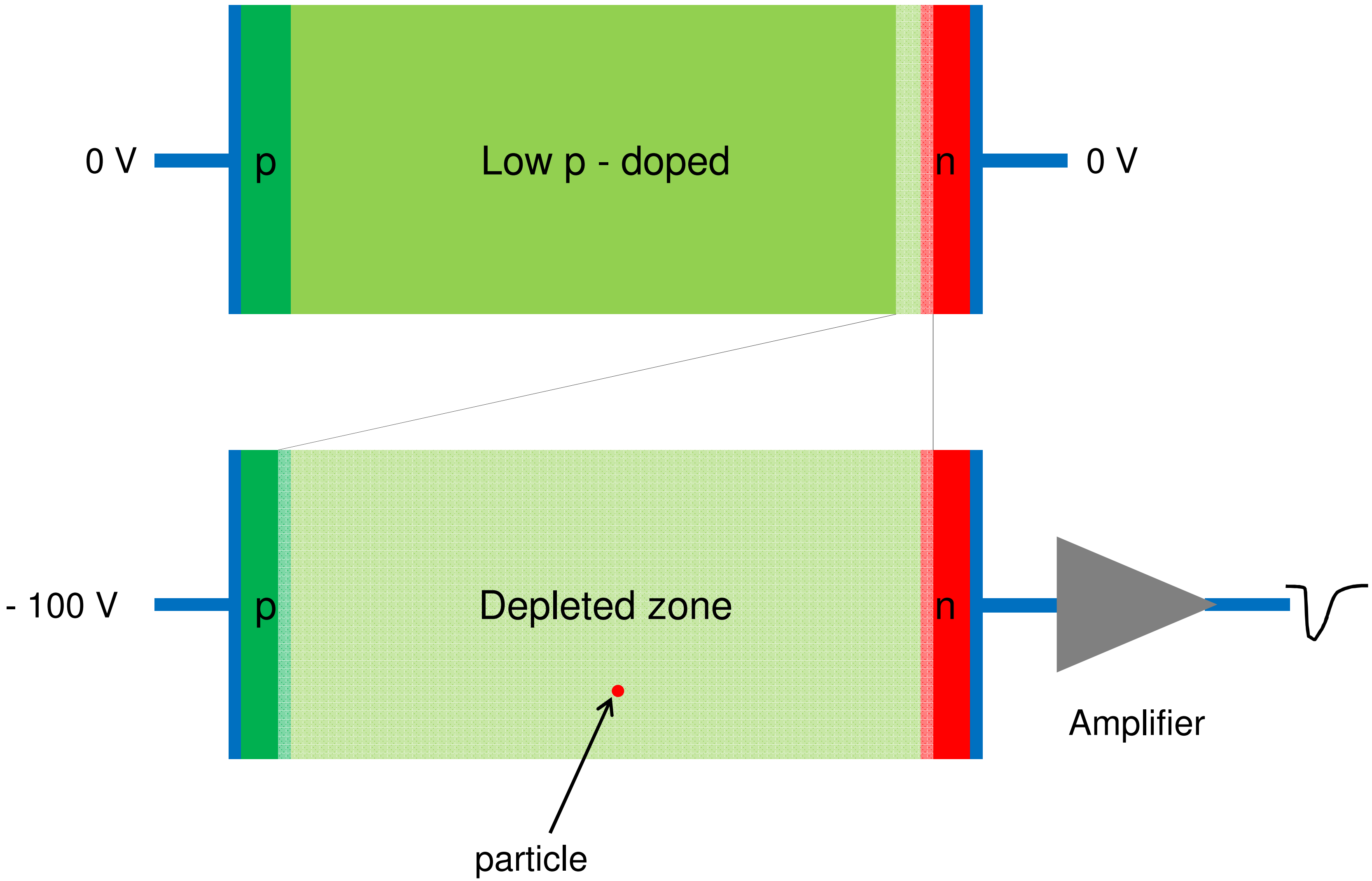
Signals in a pn-diode



Summary pn-diode

- By clever doping, a **depletion zone** is created
  With high external voltage (100V), it can be ‘thick’ (0.3 mm)
- There is a strong **E-Field** in the depletion zone
- Electrons (and holes), created by particles / light
  are separated and pulled to the electrodes
- They are detected with an **amplifier**
- Example: In 300µm silicon, we get for
  - Photon 1 electron
  - 10keV X-ray 2.800 electrons
  - Fast particle 18.000 electrons
- The electronic **noise** must be below this
- NB: electron deficiencies (holes) were omitted here
  We need them to ‘see’ the full signal!

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DETECTOR TYPES

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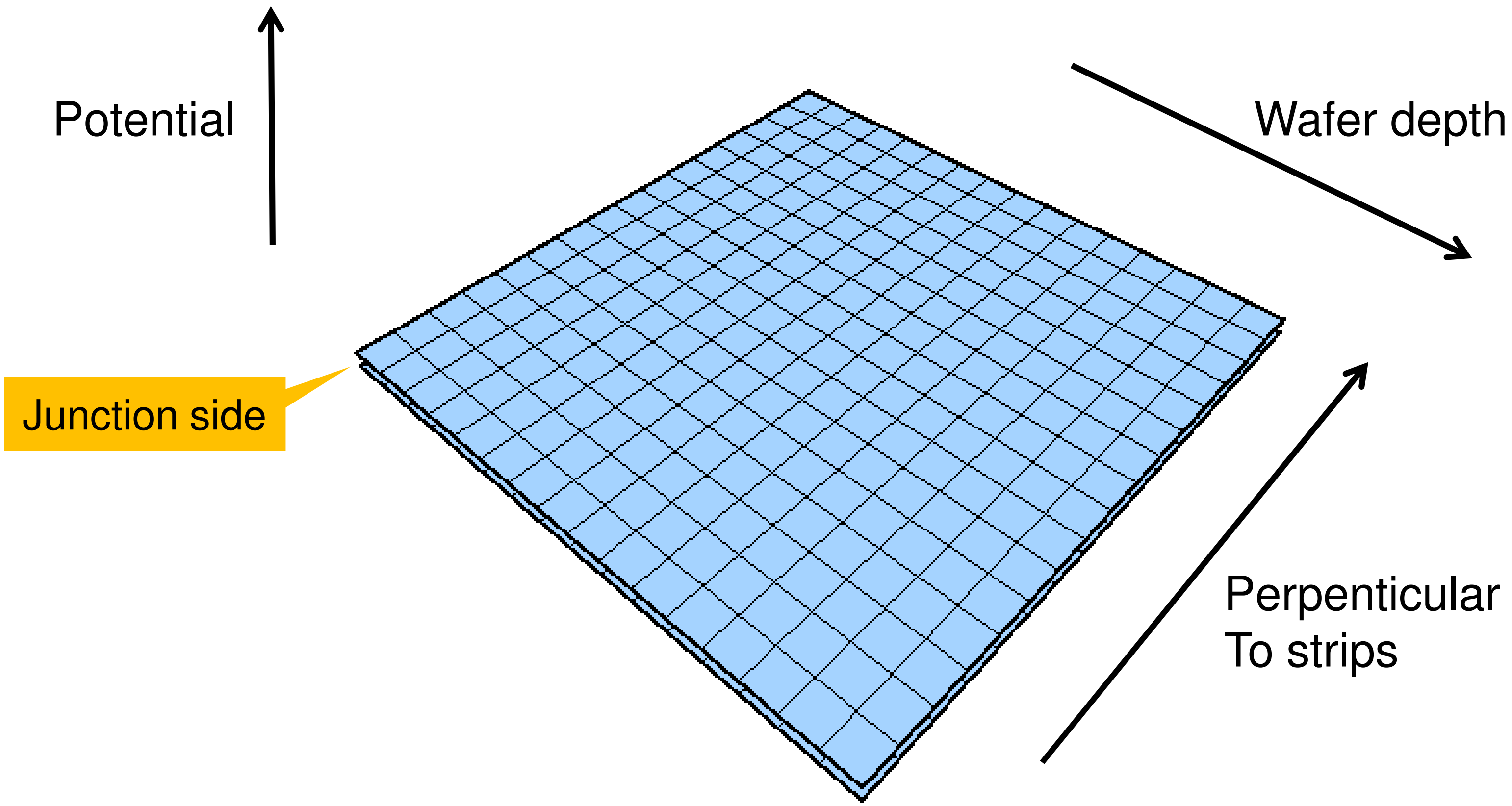
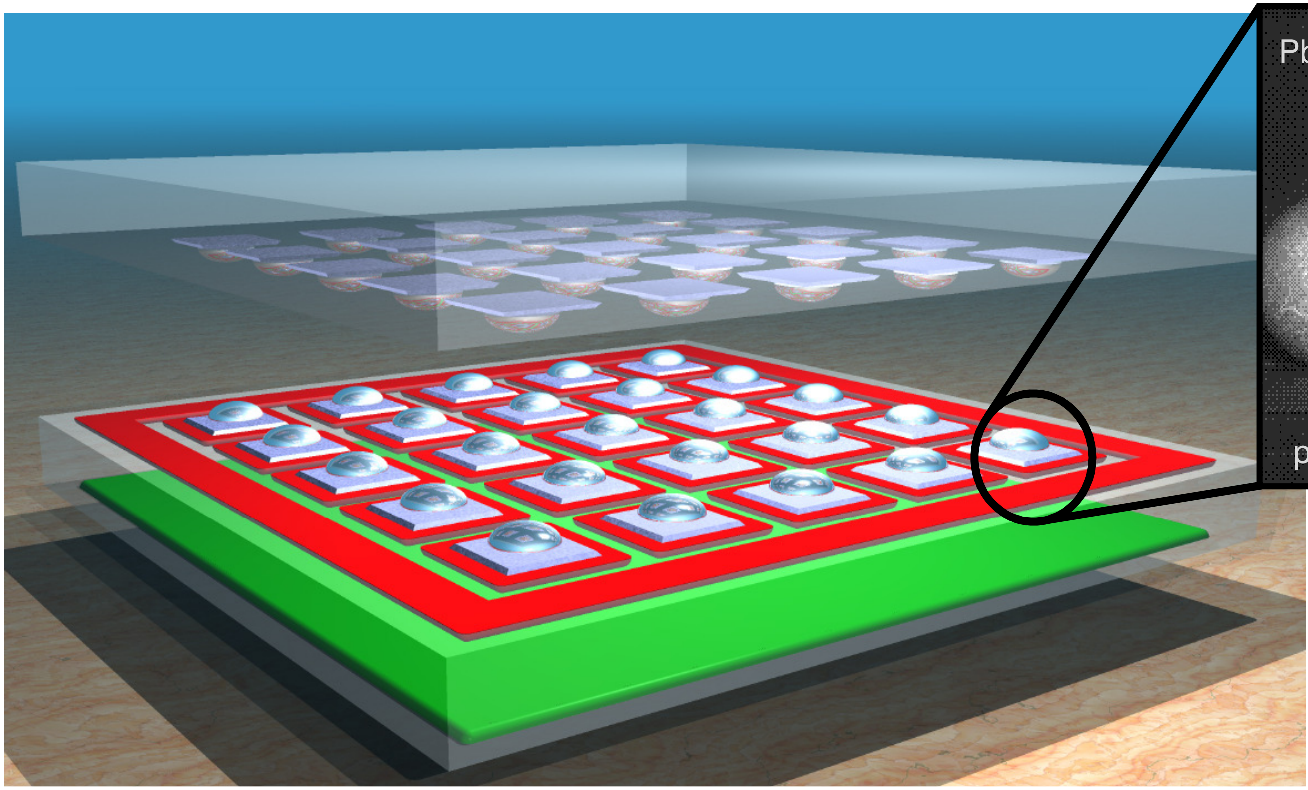
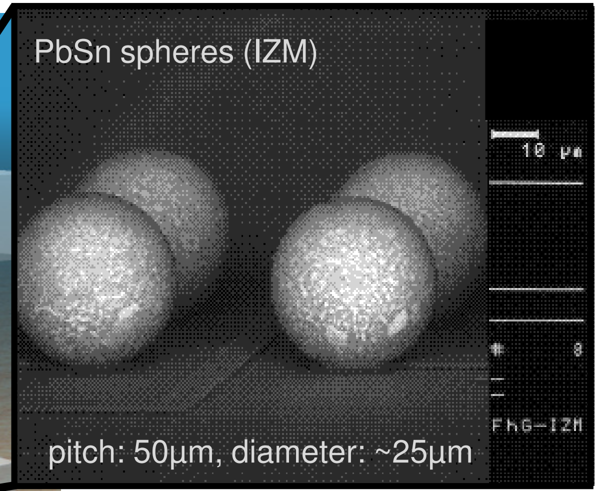
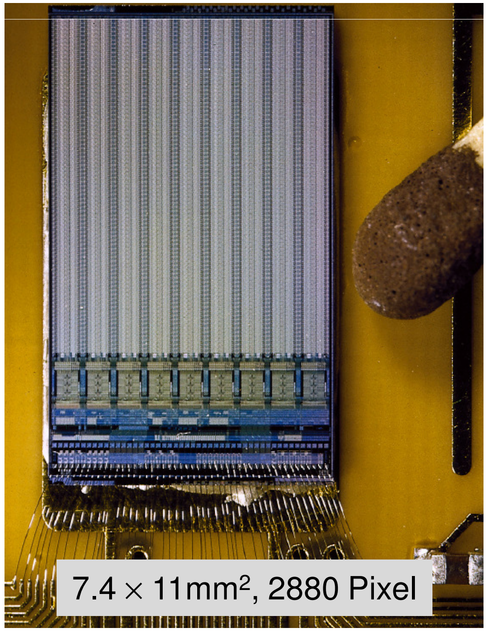
Animation of Normal Depletion



Hybrid Pixel: Chips + Detector (Flip Chip)



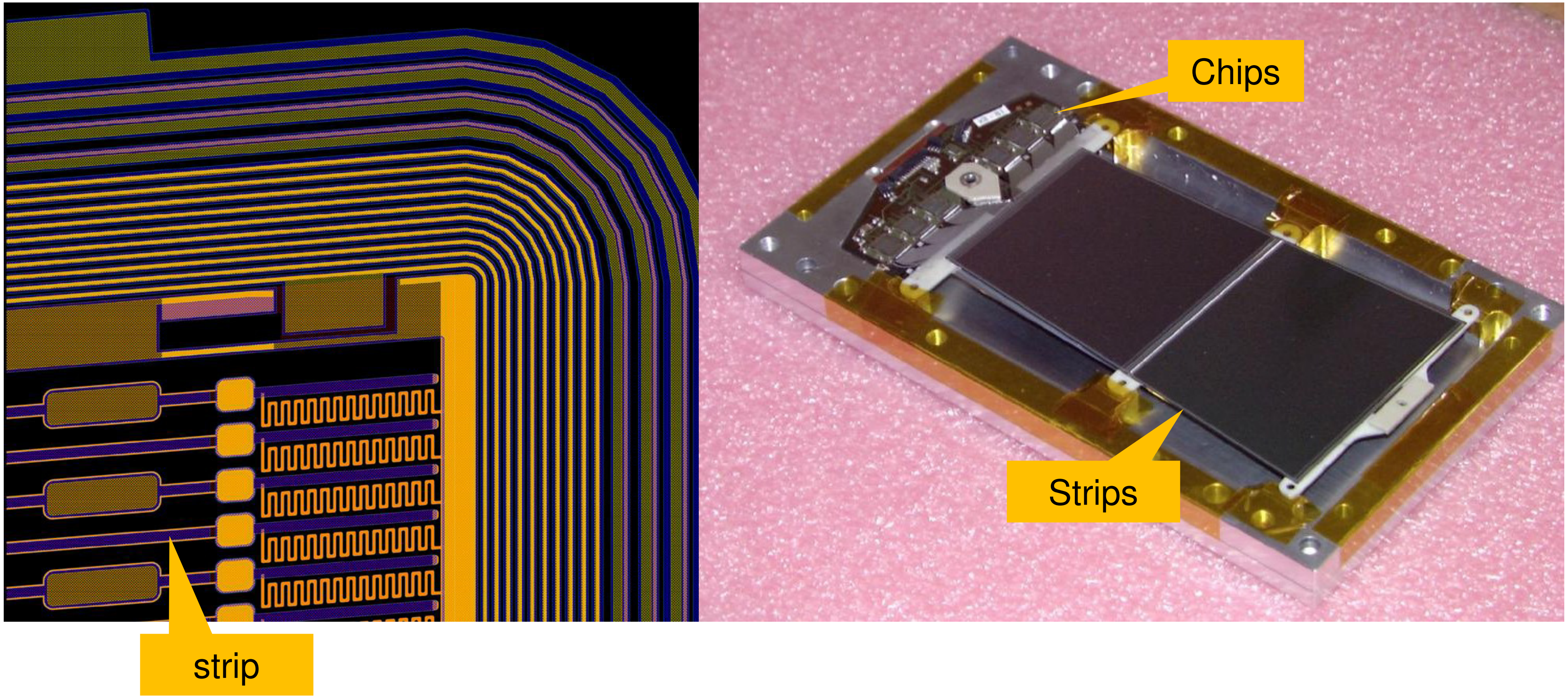




- Sensor: pn-diode with segmented electrode, also other materials, also gas
- Chip: Amplification & readout
- Interconnect: many ‘bump’ spheres
- Advantage: flexible readout, fast

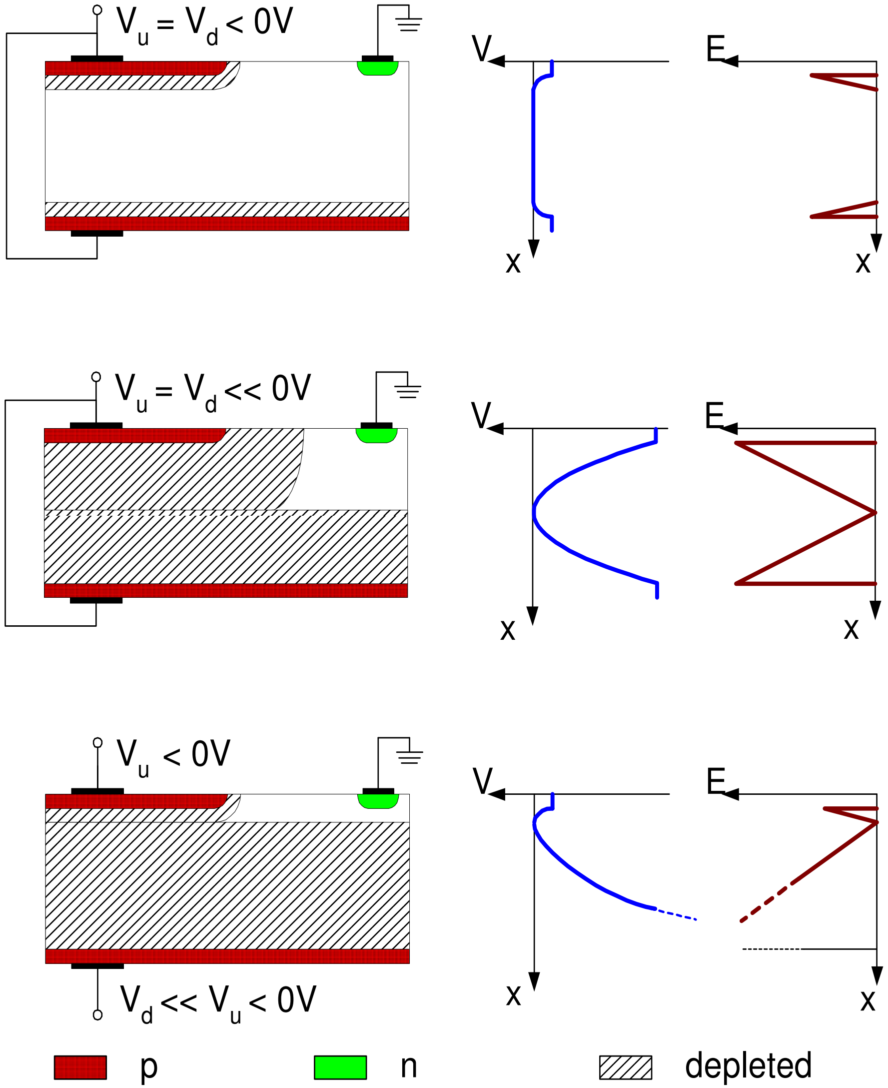
Strip Detectors

- One (or both) sides are segmented into strips (~50µm)
- Readout with chips ate the side
- Advantage: Few channels for high spatial resolution, fast



Fully depleted CCDs: Sideward Depeletion

- Depletion from **both sides**
- This gives a **potential minimum in the volume** (for electrons)
- With asymmetric voltages, the minimum can be moved just **below the surface**



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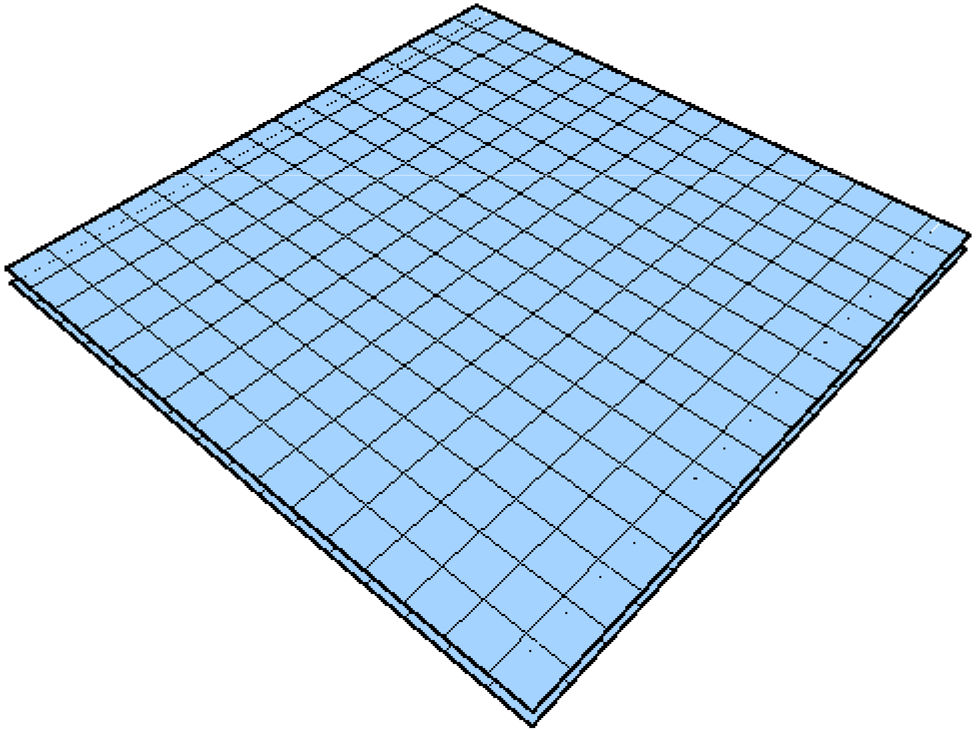
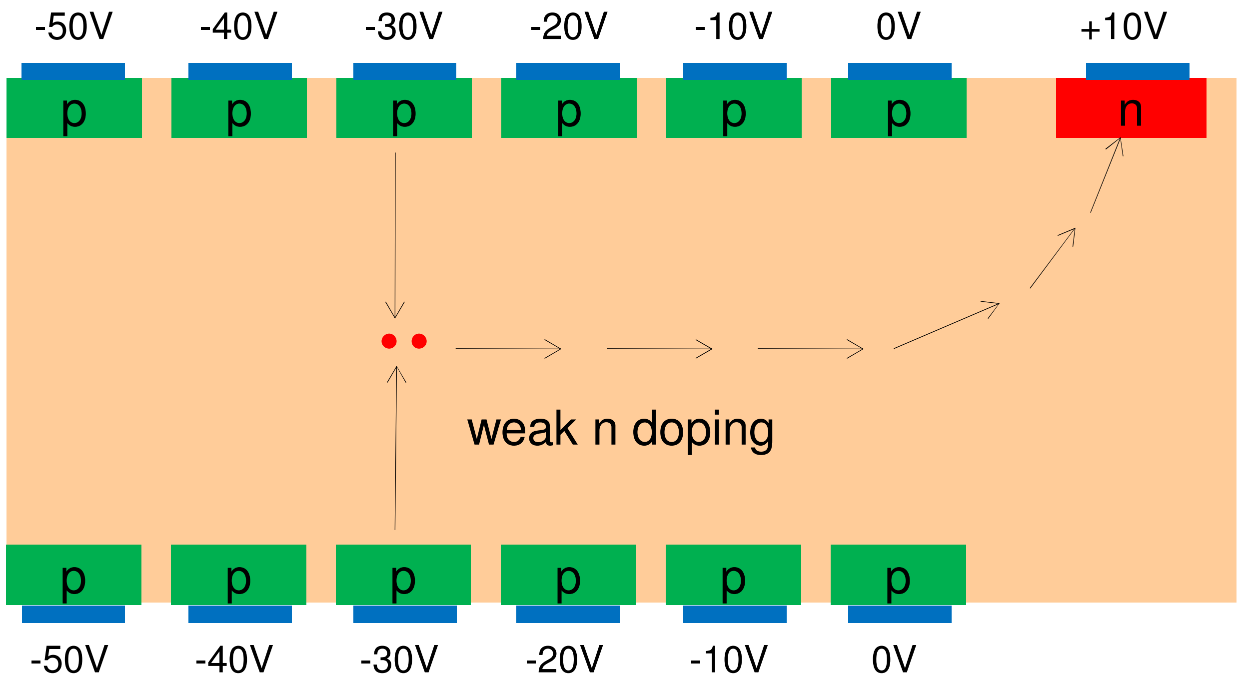
Animation of Symmetric/Assym. Sideward Depletion



Silicon Drift Detector

- Both sides are segmented
- Increasing potentials create a *lateral* field



- Advantages: few readout electrodes, no extra material in active area, very low noise (few e^-)

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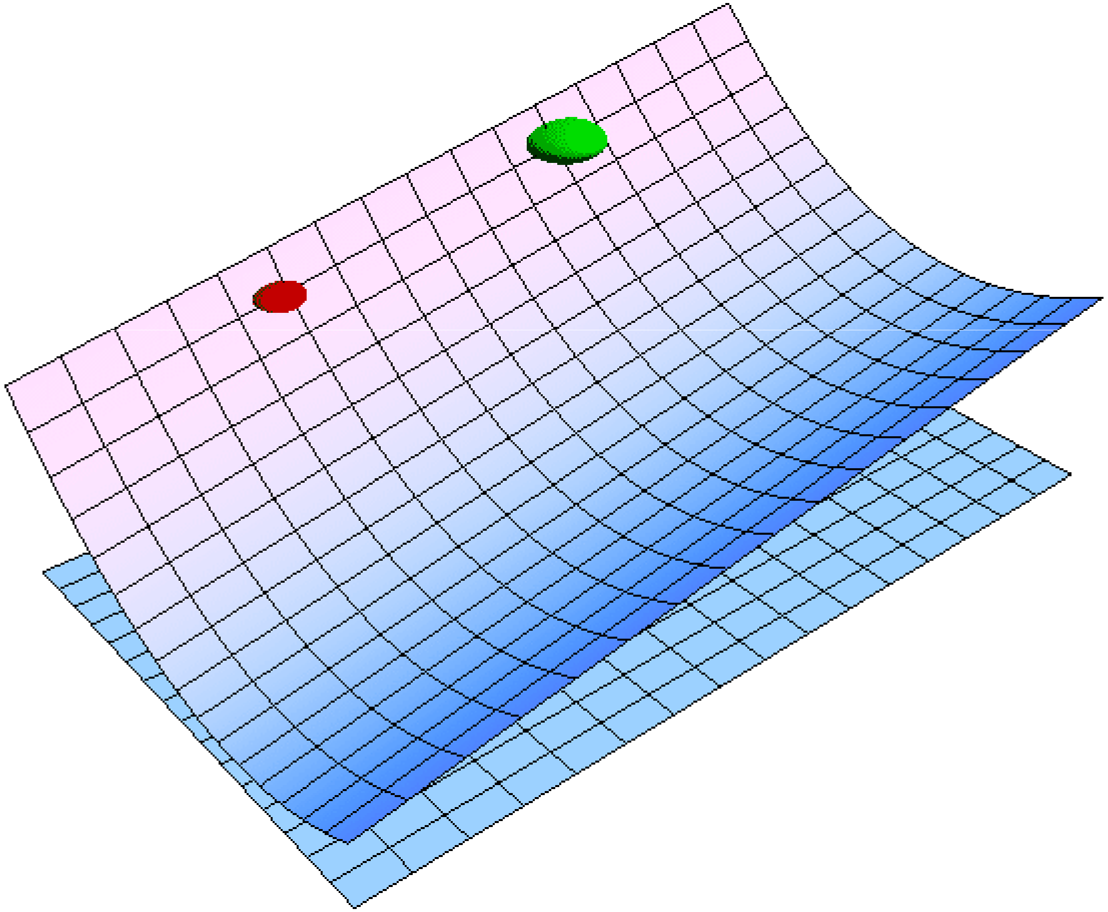
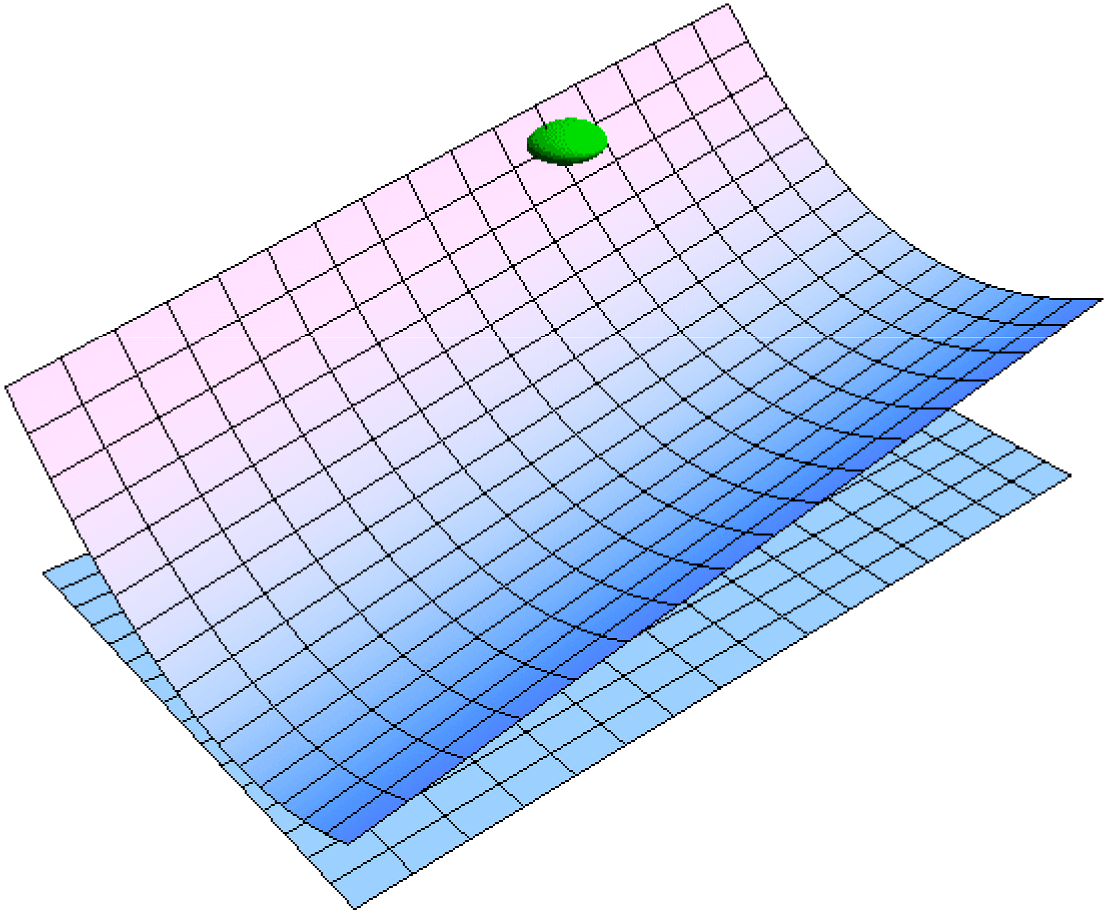
Animation Silicon Drift Detector: Synchronous Case

- Position is encoded in arrival time difference
- This requires charges to start *at the same time*!



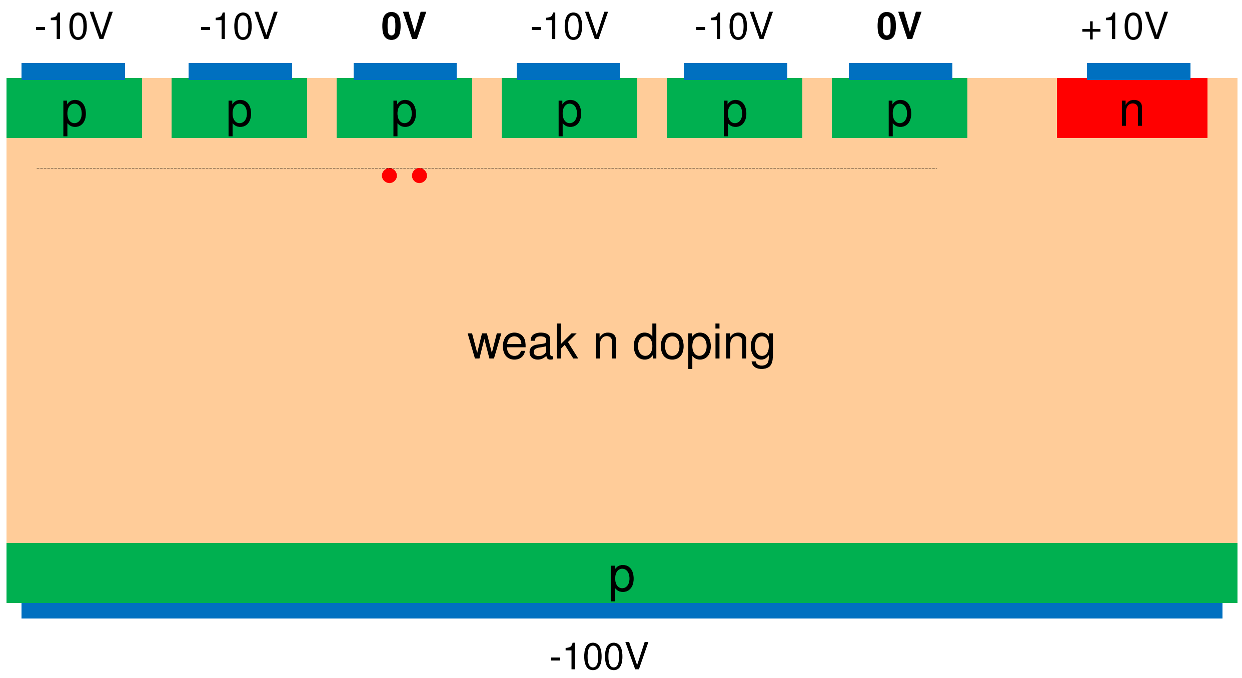
Animation Silicon Drift Detector: Problem

- Position *cannot be reconstructed* drift start unknown!
- e.g.: radioactive decays



Fully depleted CCD

- Upper side is divided into strips
- Electrons accumulate under the positive strips
- The are ‚shifted‘ with positive voltages to the edge



- Advantages: few readout electrodes, no extra material in active area, very low noise (few e^-)

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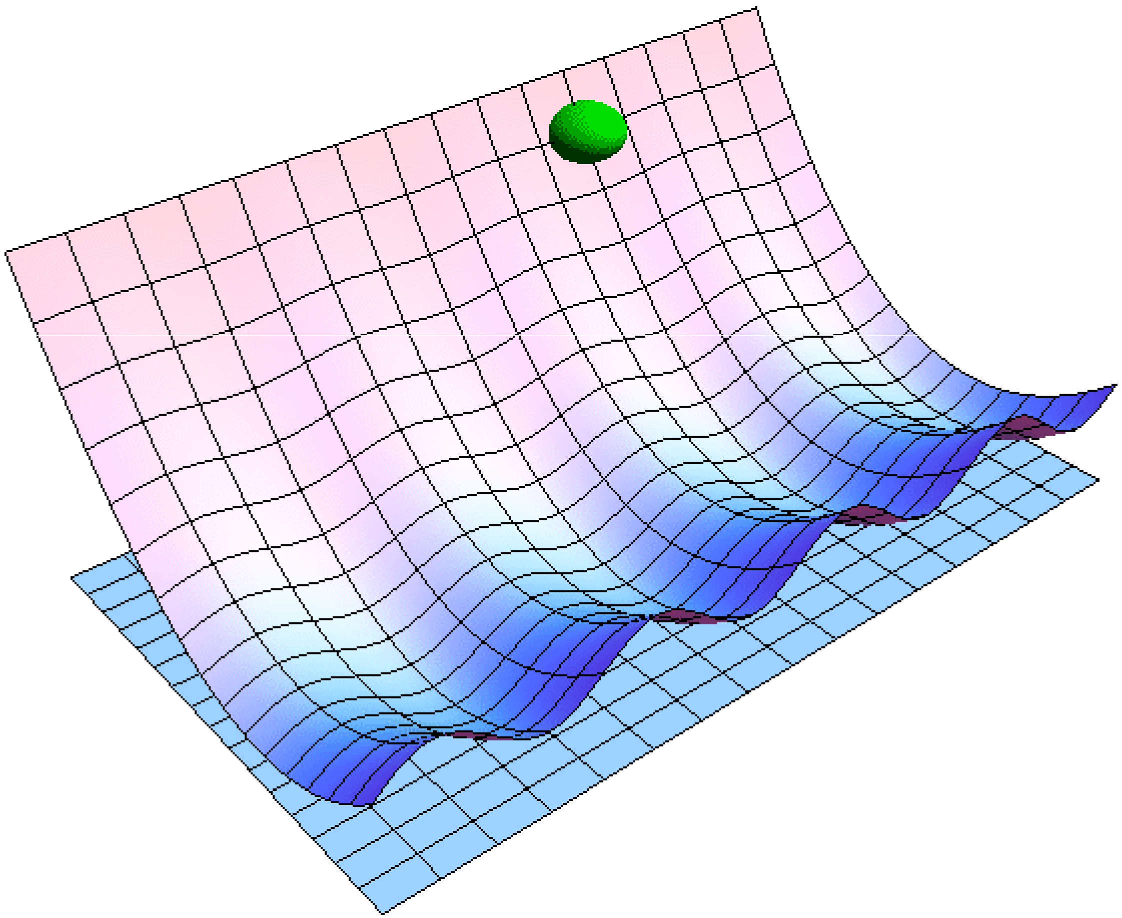
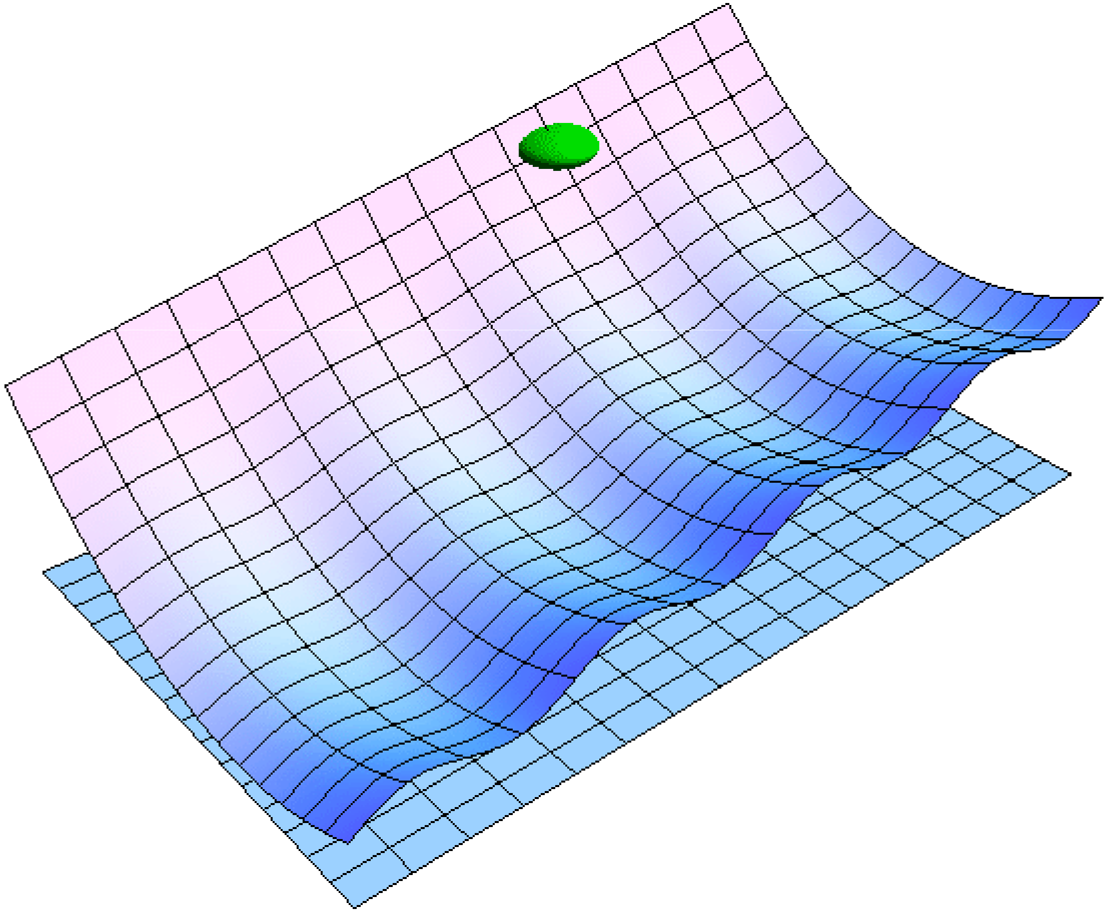
Animation: Fully Depleted CCD



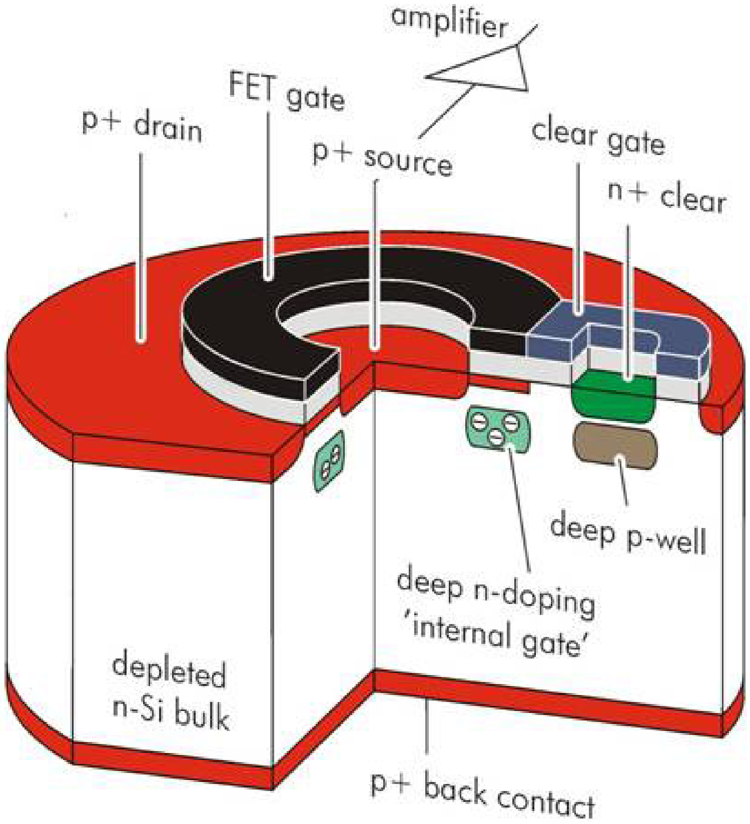
Controlled Drift Detector

- First Collect Charges in potential pockets
- Then drift by *switching off* the potential wells



Internal Amplification: DEPFETs

- Charge collection like in CCD
- p-channel Transistor **inside the detector** amplifies signal



- Very low noise, fast

Further types

- DSSD — Double Sided Strip Detector:
  n- and p- side are patterned (orth. / oblique)
- MAPS — Monolithic Active Pixel Sensor:
  Integration of Sensor and readout into CMOS
- APDs — Avalanche Photo Diodes:
  Internal Amplification with very high E-fields
- SiPMs — Silicon Photo Multiplier:
  Decoupled arrays of small APDs for high rate
- PingPong — Multiple readout of same charge $\rightarrow$ noise < 1 e
- ….

System Design

- A full Detector System consists of many components
  - Sensors
  - Front End Chips
  - Front End ‘Hybrids’
  - Support Mechanics
  - Cooling
  - Power Supplies, HV
  - Detector Slow control (temp. Mon, moisture, HV,..)
  - Backend Electronics (data transport & sorting, Trigger)
  - Data Acquisition Software
  - (Online) Monitoring Software
  - Analysis Software