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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)

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Organization

- Lecture:
  - Wednesday, 11:15, here
  - Slides will be on SuS web site
    - http://sus.ziti.uni-heidelberg.de/Lehre/Detectors1920
  - Slides from 18/19 are available – they are very similar

- Exercises:
  - Tuesday, starting 5.11
  - Held by me and maybe partially a student

- CP:
  - 6, (accepted for MSc Physics and MSc Computer Engineering)

- Examination:
  - Oral examination, date can be agreed

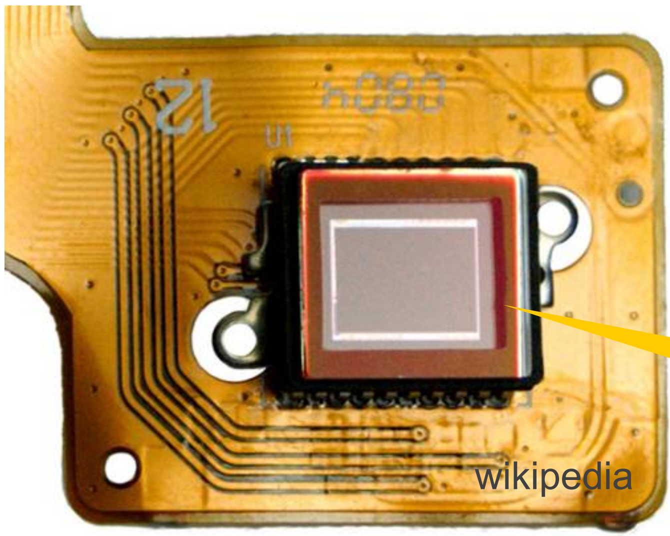
Introduction / Motivation

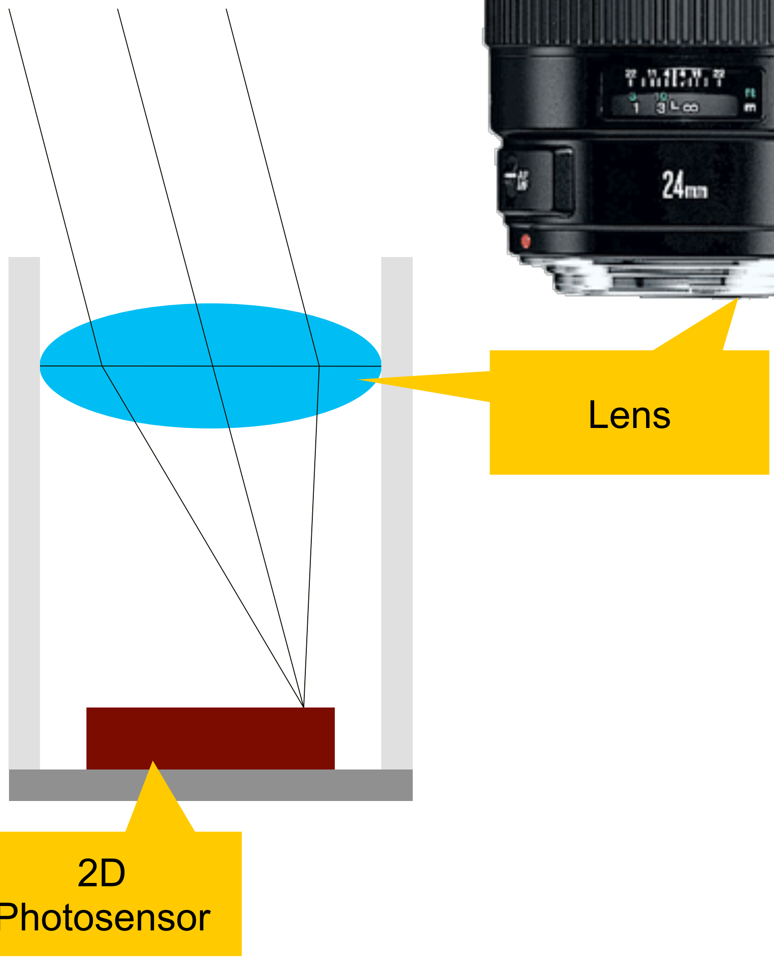
Cameras for the Invisible

Content

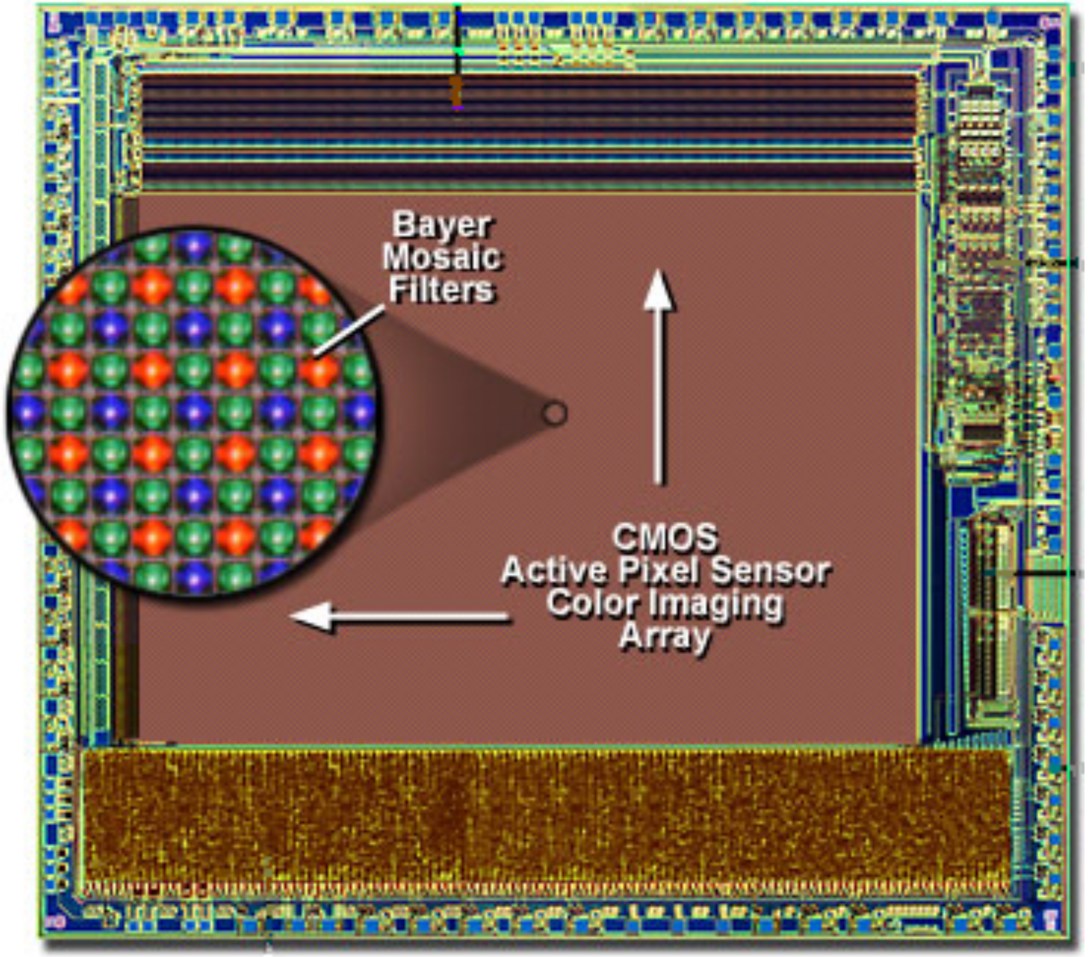
- The ‚normal' digital camera
- Basics:
  - Photons & other Particles
  - What do they do in silicon?
  - How does a silicon detector look like?
- Some types:
  - Pixel
  - CCDs
  - DEPFET
  - others…
- Applications:
  - Astronomy, Medicine, Material Science, Biology, Physics,…

What‘s in a normal camera?

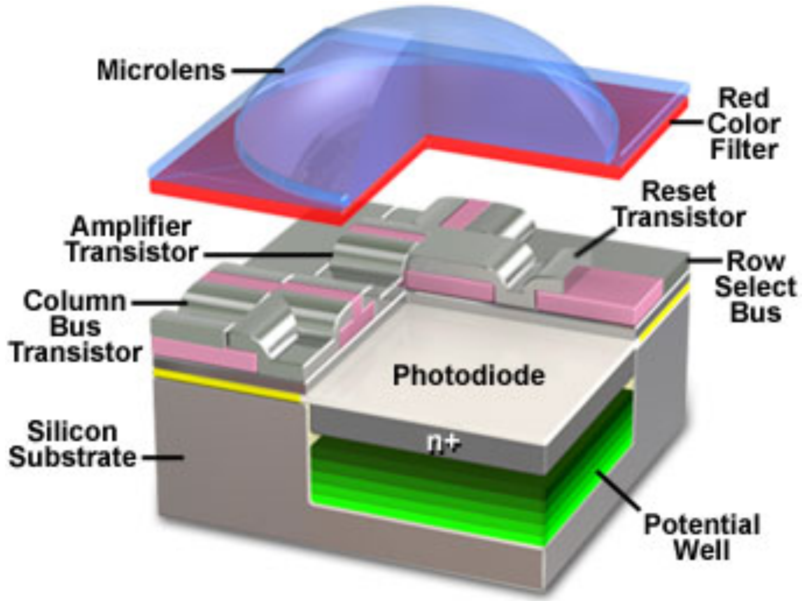




The ‚CMOS‘ Photo Sensor

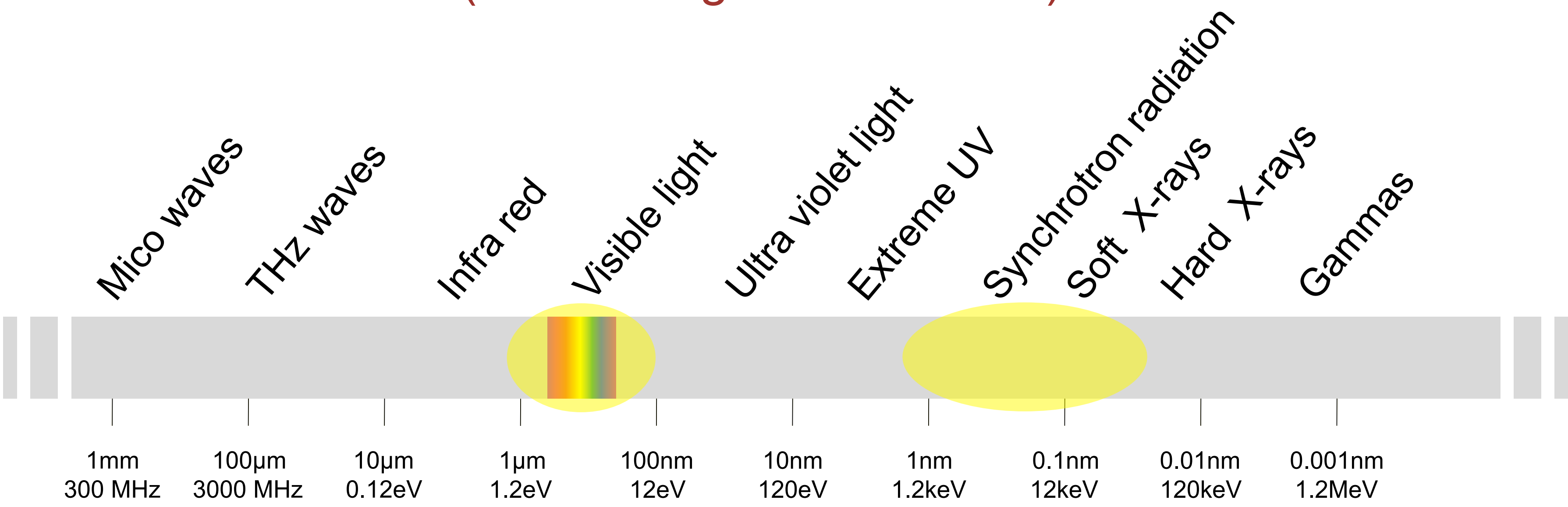


http://micro.magnet.fsu.edu/primer/digitalimaging/cmosimagesensors.html



Types of Radiation

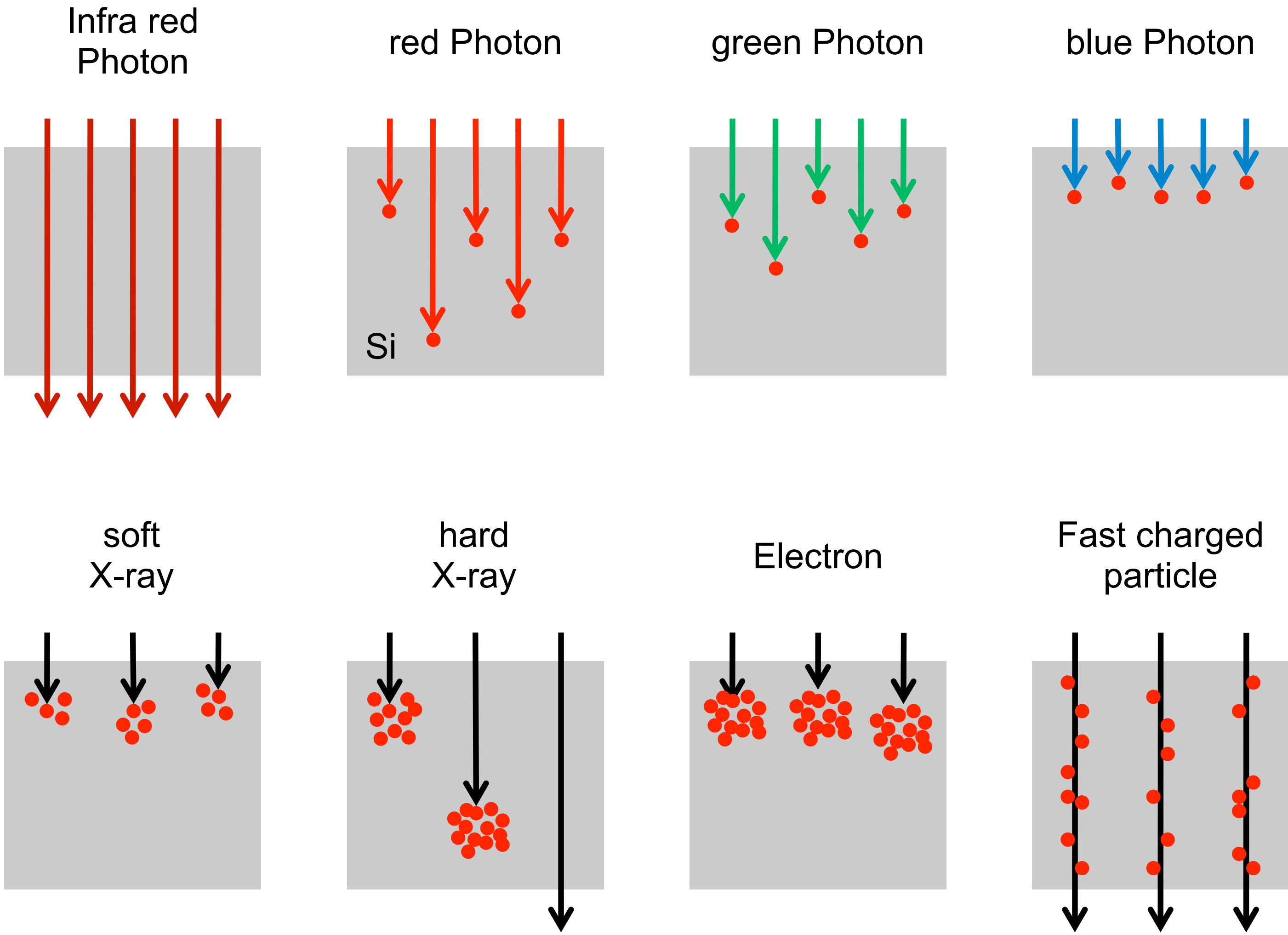
- Photons (electromagnetic radiation)



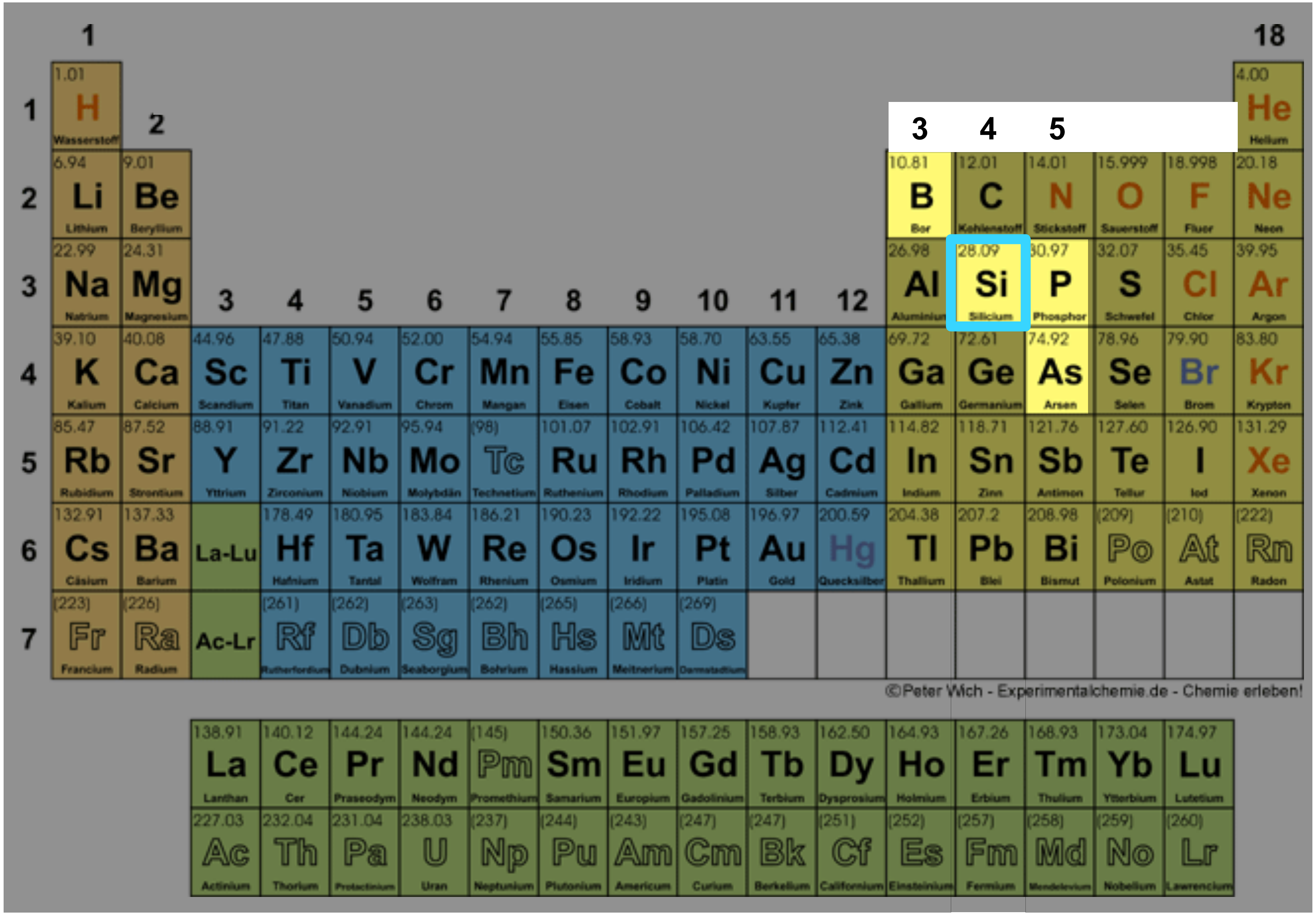
- Electrons (radioactive decays, electron microscope)
- Fast charged particles (physics, cosmic rays)
- Ions, neutrons, neutrinos,…

Radiation in Silicon

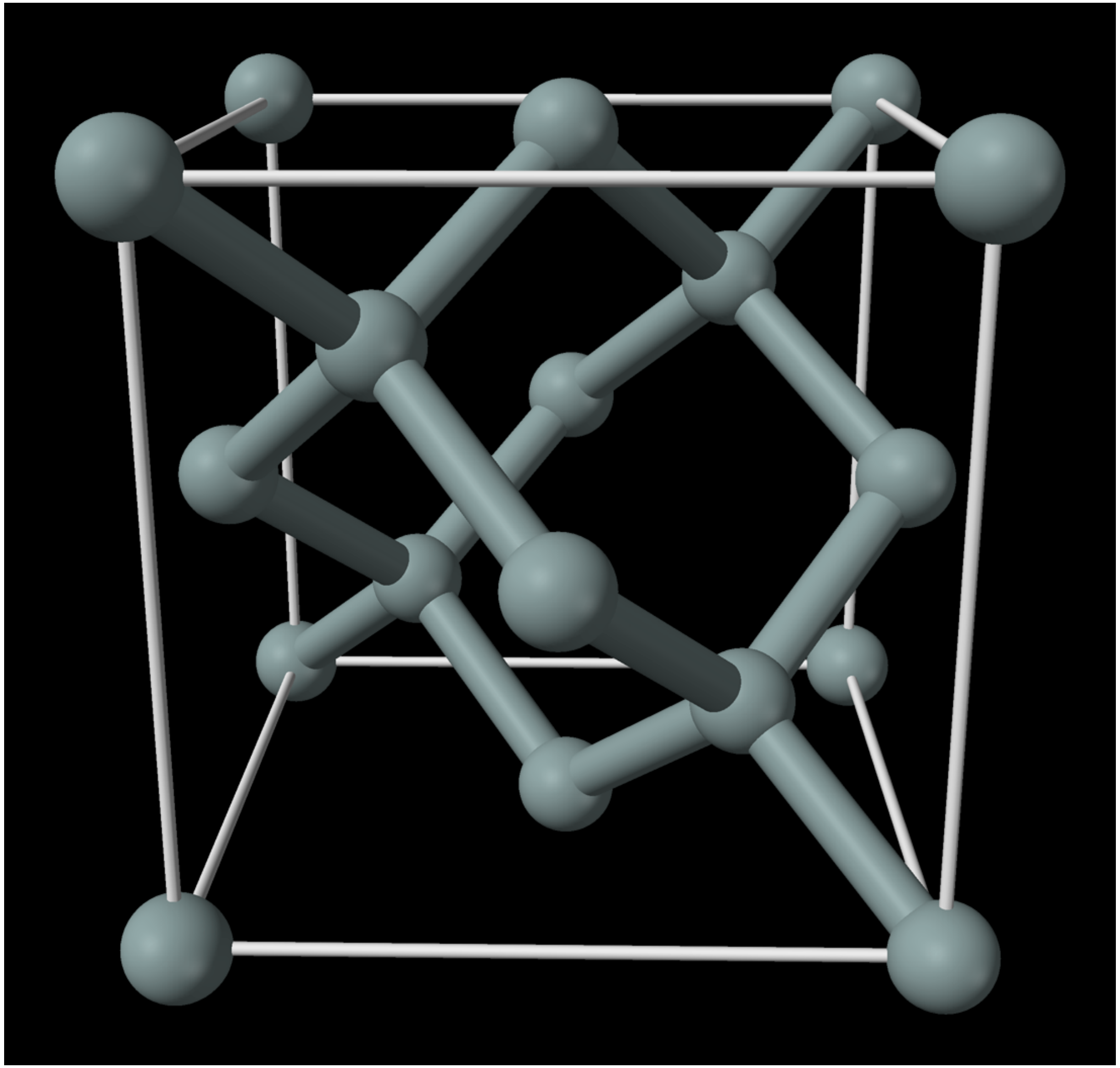
- Atoms are ionized (electrons • are knocked off the shell)



Silicon

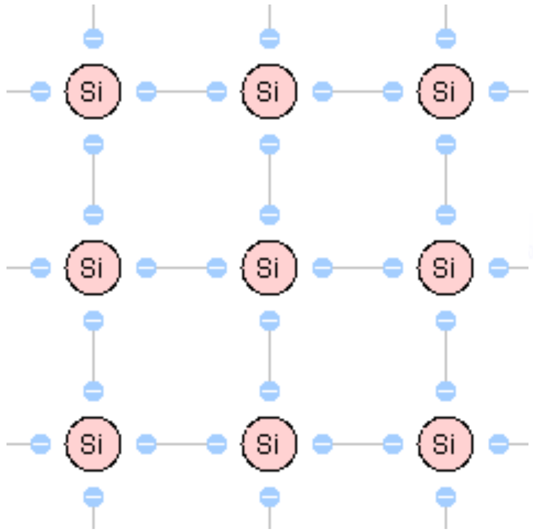

1
18
2
3 4 5
3 4 5 6 7 8 9 10 11 12
1 H 1.01 Wasserstoff
He 4.00 Helium
2 Li 6.94 Be 9.01 B 10.81 C 12.01 N 14.01 O 15.999 F 18.998 Ne 20.18
3 Na 22.99 Mg 24.31 Al 26.98 Si 28.09 Silicium P 30.97 S 32.07 Cl 35.45 Ar 39.95
4 K 39.10 Ca 40.08 Sc 44.96 Ti 47.88 V 50.94 Cr 52.00 Mn 54.94 Fe 55.85 Co 58.93 Ni 58.70 Cu 63.55 Zn 65.38 Ga 69.72 Ge 72.61 As 74.92 Se 78.96 Br 79.90 Kr 83.80
5 Rb 85.47 Sr 87.52 Y 88.91 Zr 91.22 Nb 92.91 Mo 95.94 Tc (98) Ru 101.07 Rh 102.91 Pd 106.42 Ag 107.87 Cd 112.41 In 114.82 Sn 118.71 Sb 121.76 Te 127.60 I 126.90 Xe 131.29
6 Cs 132.91 Ba 137.33 La-Lu Hf 178.49 Ta 180.95 W 183.84 Re 186.21 Os 190.23 Ir 192.22 Pt 195.08 Au 196.97 Hg 200.59 Tl 204.38 Pb 207.2 Bi 208.98 Po (209) At (210) Rn (222)
7 Fr (223) Ra (226) Ac-Lr Rf (261) Db (262) Sg (263) Bh (262) Hs (265) Mt (266) Ds (269)
©Peter Wich - Experimentalchemie.de - Chemie erleben!
La 138.91 Ce 140.12 Pr 144.24 Nd 144.24 Pm (145) Sm 150.36 Eu 151.97 Gd 157.25 Tb 158.93 Dy 162.50 Ho 164.93 Er 167.26 Tm 168.93 Yb 173.04 Lu 174.97
Ac 227.03 Th 232.04 Pa 231.04 U 238.03 Np (237) Pu (244) Am (243) Cm (247) Bk (247) Cf (251) Es (252) Fm (257) Md (258) No (259) Lr (260)

Silicon Crystal



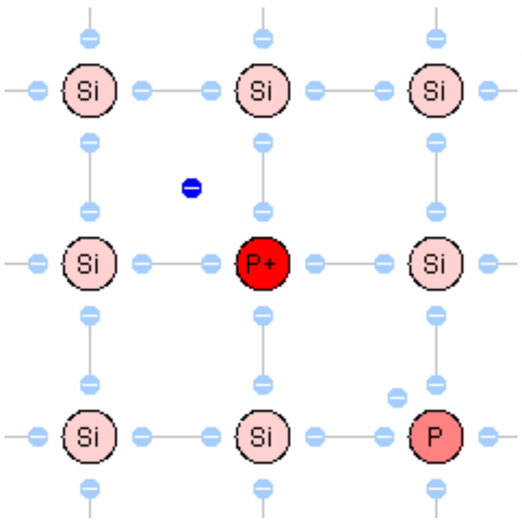
Face centered
Cubic lattice

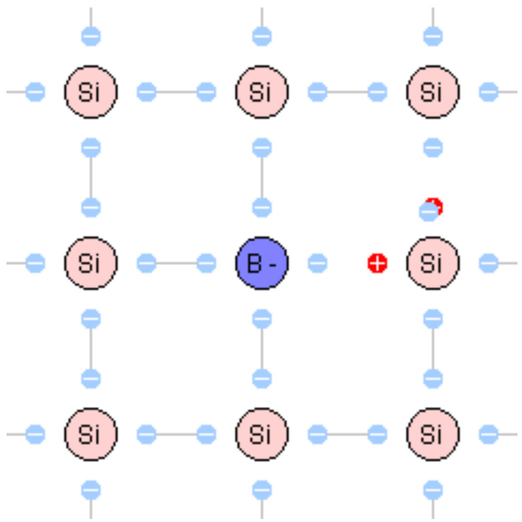
Silicon: Crystal & Doping



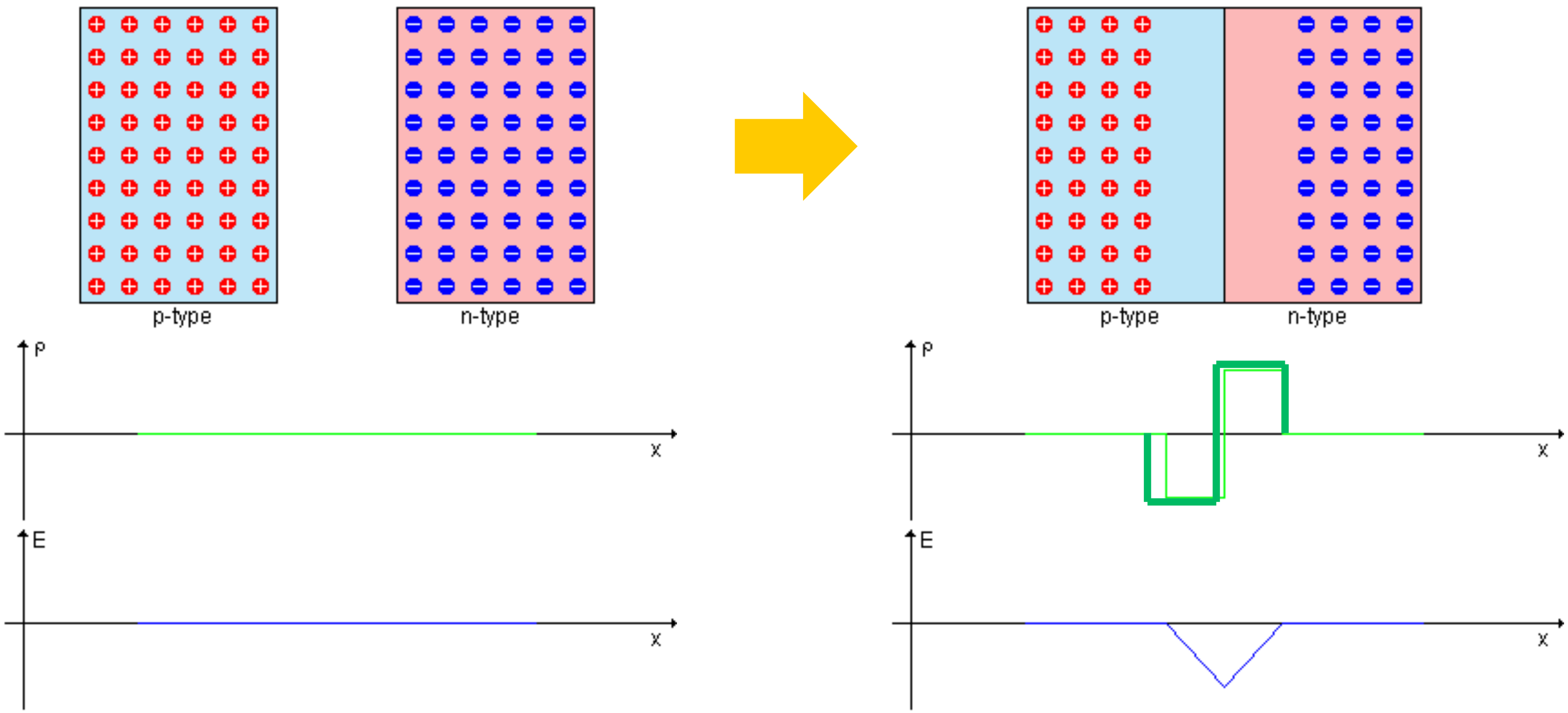
doping with
5-valued atoms:
- **N-conductor**
- Donators **positive**

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



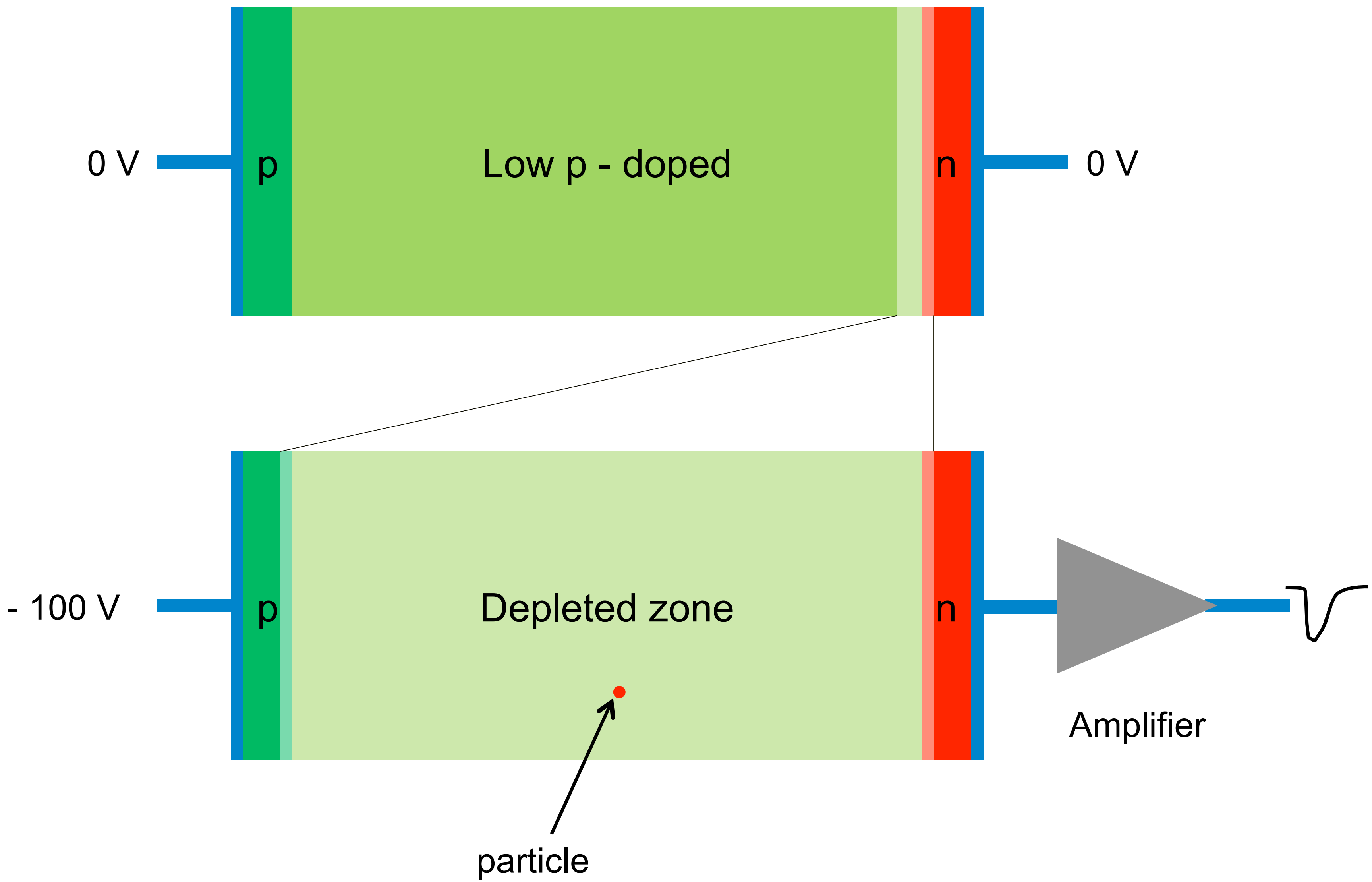


The pn-junction (diode)



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

Signals in a pn-diode



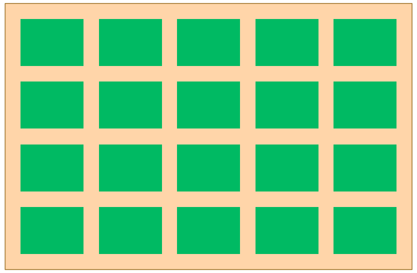
Summary pn-diode

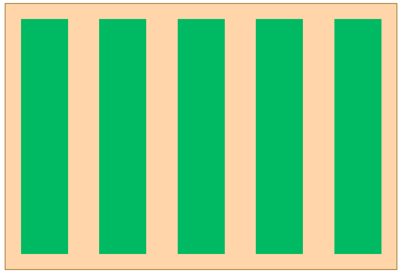
- By clever doping, a **depletion zone** is created
  With high external voltage (100V), it can be 'thick' (0.3 mm)
- There is a strong **E-Field** in the depletion zone
- Electrons (and holes), created by particles / light
  are separated and pulled to the electrodes
- They are detected with an **amplifier**
- 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!

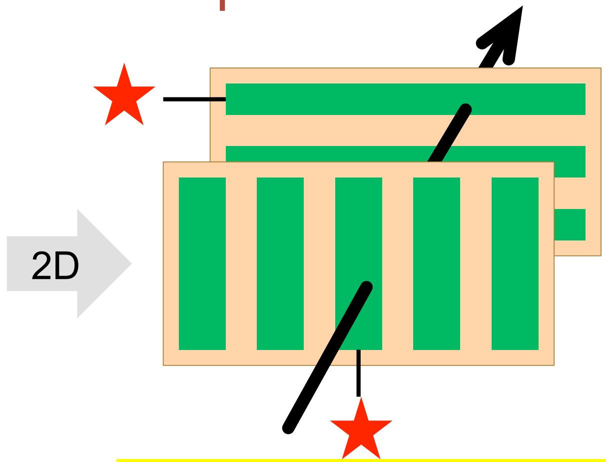
DETECTOR TYPES

Pixel and Strips

- The surface can be segmented to provide spatial information:







PIXELS

+ 2D information
+ complex images possible
+ small capacitances, → low noise
+ single sided device

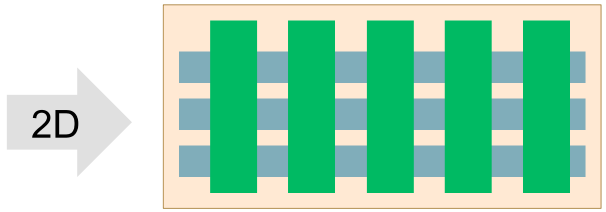
- many amplifiers
- small areas (chip size is limited)

STRIPS

- Only **1D**
+ large areas
+ few amplifier

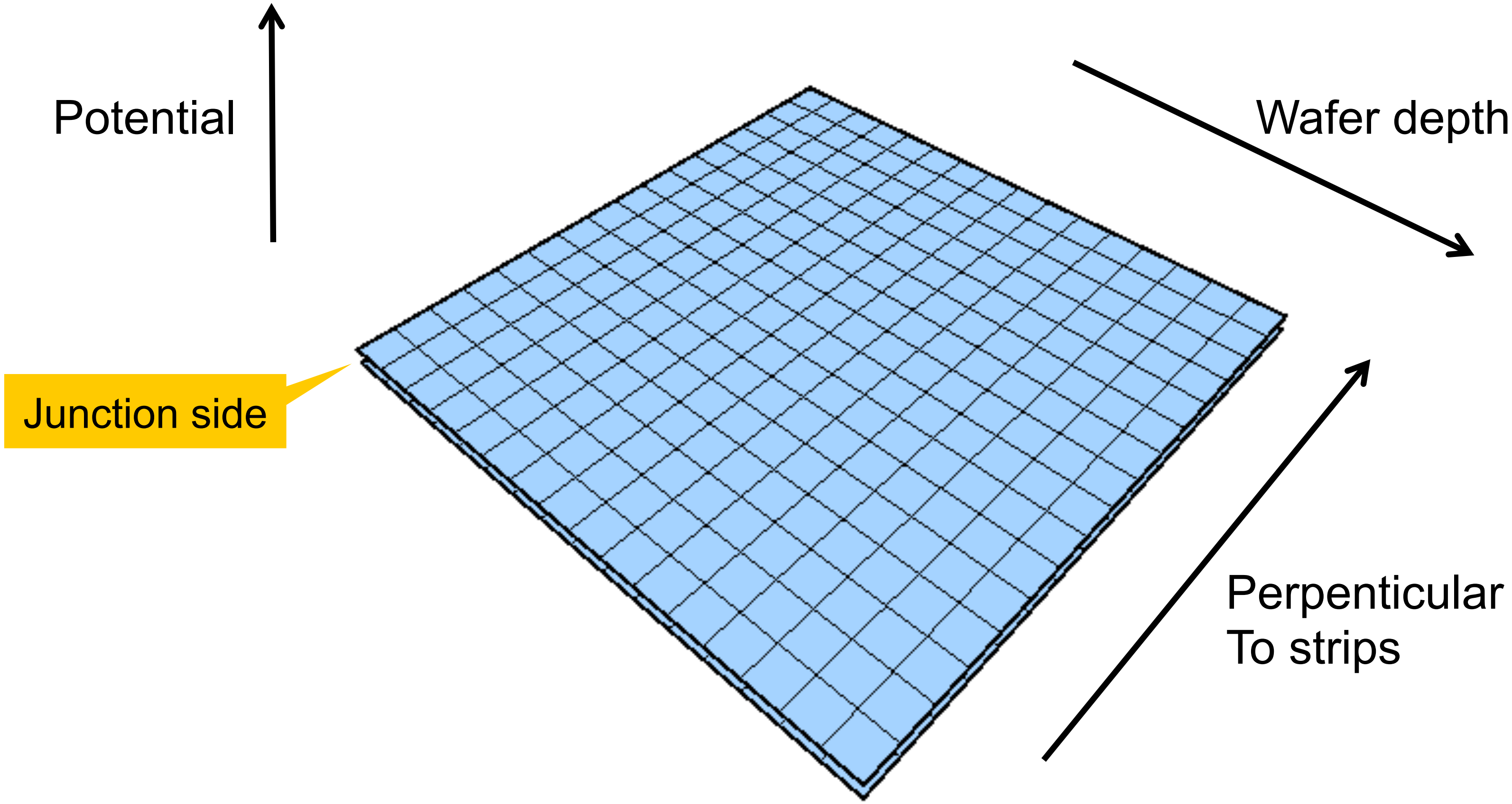
- large capacitances, → high noise

two layers
- only for penetrating particles
- more material (scattering)

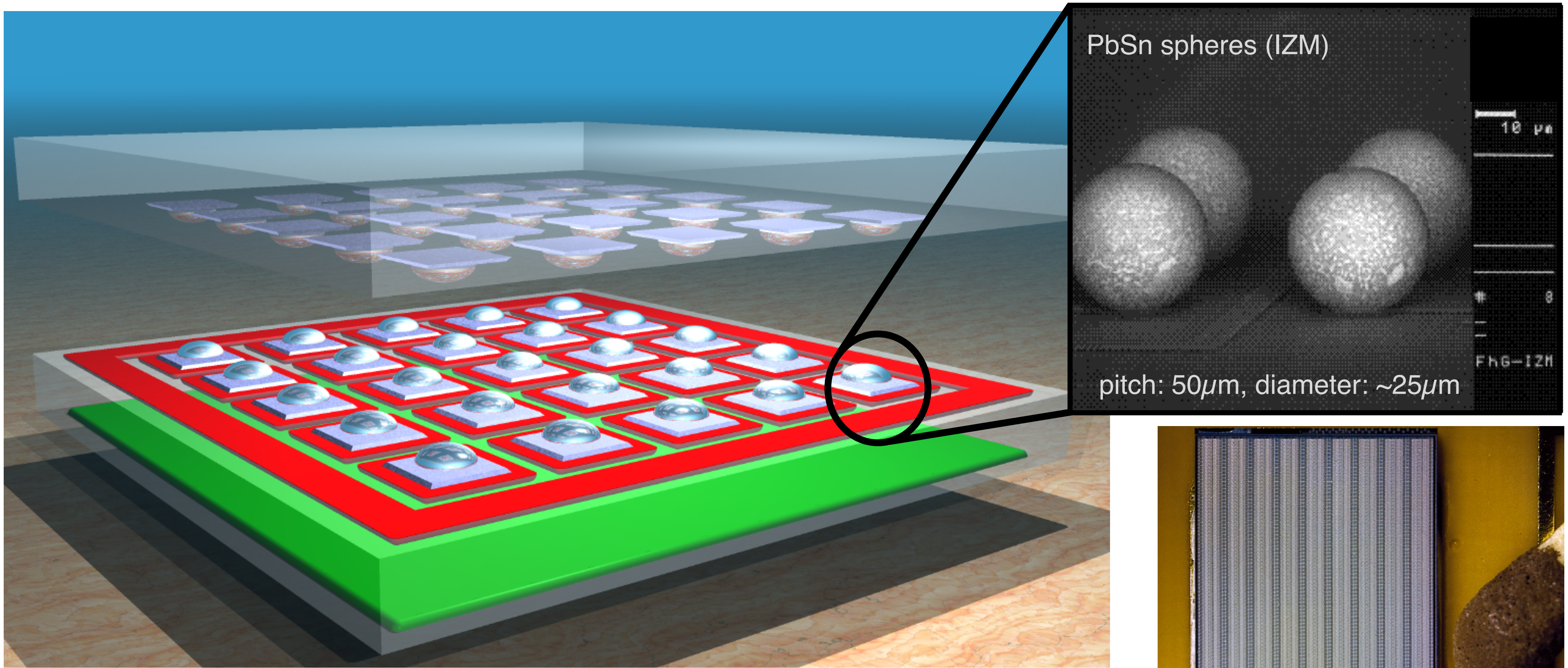


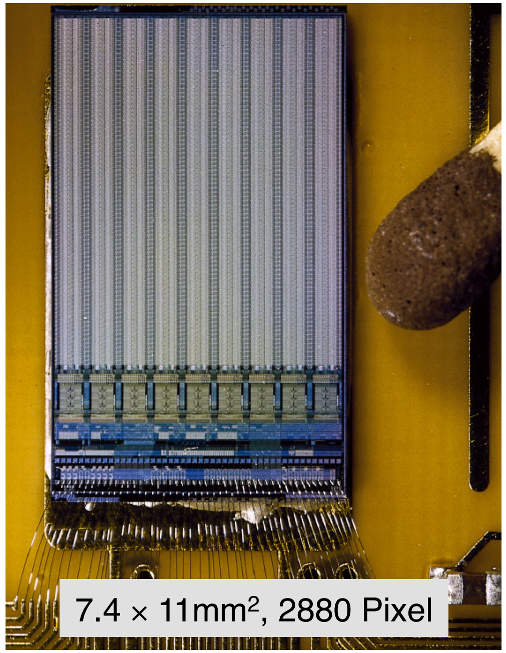
double sided
+ for absorbing particles!
- isolation of strips, potential difference front/back, cost

Animation of Normal Depletion



Hybrid Pixel: Chips + Detector (Flip Chip)

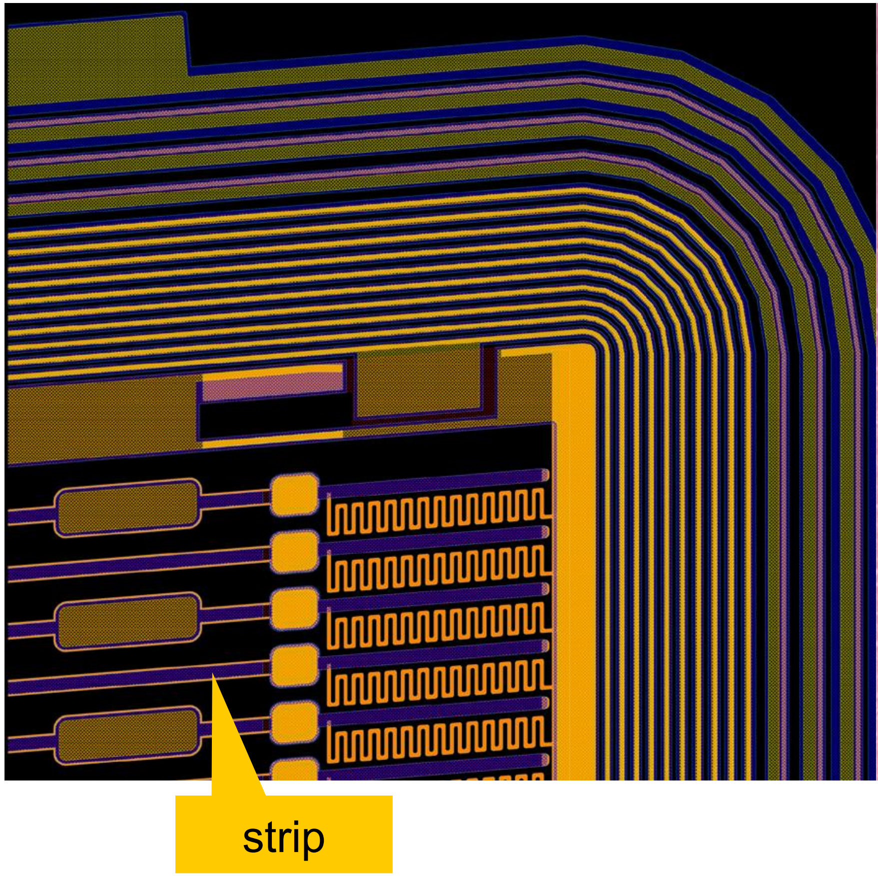


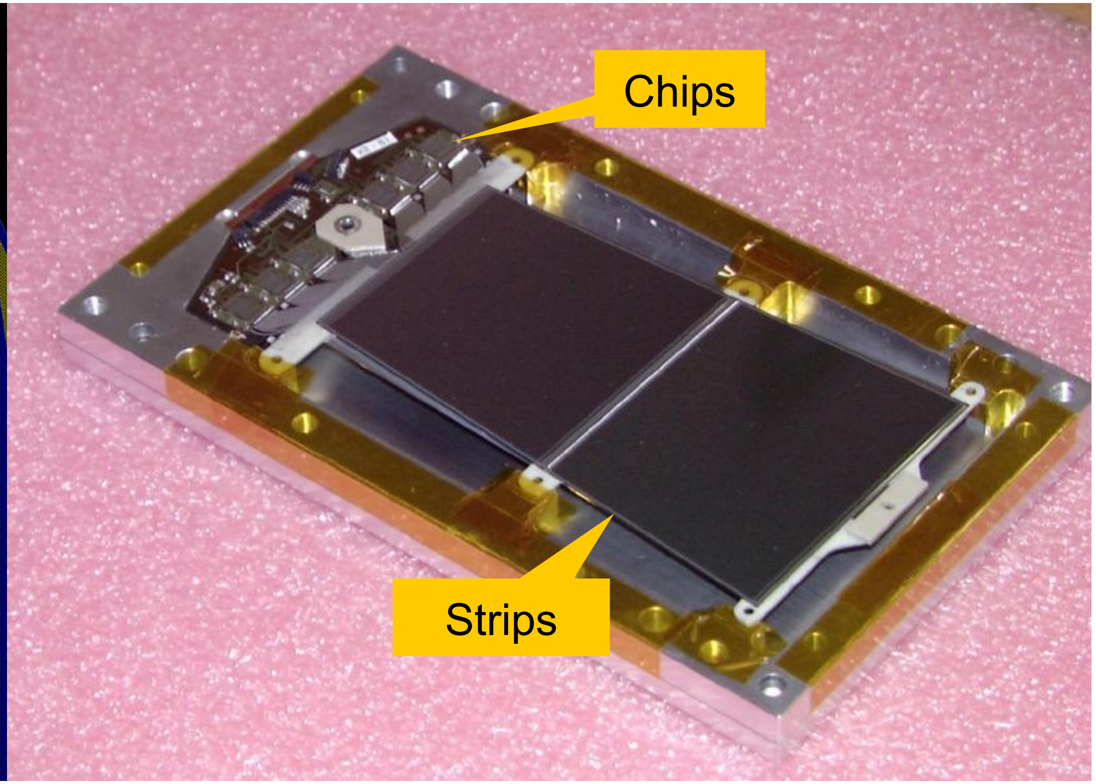


- Sensor: pn-diode with segmented electrode, also other materials, also gas
- Chip: Amplification & readout
- Interconnect: many ‘bump’ spheres
- Advantage: flexible readout, fast

Strip Detectors

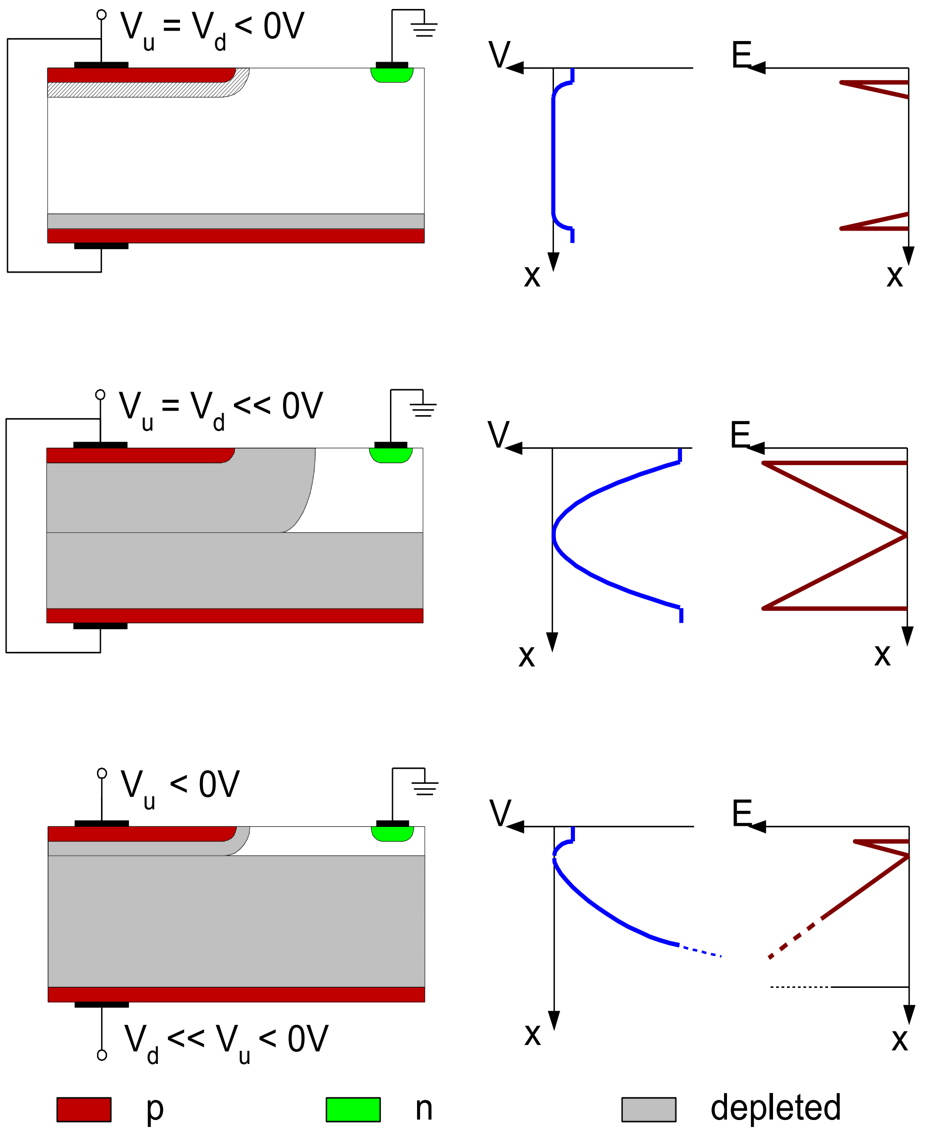
- One (or both) sides are segmented into strips (~50µm)
- Readout with chips at the side
- Advantage: Few channels for high spatial resolution, fast



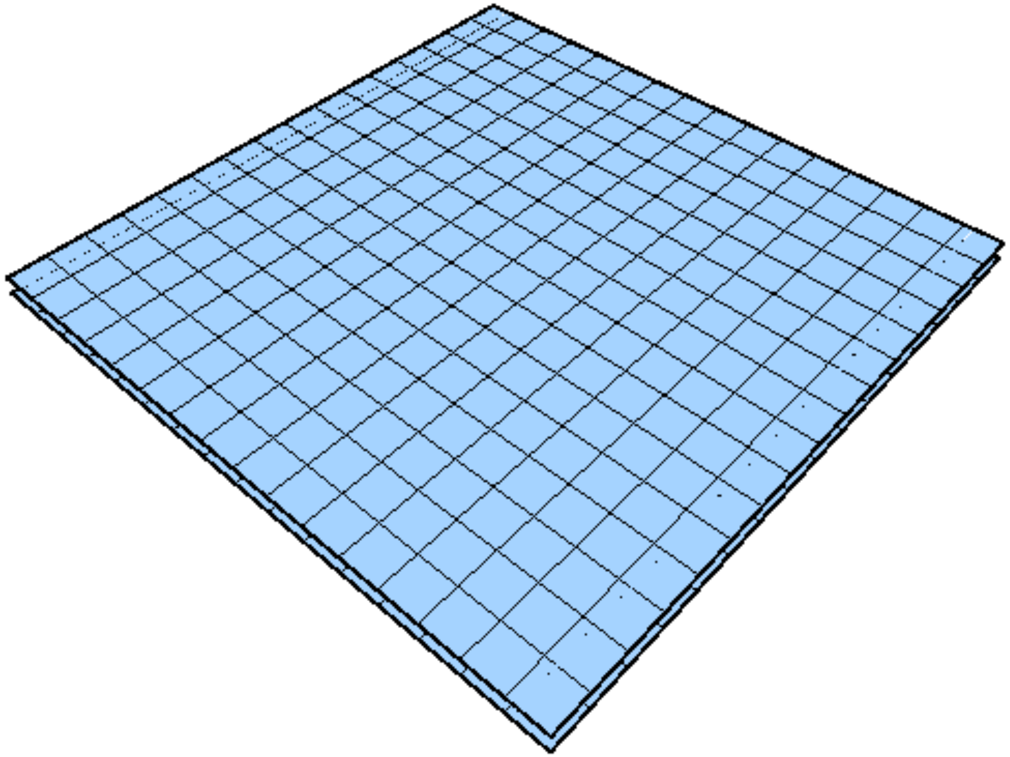


Fully depleted CCDs: Sideward Depletion

- 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**

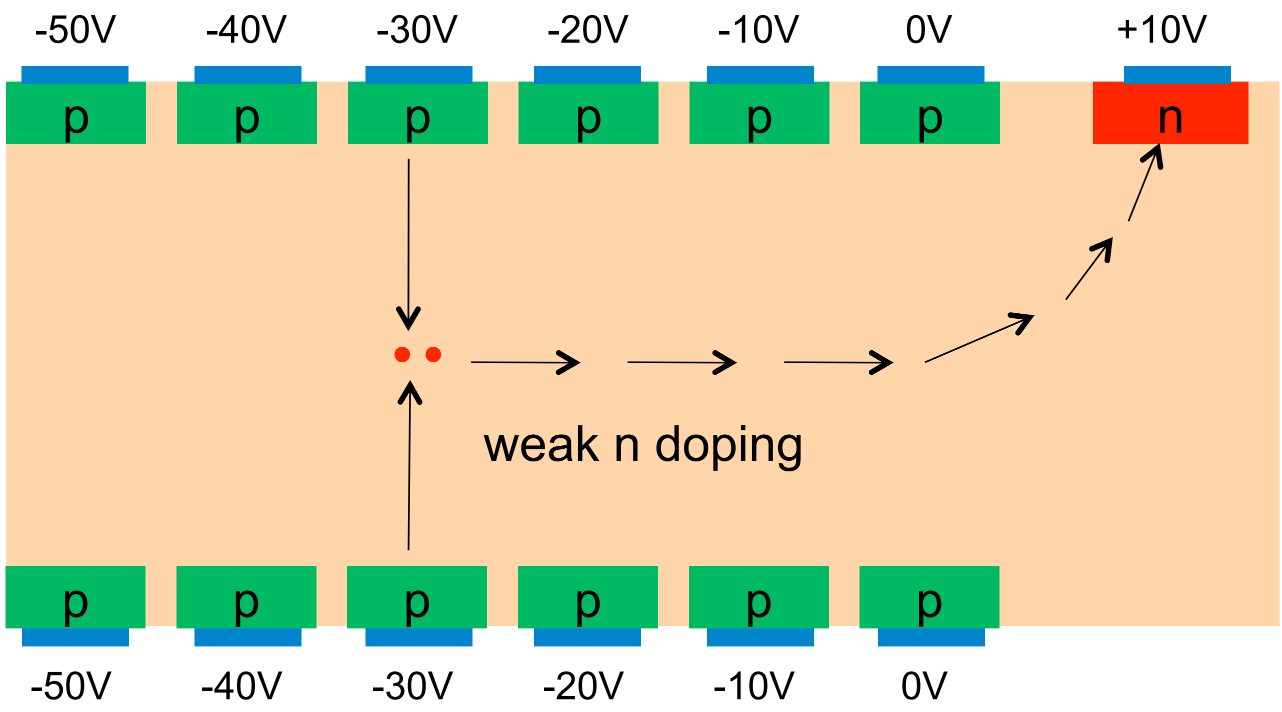


Animation of Symmetric/Assym. Sideward Depletion



Silicon Drift Detector

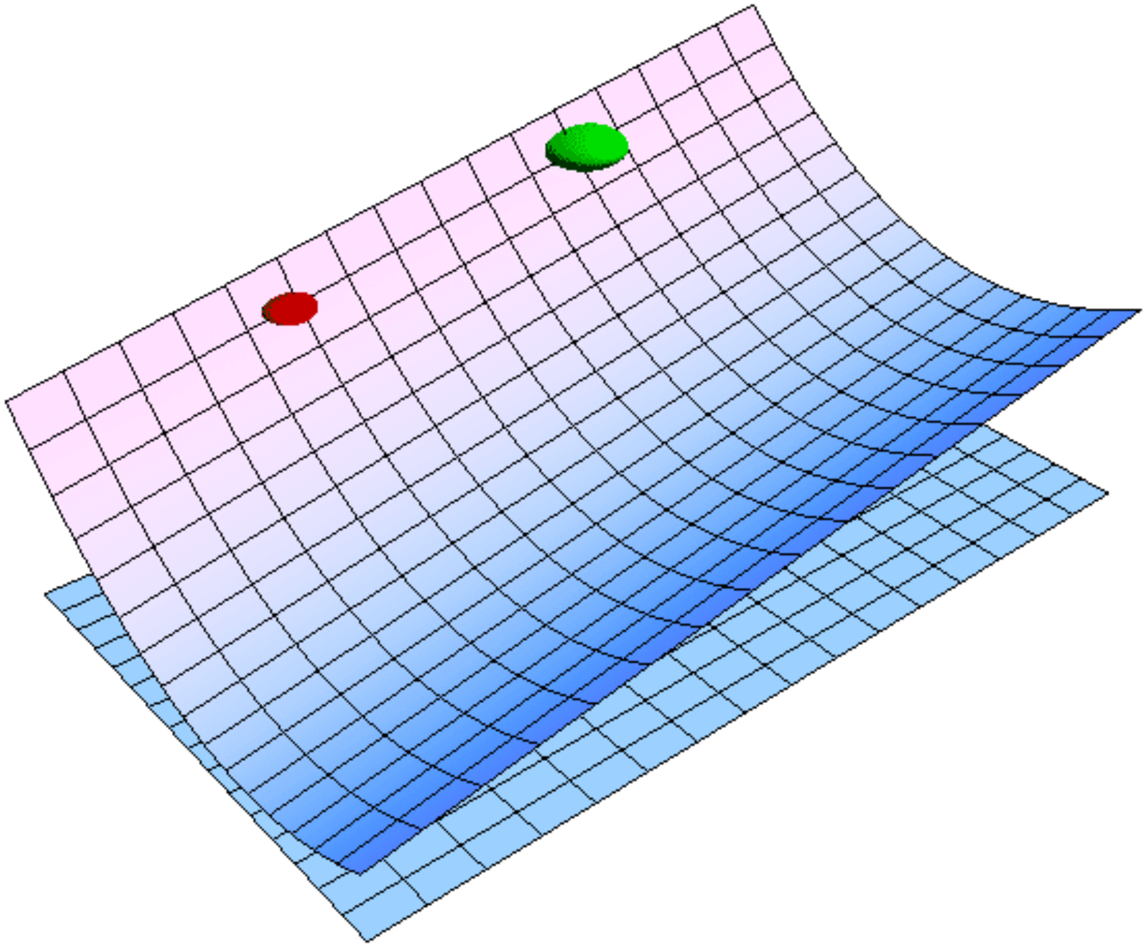
- Both sides are segmented
- Increasing potentials create a *lateral* field



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

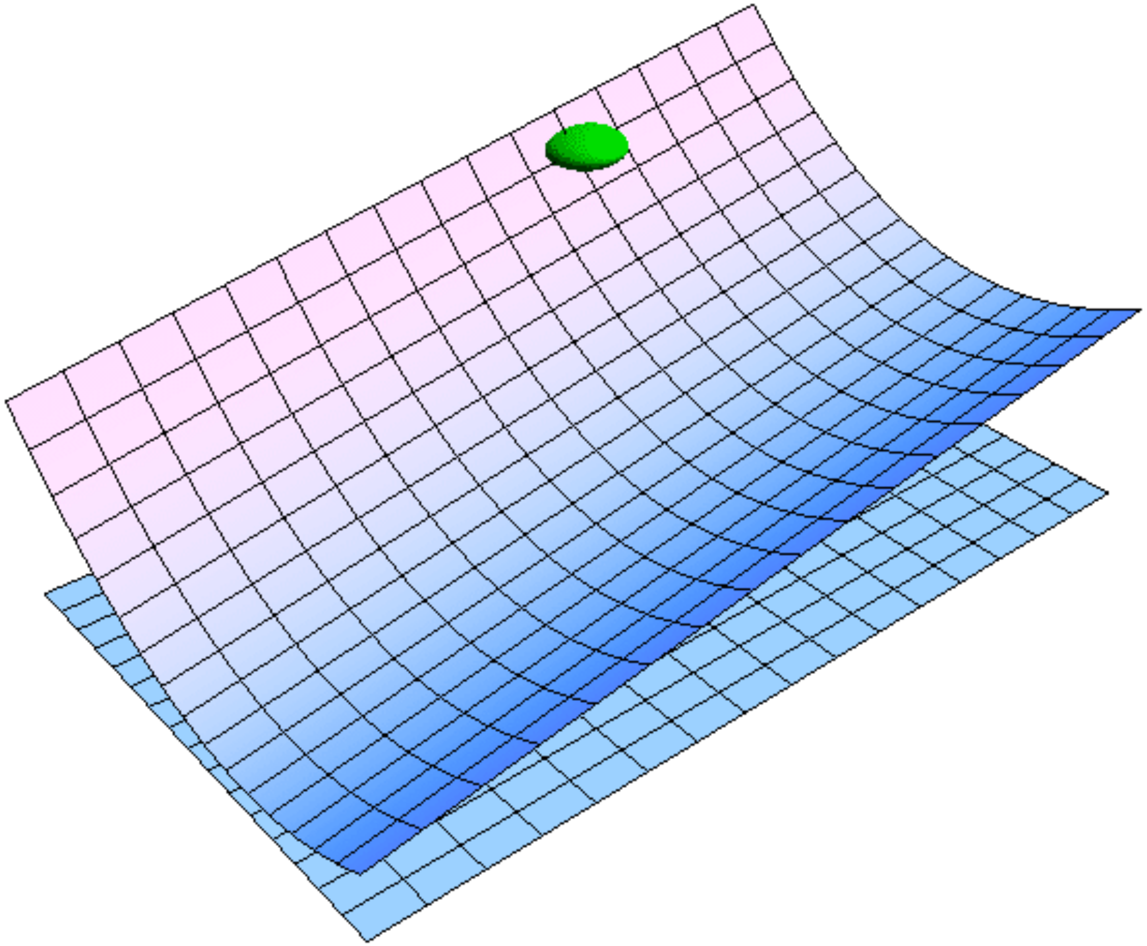
Animation Silicon Drift Detector: Synchronous Case

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



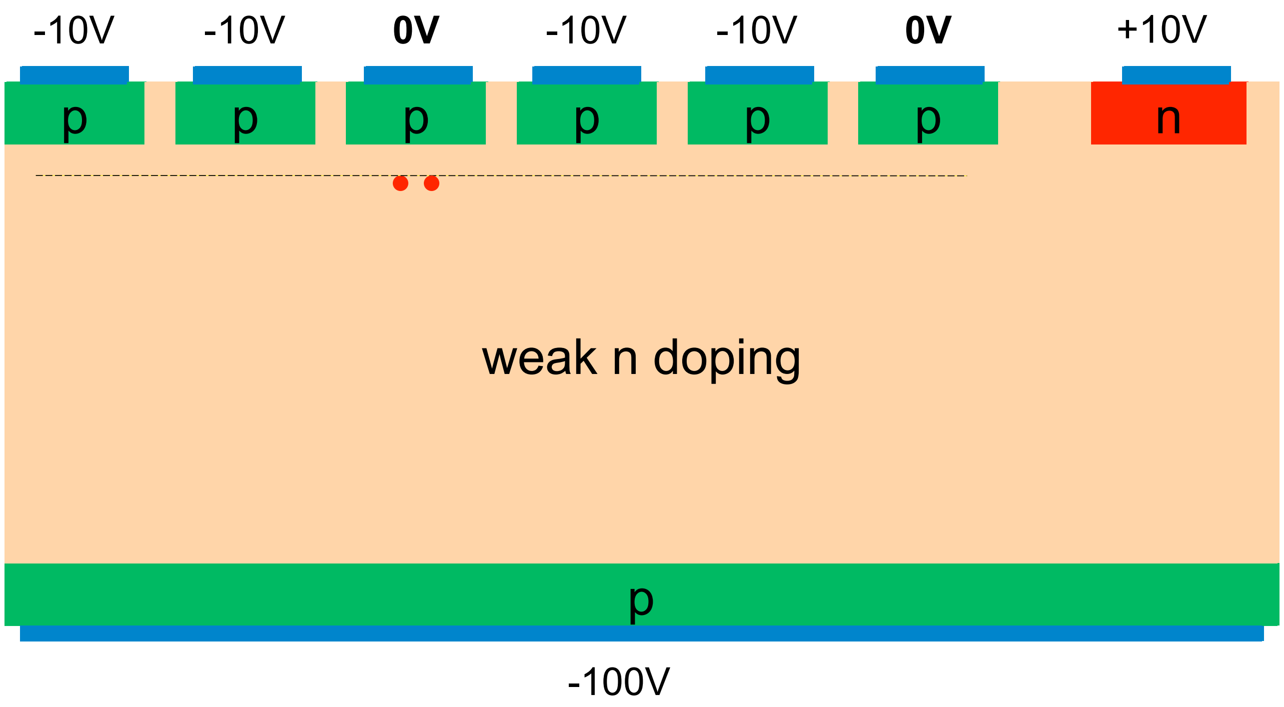
Animation Silicon Drift Detector: Problem

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



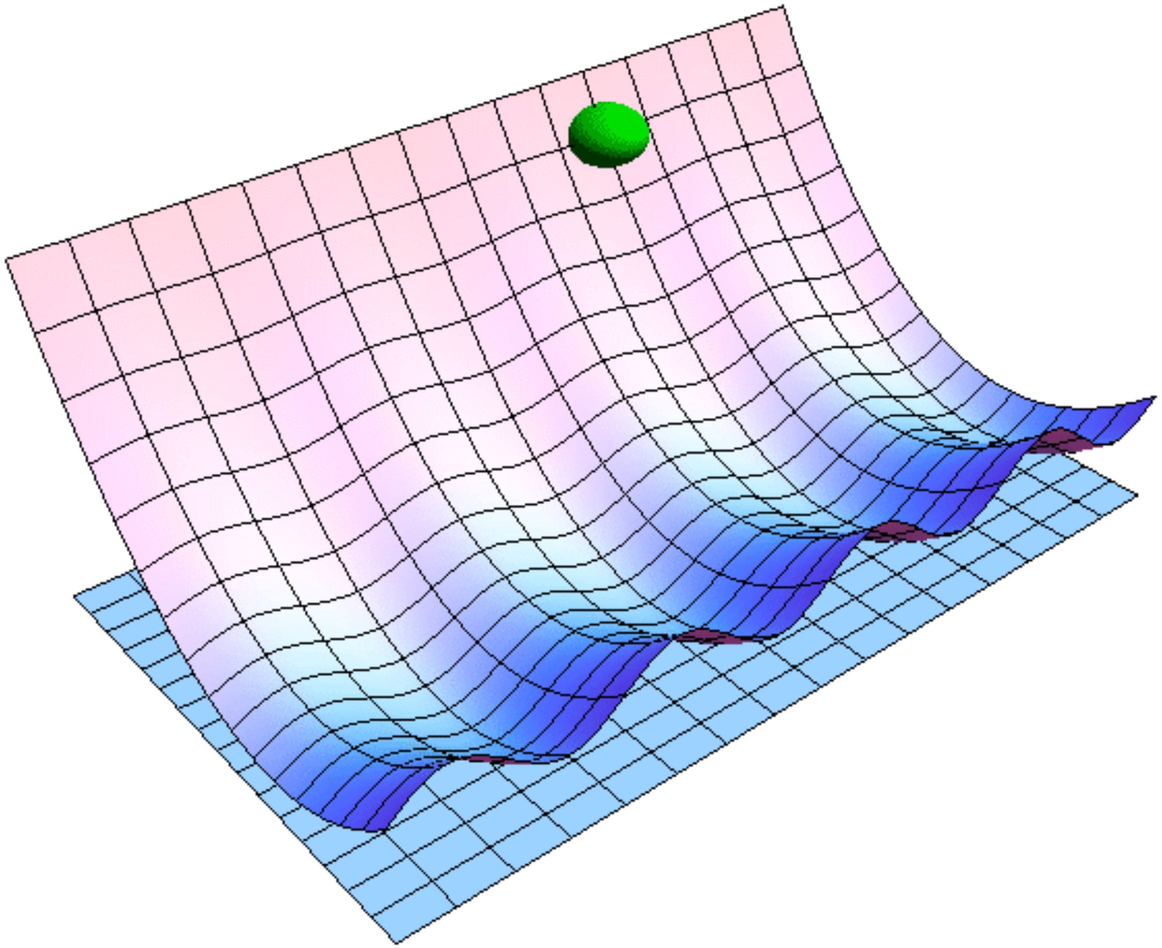
Fully depleted CCD

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



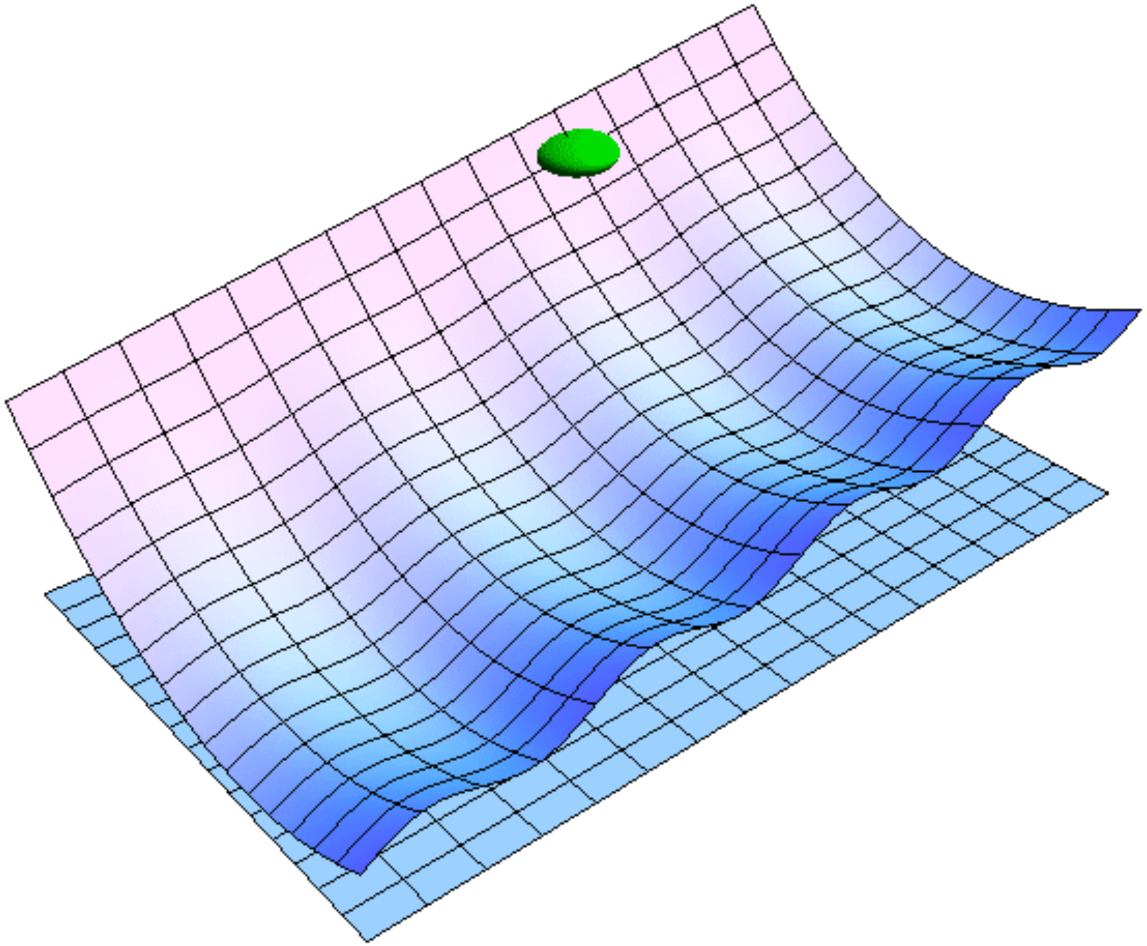
- Advantages: few readout electrodes, no extra material in active area, very low noise (few e^-)

Animation: Fully Depleted CCD



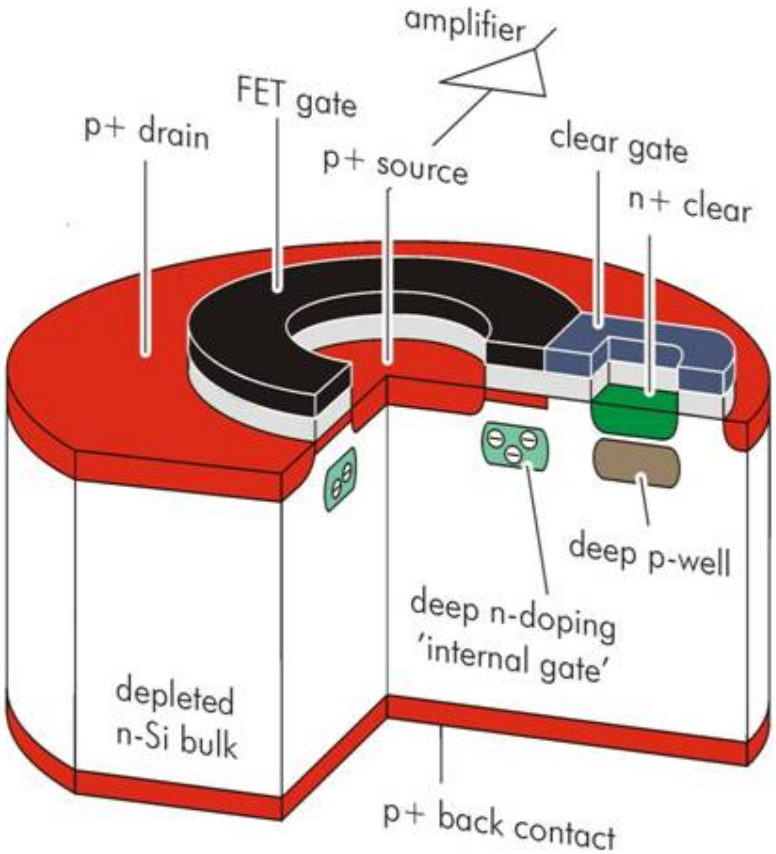
Controlled Drift Detector

- 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 → 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