



# Silicon Detectors and Readout Electronics

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# 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

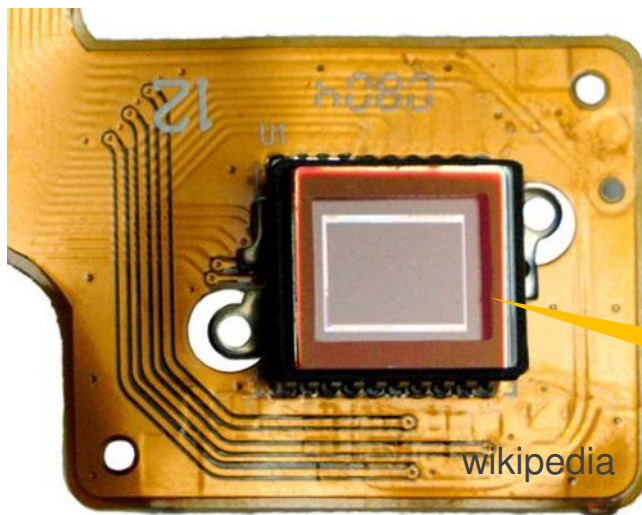
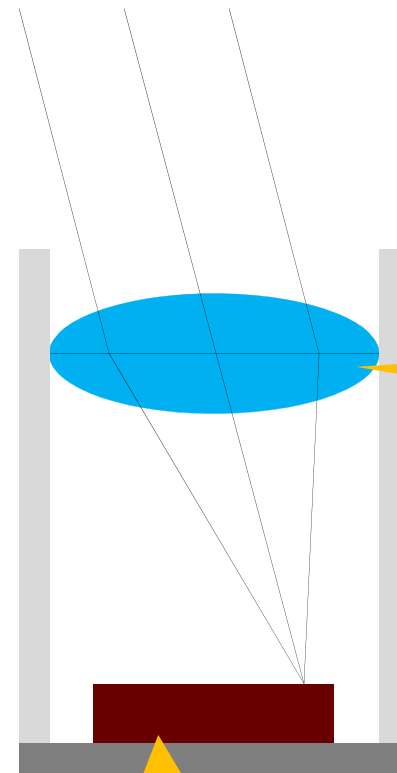


# Content

- 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,...

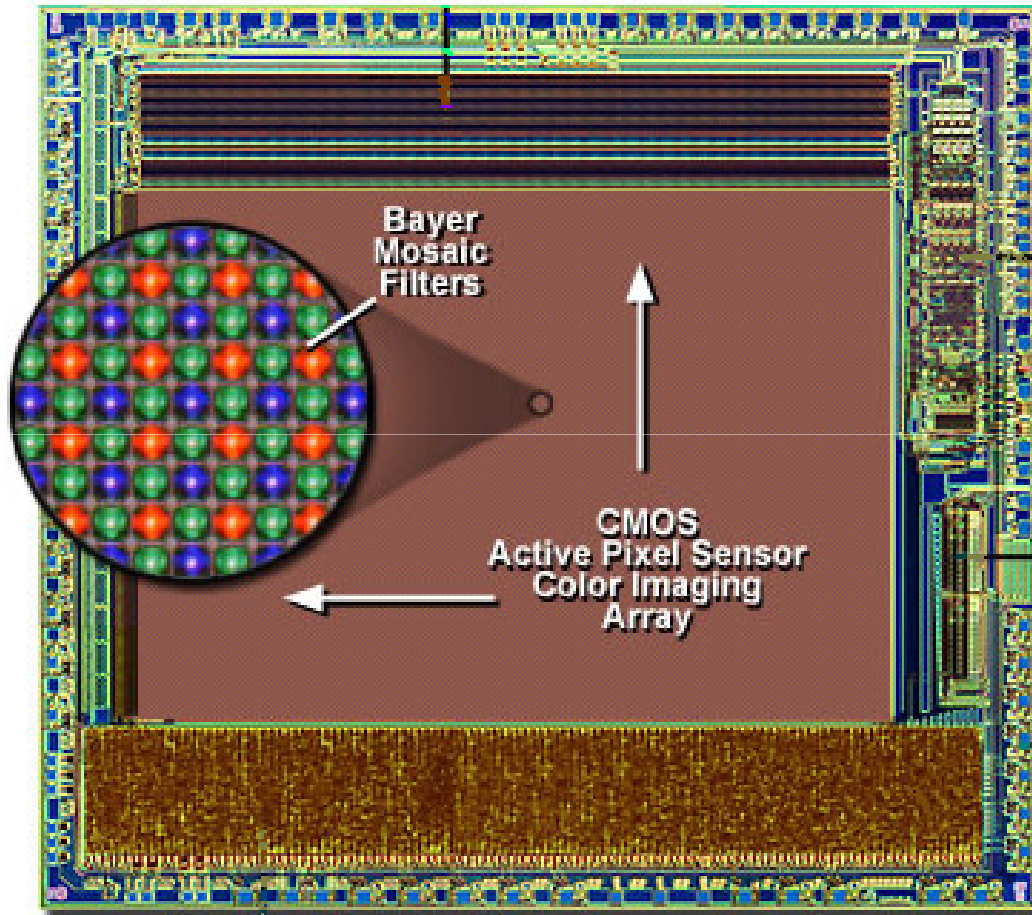


# What's in a normal camera?

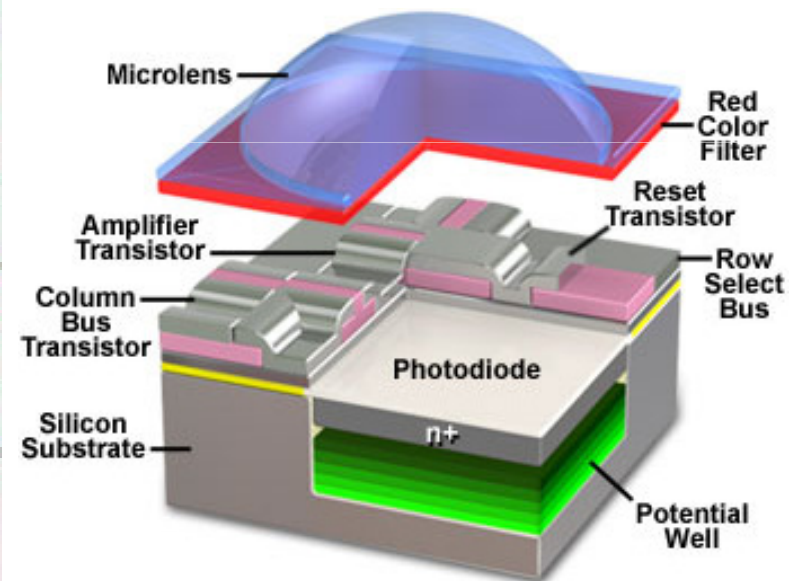




# The ,CMOS' Photo Sensor



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

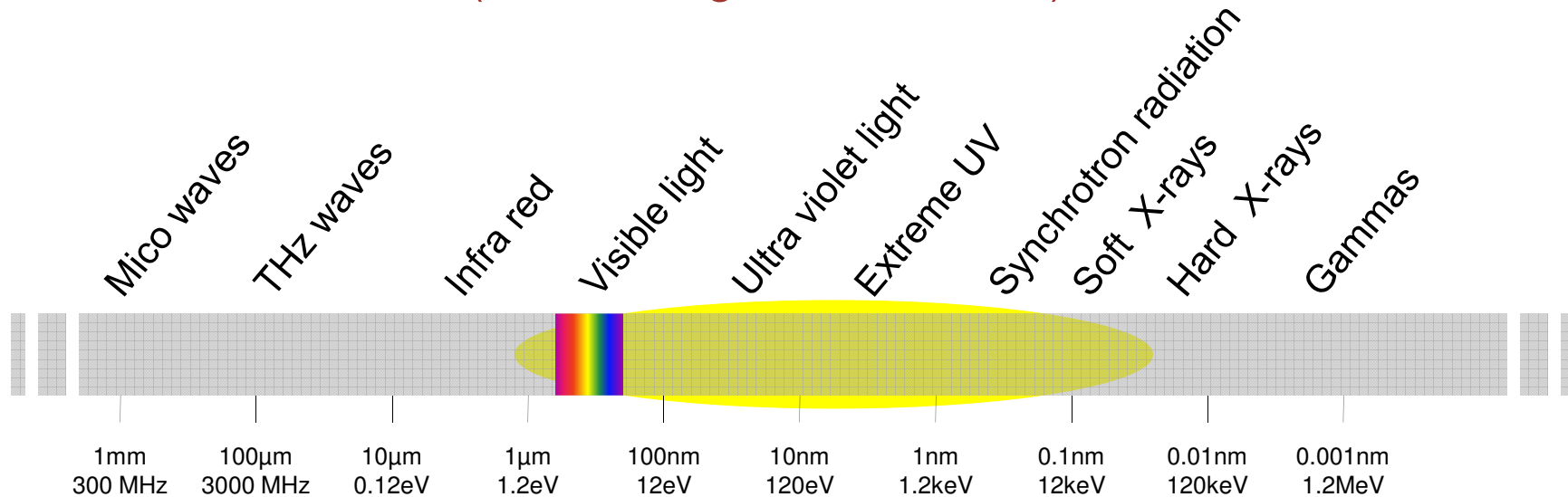






# Types of Radiation

- Photons (electromagnetic radiation)

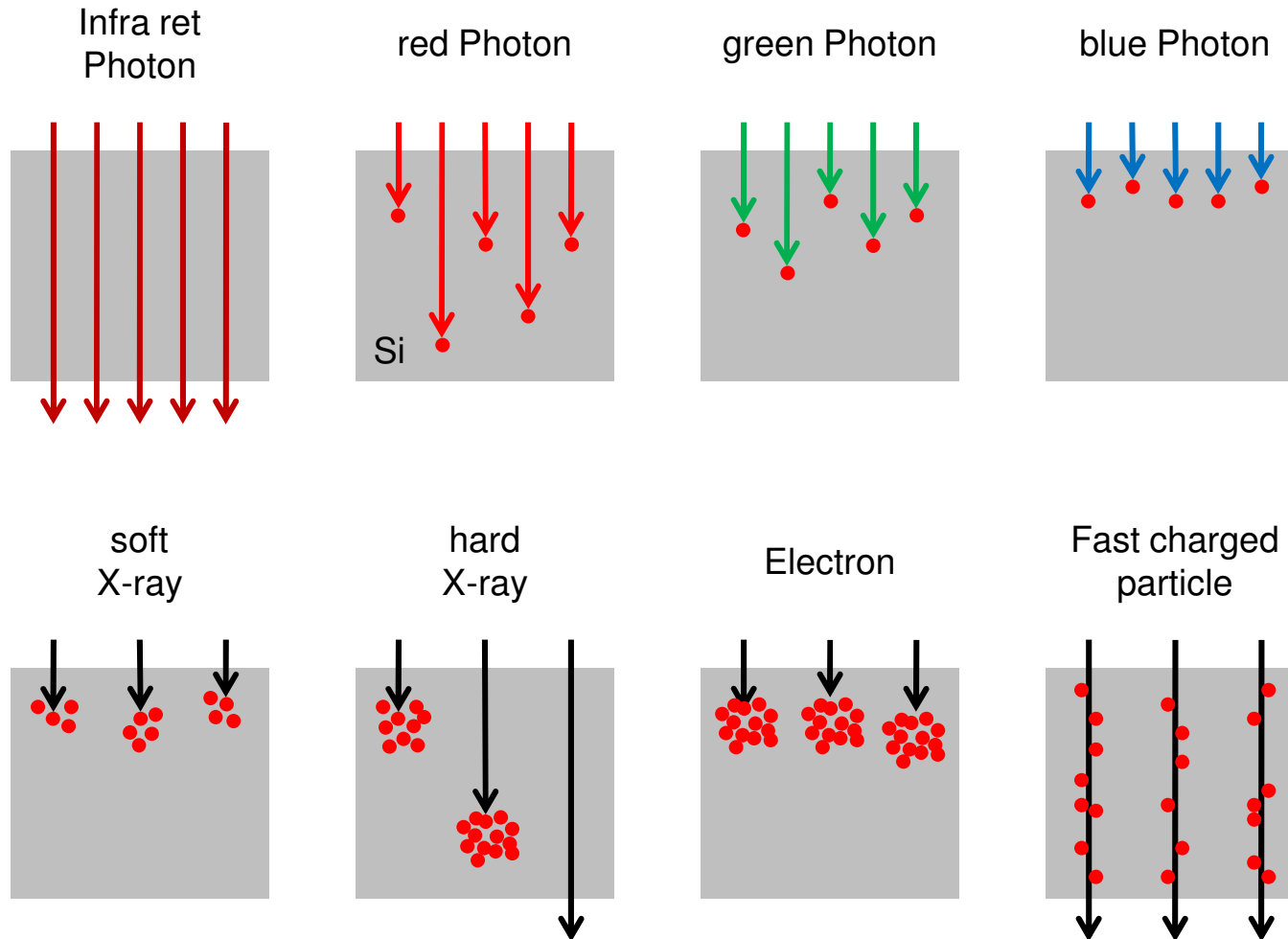


- Electrons (radioactive decays, electron microscope)
- Fast charged particles (physics, cosmic rays)
- Ions, neutrons, neutrinos,...



# Radiation in Silicon

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



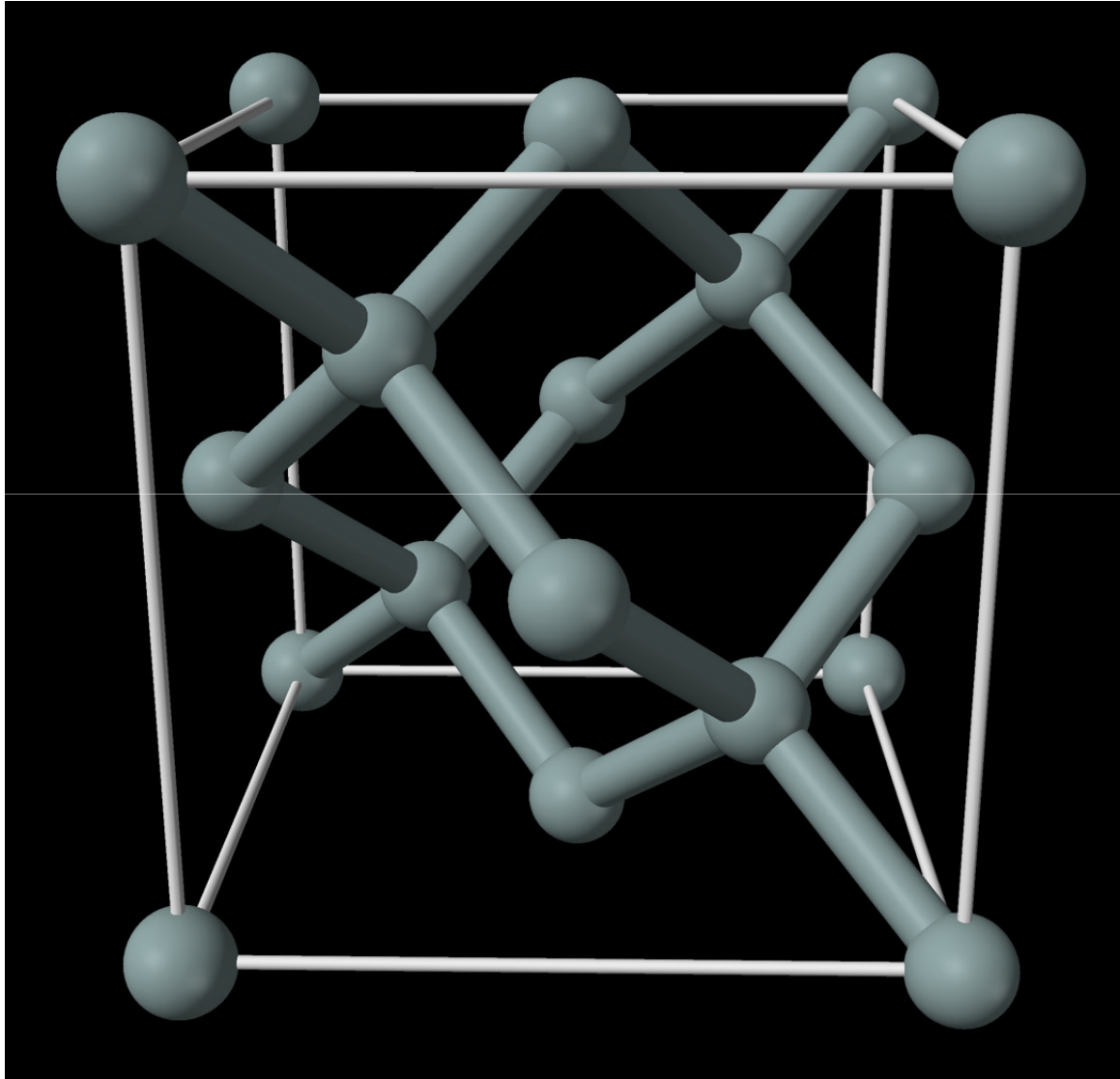


# Silicon

1												18						
1	<b>H</b> 1.01 Wasserstoff											3 4 5			<b>He</b> 4.00 Helium			
2	<b>Li</b> 6.94 Lithium	<b>Be</b> 9.01 Beryllium											<b>B</b> 10.81 Bor	<b>C</b> 12.01 Kohlenstoff	<b>N</b> 14.01 Stickstoff	<b>O</b> 15.999 Sauerstoff	<b>F</b> 18.998 Fluor	<b>Ne</b> 20.18 Neon
3	<b>Na</b> 22.99 Natrium	<b>Mg</b> 24.31 Magnesium	3	4	5	6	7	8	9	10	11	12	<b>Al</b> 26.98 Aluminium	<b>Si</b> 28.09 Silicium	<b>P</b> 30.97 Phosphor	<b>S</b> 32.07 Schwefel	<b>Cl</b> 35.45 Chlor	<b>Ar</b> 39.95 Argon
4	<b>K</b> 39.10 Kalium	<b>Ca</b> 40.08 Calcium	<b>Sc</b> 44.96 Scandium	<b>Ti</b> 47.88 Titan	<b>V</b> 50.92 Vanadium	<b>Cr</b> 52.00 Chrom	<b>Mn</b> 54.94 Mangan	<b>Fe</b> 55.85 Eisen	<b>Co</b> 58.93 Cobalt	<b>Ni</b> 58.70 Nickel	<b>Cu</b> 63.55 Kupfer	<b>Zn</b> 65.38 Zink	<b>Ga</b> 69.72 Gallium	<b>Ge</b> 72.61 Germanium	<b>As</b> 74.92 Arsen	<b>Se</b> 78.96 Selen	<b>Br</b> 79.90 Brom	<b>Kr</b> 83.80 Krypton
5	<b>Rb</b> 85.47 Rubidium	<b>Sr</b> 87.62 Strontium	<b>Y</b> 88.91 Yttrium	<b>Zr</b> 91.22 Zirkon	<b>Nb</b> 92.91 Niobium	<b>Mo</b> 95.94 Molybdän	<b>Tc</b> 98 Technetium	<b>Ru</b> 101.07 Ruthenium	<b>Rh</b> 102.91 Rhenium	<b>Pd</b> 106.42 Palladium	<b>Ag</b> 107.87 Silber	<b>Cd</b> 112.41 Cadmium	<b>In</b> 114.82 Indium	<b>Sn</b> 118.71 Zinn	<b>Sb</b> 121.76 Antimon	<b>Te</b> 127.60 Tellur	<b>I</b> 126.90 Jod	<b>Xe</b> 131.29 Xenon
6	<b>Cs</b> 132.91 Cäsium	<b>Ba</b> 137.33 Barium	<b>La-Lu</b>	<b>Hf</b> 178.49 Hafnium	<b>Ta</b> 180.95 Tantal	<b>W</b> 183.84 Wolfram	<b>Re</b> 186.21 Rhenium	<b>Os</b> 190.23 Osmium	<b>Ir</b> 192.22 Iridium	<b>Pt</b> 195.08 Platin	<b>Au</b> 196.97 Gold	<b>Hg</b> 200.59 Quecksilber	<b>Tl</b> 204.38 Thallium	<b>Pb</b> 207.2 Blei	<b>Bi</b> 208.98 Bismut	<b>Po</b> 209 Polonium	<b>At</b> 210 Astat	<b>Rn</b> 222 Radon
7	<b>Fr</b> 223 Francium	<b>Ra</b> 226 Radium	<b>Ac-Lr</b>	<b>Rf</b> 261 Rutherfordium	<b>Db</b> 262 Dubnium	<b>Sg</b> 263 Seaborgium	<b>Bh</b> 264 Bohrium	<b>Hs</b> 265 Hassium	<b>Mt</b> 266 Meitnerium	<b>Ds</b> 269 Darmstadtium								
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		138.91	140.12	144.24	144.24	145	150.36	151.97	157.25	158.93	162.50	164.93	167.26	168.93	173.04	175.07		
		<b>La</b> Lanthan	<b>Ce</b> Cer	<b>Pr</b> Praseodym	<b>Nd</b> Neodym	<b>Pm</b> Promethium	<b>Sm</b> Samarium	<b>Eu</b> Europium	<b>Gd</b> Gadolinium	<b>Tb</b> Terbium	<b>Dy</b> Dysprosium	<b>Ho</b> Holmium	<b>Er</b> Erbium	<b>Tm</b> Thulium	<b>Yb</b> Ytterbium	<b>Lu</b> Lutetium		
		227.03	232.04	231.04	238.03	237	244	243	247	247	251	252	257	258	259	260		
		<b>Ac</b> Actinium	<b>Th</b> Thorium	<b>Pa</b> Protactinium	<b>U</b> Uran	<b>Np</b> Neptunium	<b>Pu</b> Plutonium	<b>Am</b> Americium	<b>Cm</b> Curium	<b>Bk</b> Berkelium	<b>Cf</b> Californium	<b>Es</b> Einsteinium	<b>Fm</b> Fermium	<b>Md</b> Mendelevium	<b>No</b> Nobelium	<b>Lr</b> Lawrencium		



# Silicon Crystal

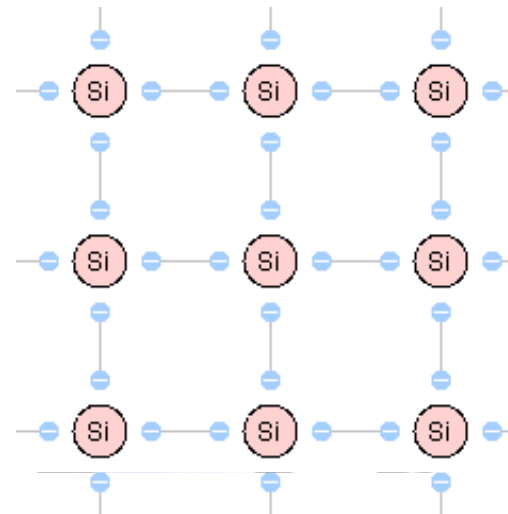
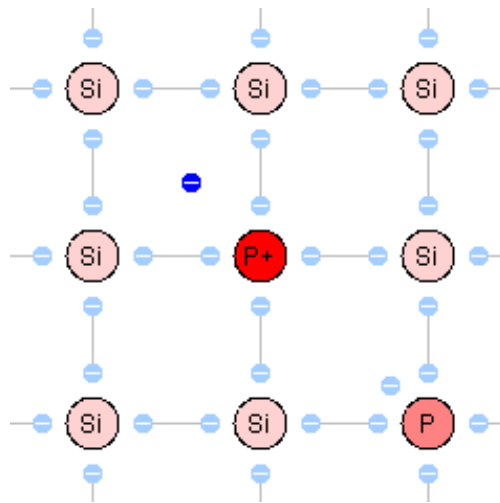


Face centered  
Cubic lattice

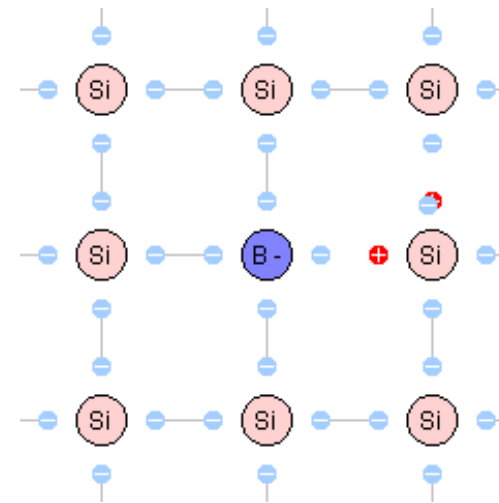


# Silicon: Crystal & Doping

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

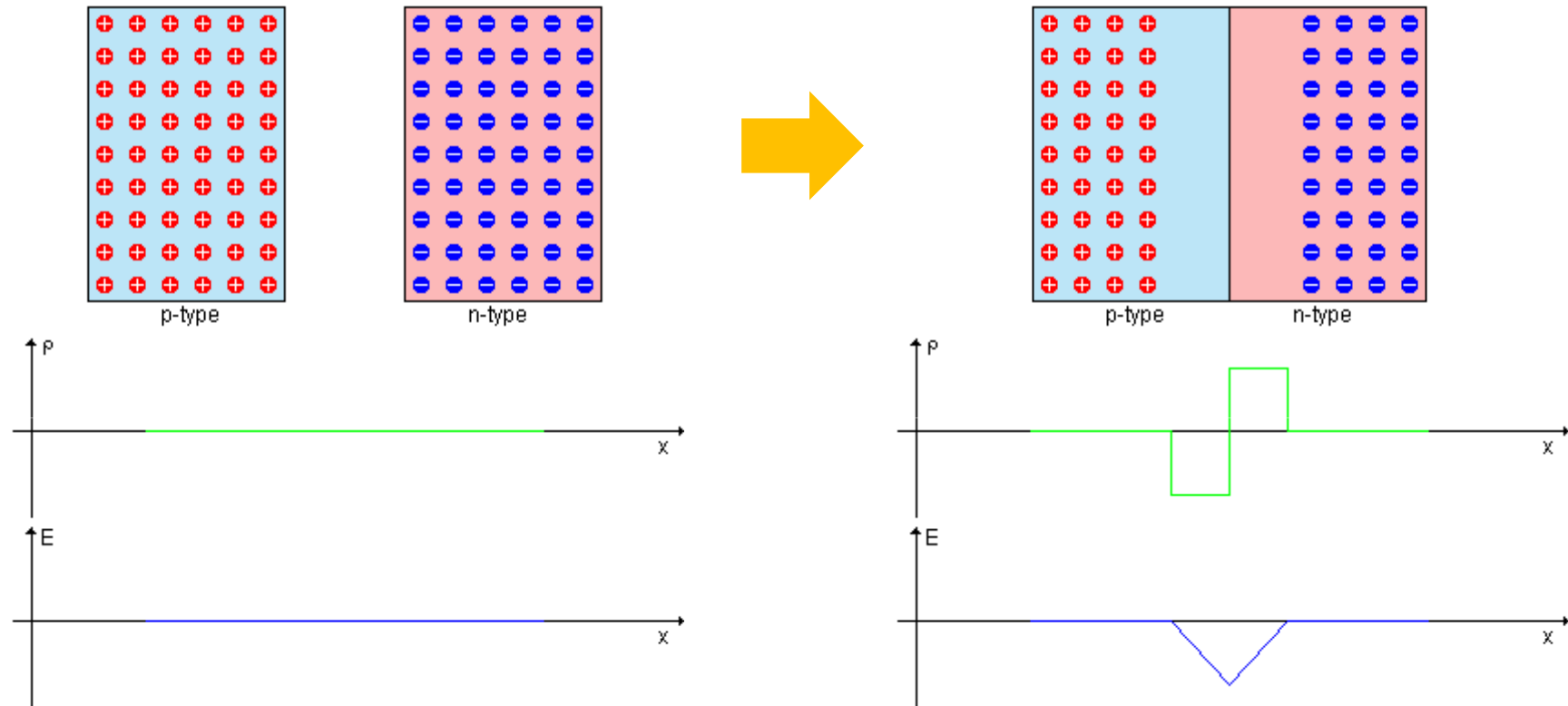


doping with  
3-valued atoms:  
- **P-conductor**  
- Acceptors **negative**





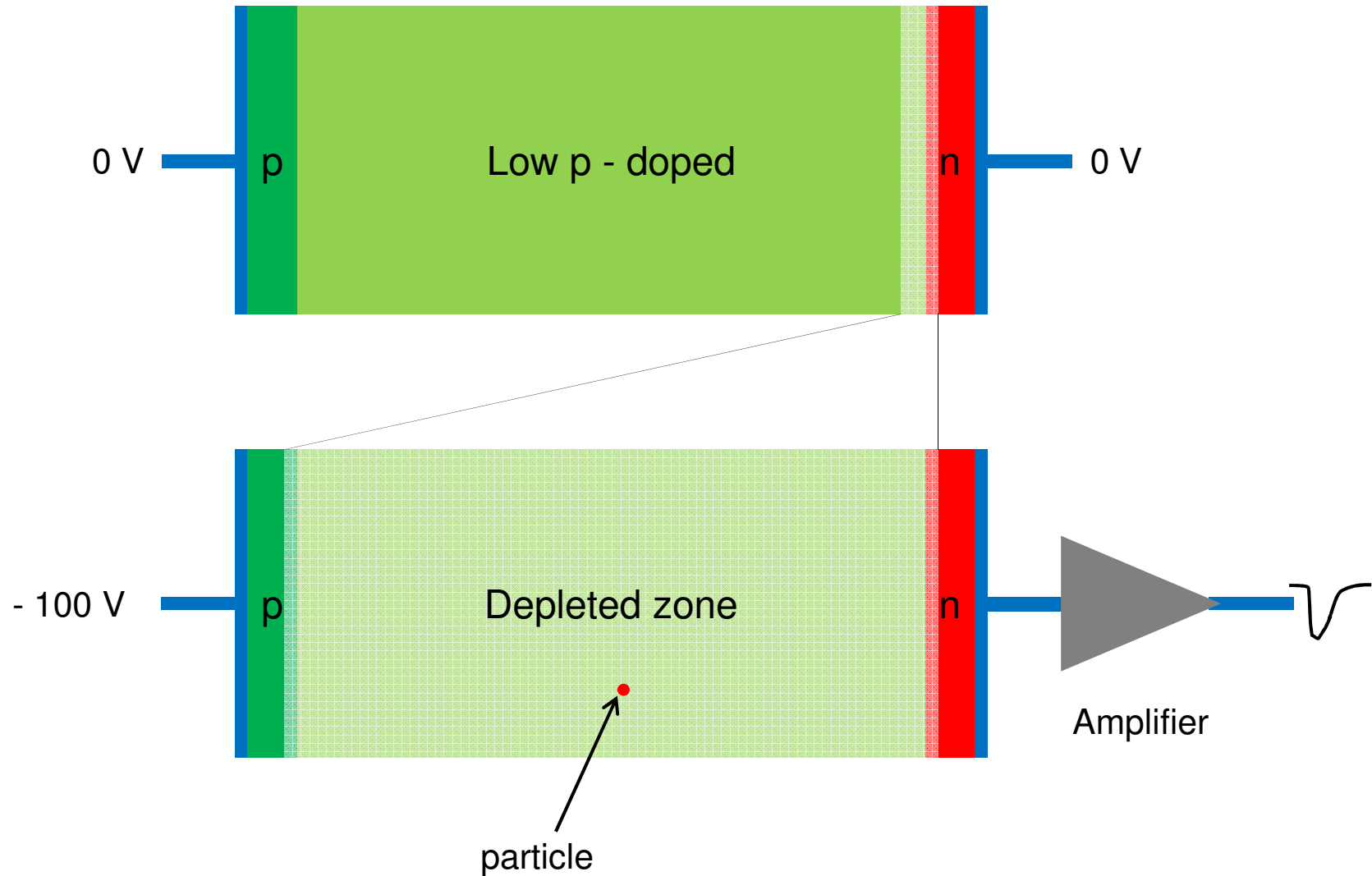
# The pn-junction (diode)



- 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 300 $\mu$ m 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!

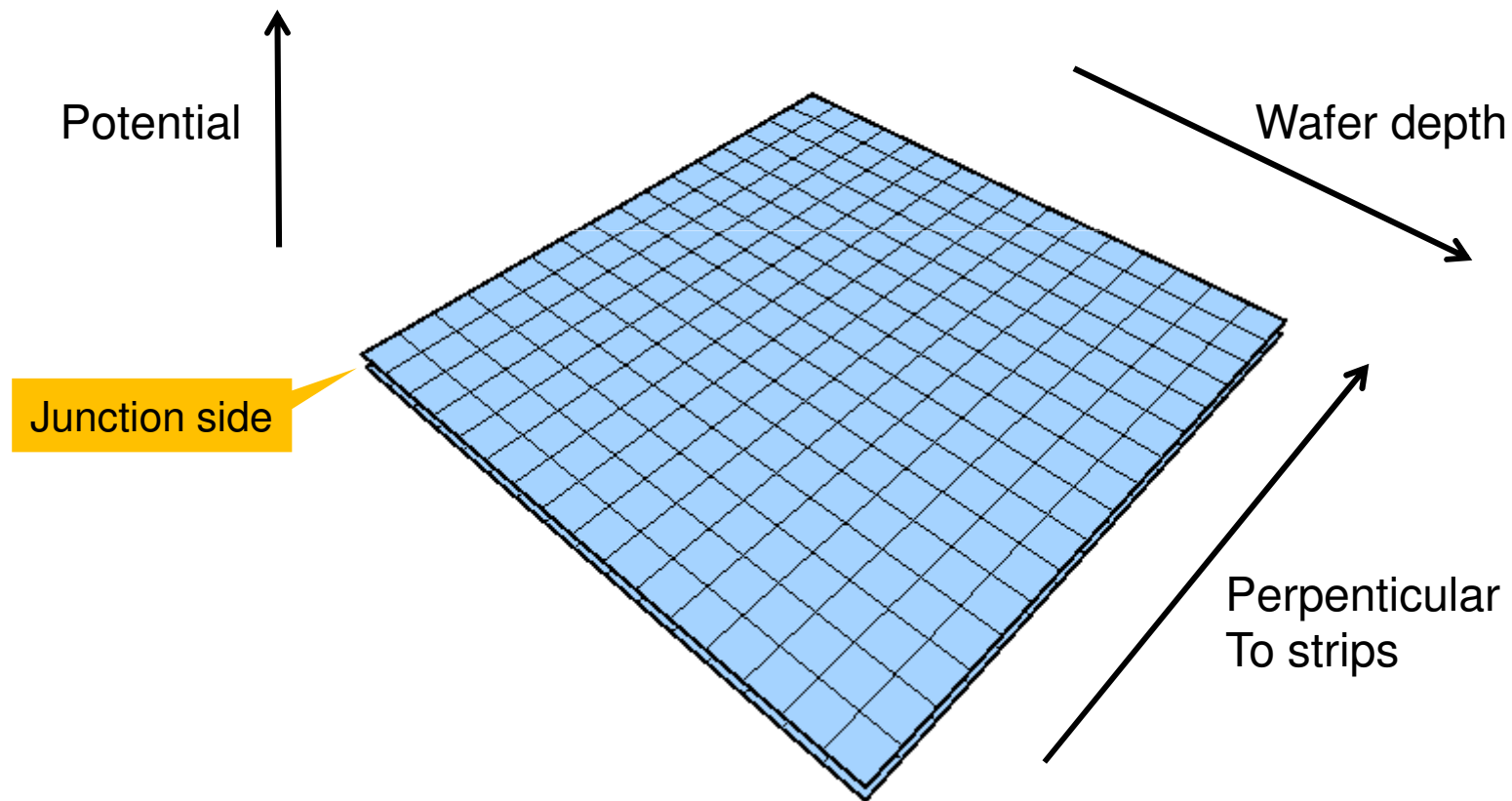




# DETECTOR TYPES

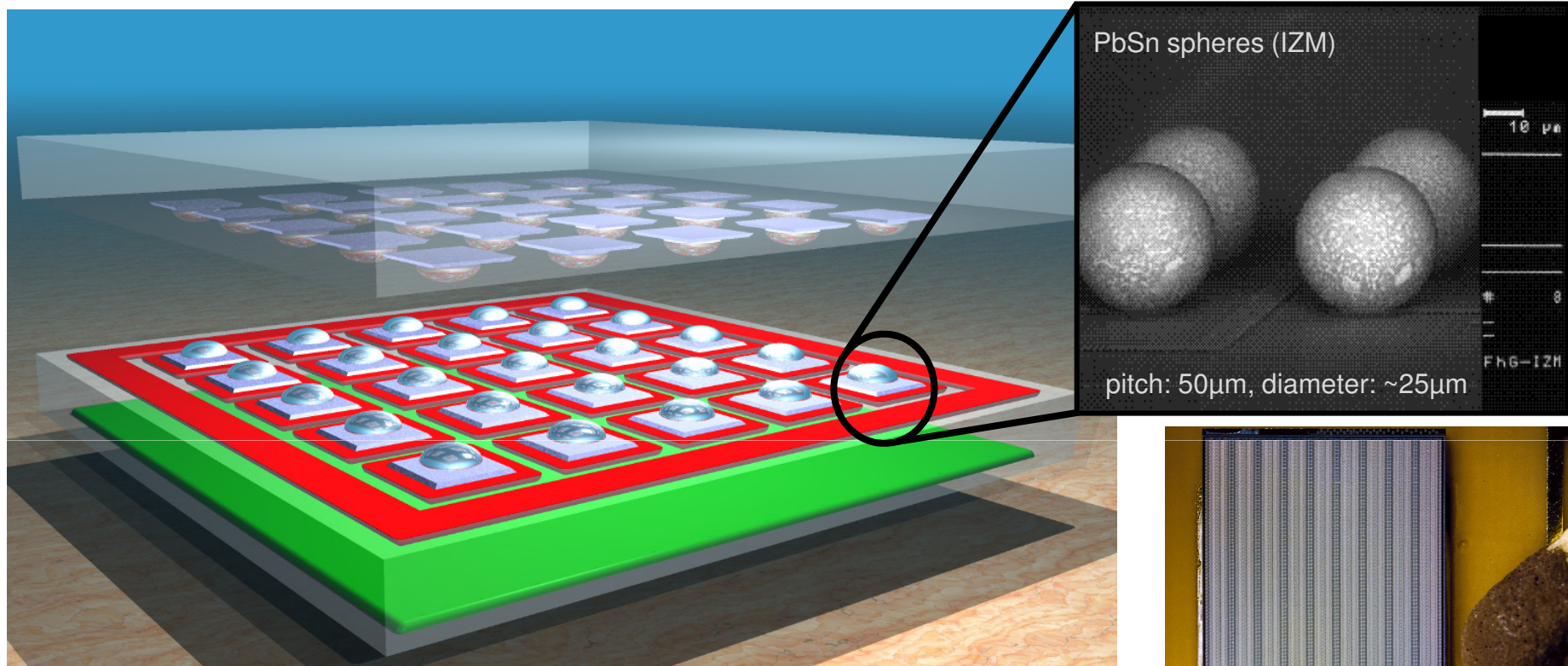


# Animation of Normal Depletion

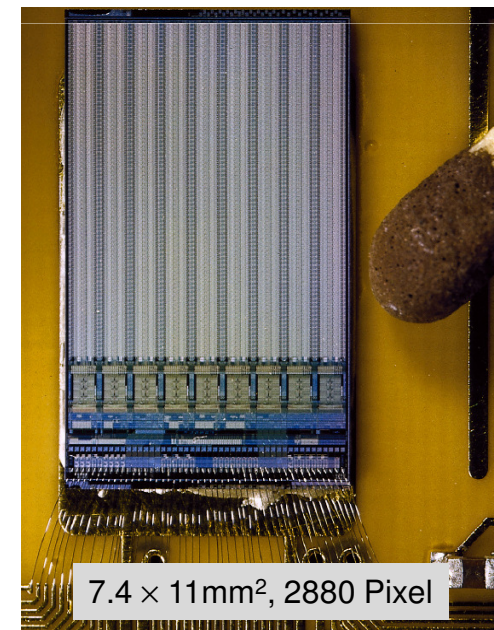




# Hybrid Pixel: Chips + Detector (Flip Chip)



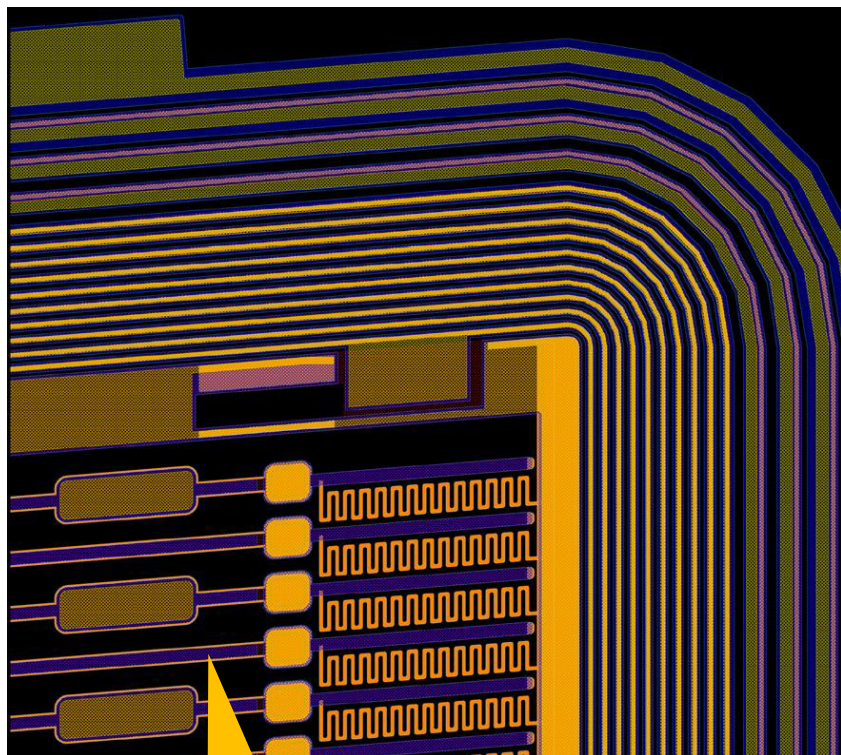
- Sensor: pn-diode with segmented electrode, also other materials, also gas
- Chip: Amplification & readout
- Interconnect: many 'bump' spheres
- Advantage: flexible readout, fast



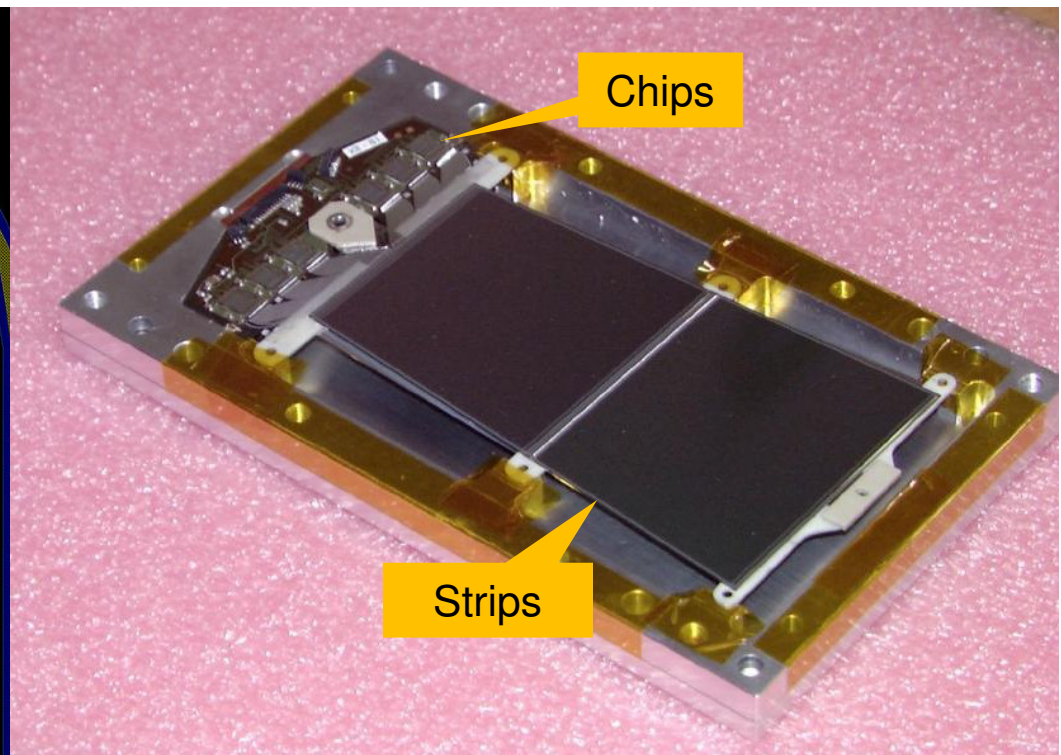


# Strip Detectors

- One (or both) sides are segmented into strips ( $\sim 50\mu\text{m}$ )
- Readout with chips at the side
- Advantage: Few channels for high spatial resolution, fast



strip



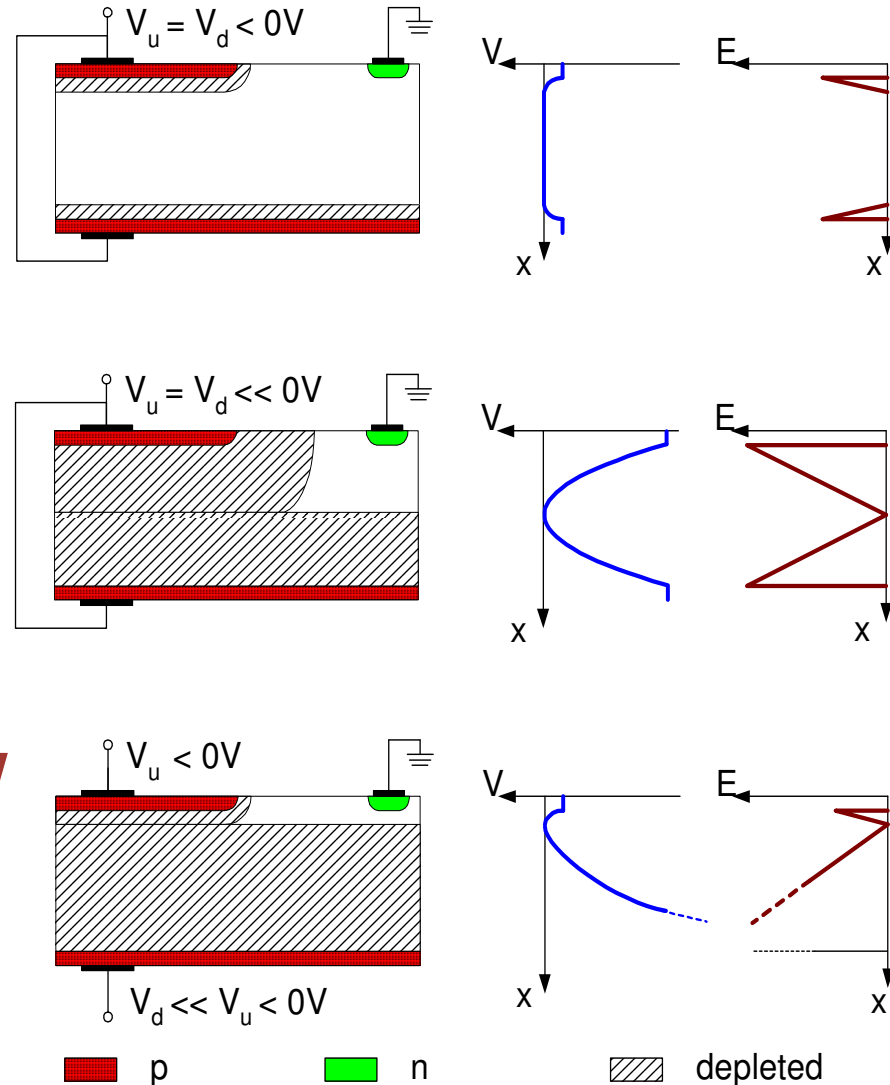
Chips

Strips



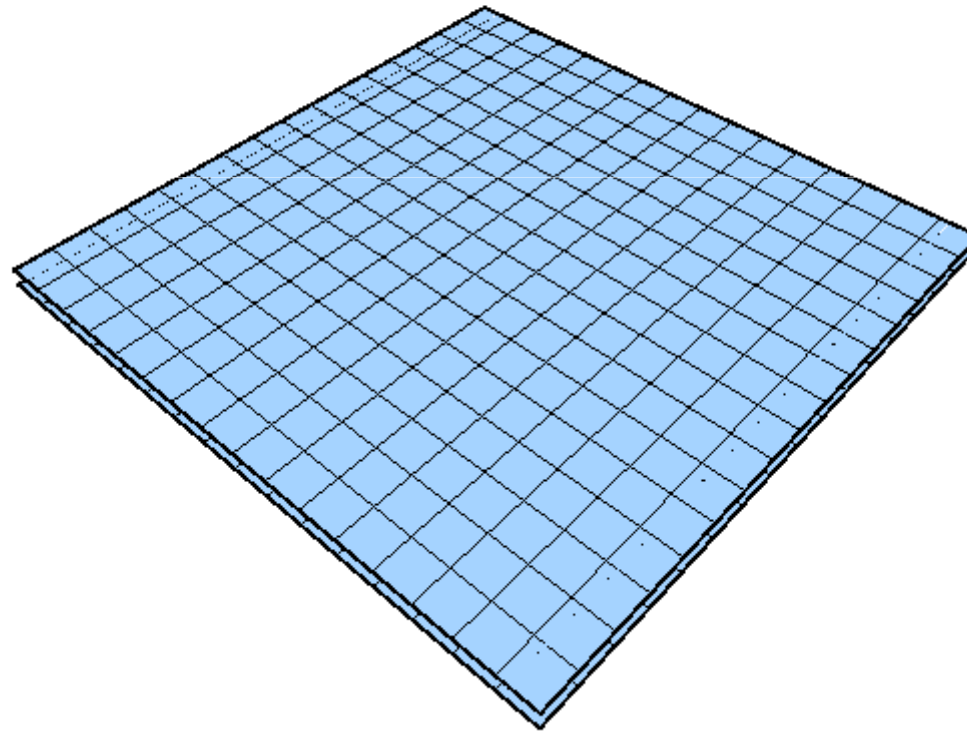
# Fully depleted CCDs: Sideward Depeletion

- 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**





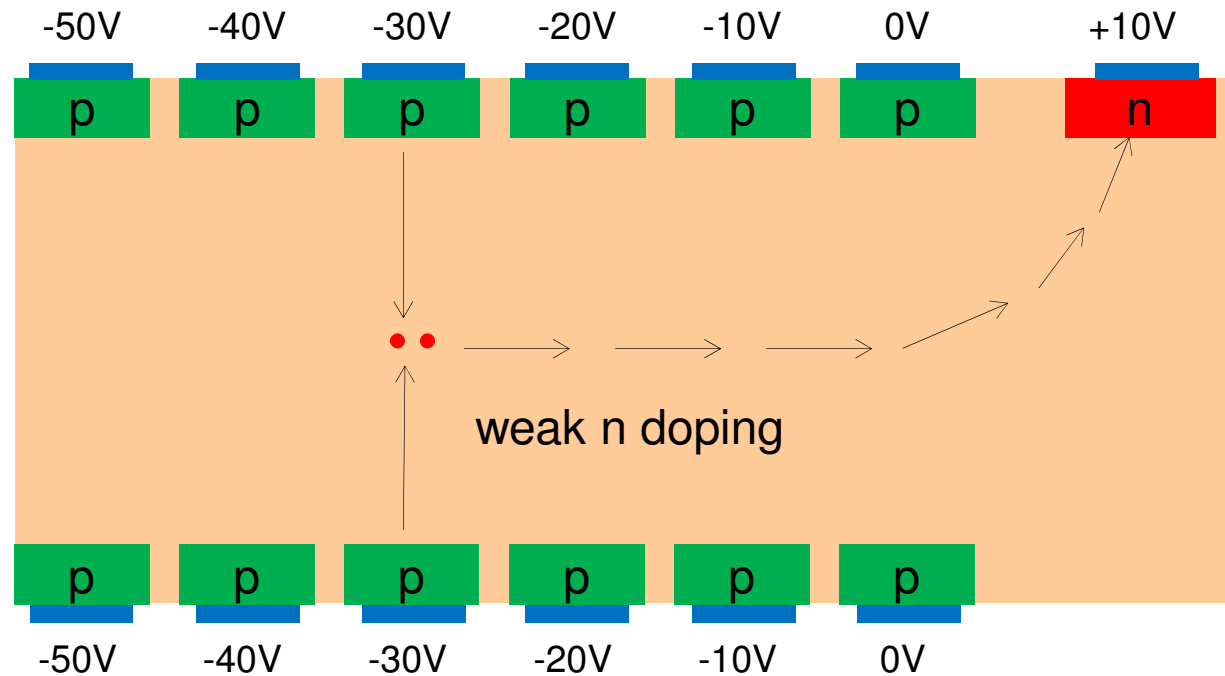
# Animation of Symmetric/Assym. Sideward Depletion





# Silicon Drift Detector

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

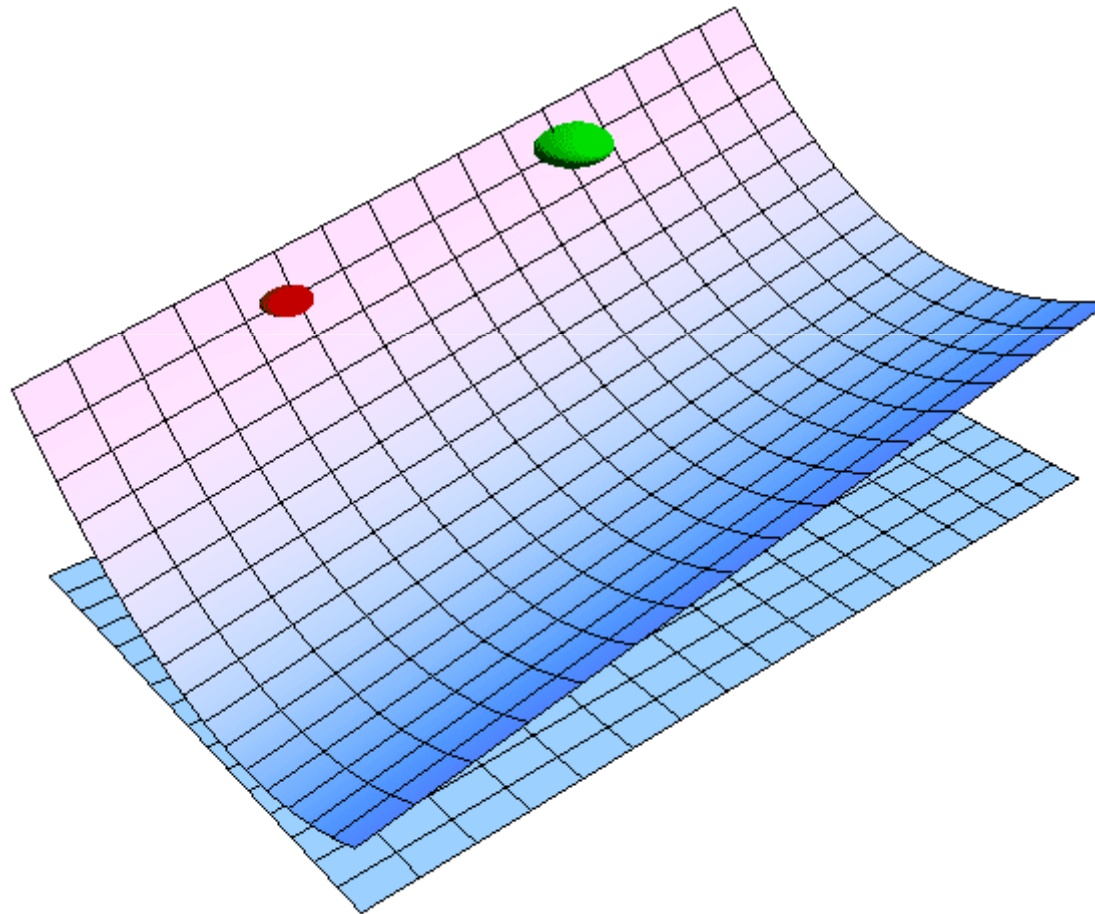


- Advantages: few readout electrodes, no extra material in active area, very low noise (few  $e^-$ )



# Animation Silicon Drift Detector: Synchronous Case

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

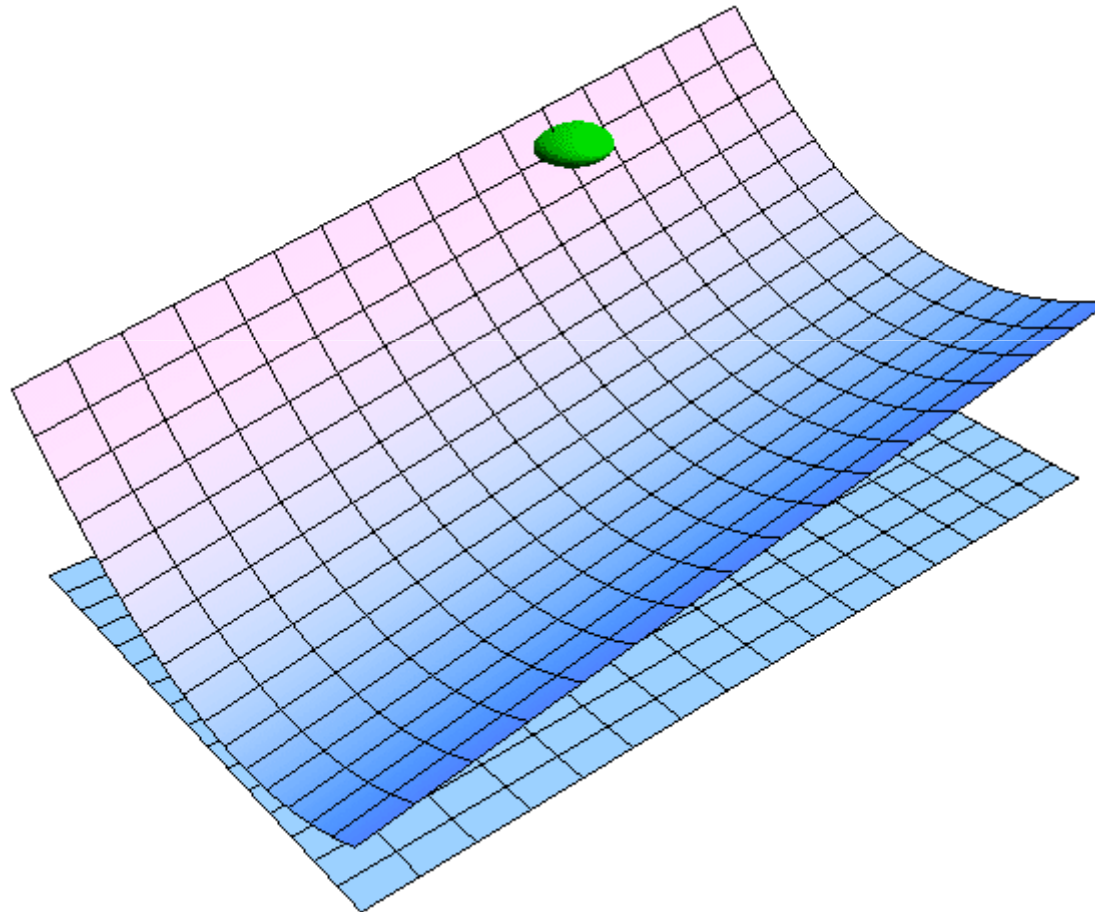






# Animation Silicon Drift Detector: Problem

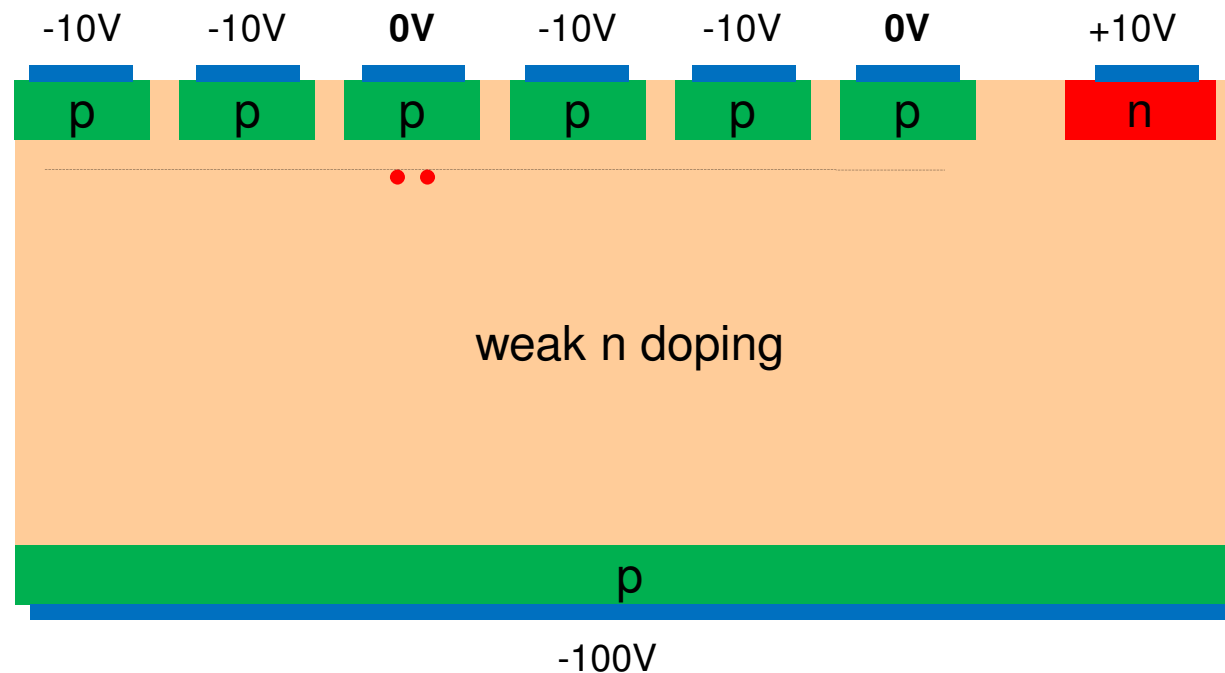
- Position *cannot be reconstructed* drift start unknown!
- e.g.: radioactive decays





# Fully depleted CCD

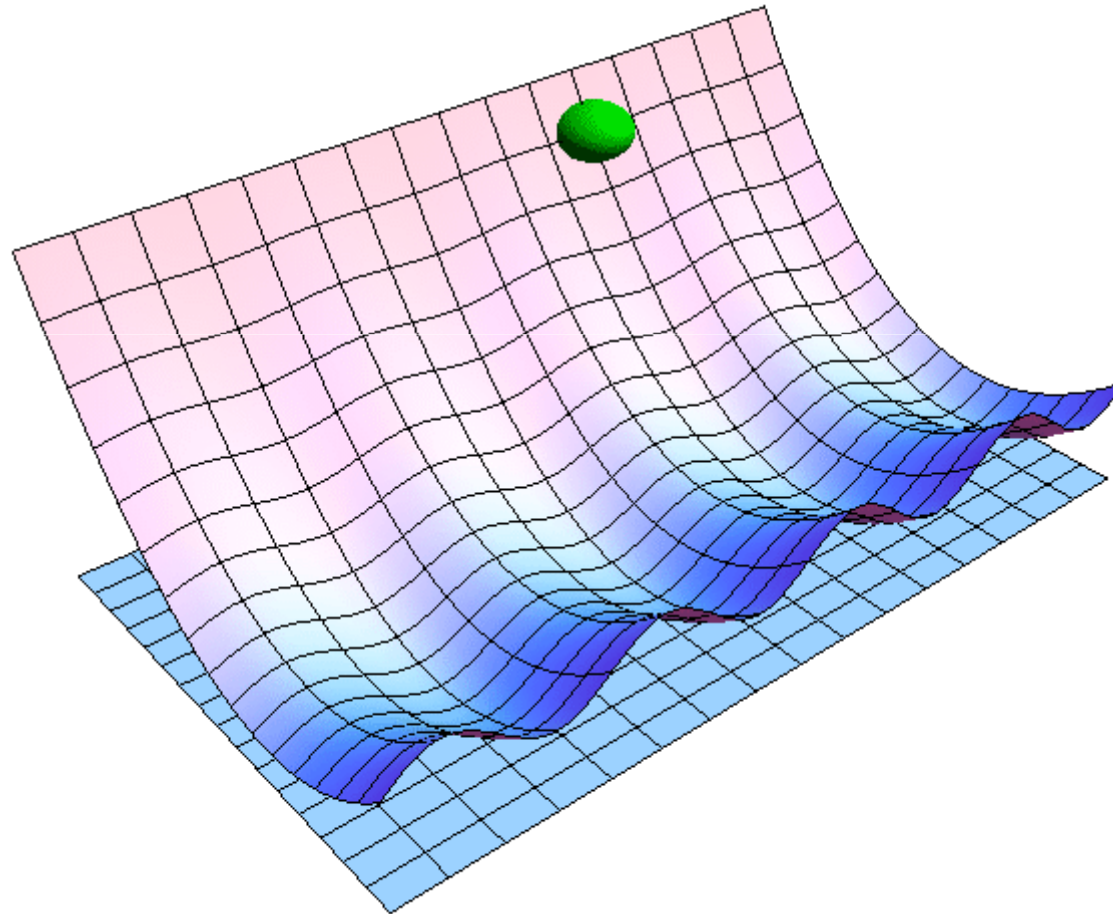
- Upper side is divided into strips
- Electrons accumulate under the positive strips
- They are 'shifted' with positive voltages to the edge



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



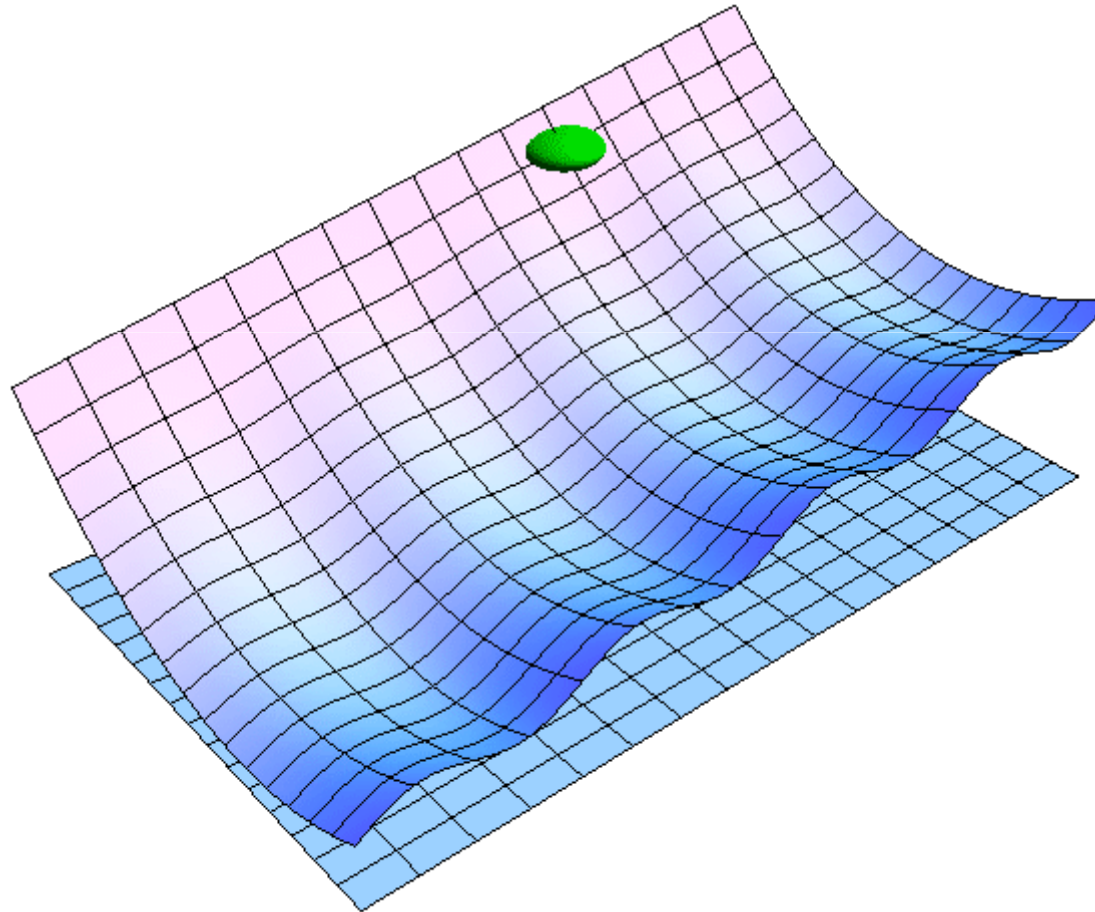
# Animation: Fully Depleted CCD





# Controlled Drift Detector

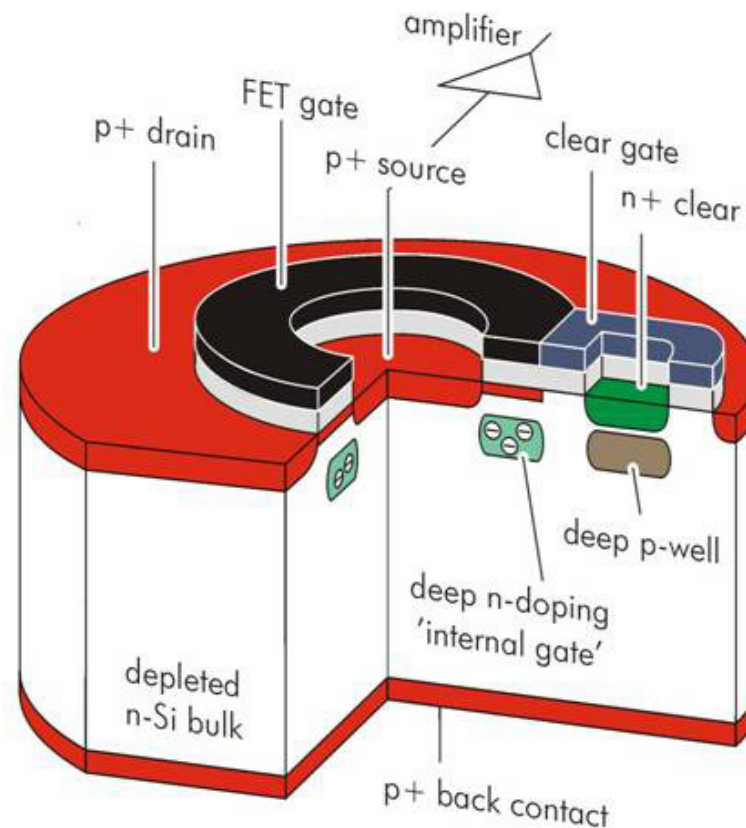
- First Collect Charges in potential pockets
- Then drift by *switching off* the potential wells





# 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  $\rightarrow$  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