Towards the Holy Grail: CMOS-Compatible, (Near-) Infrared Image Sensors

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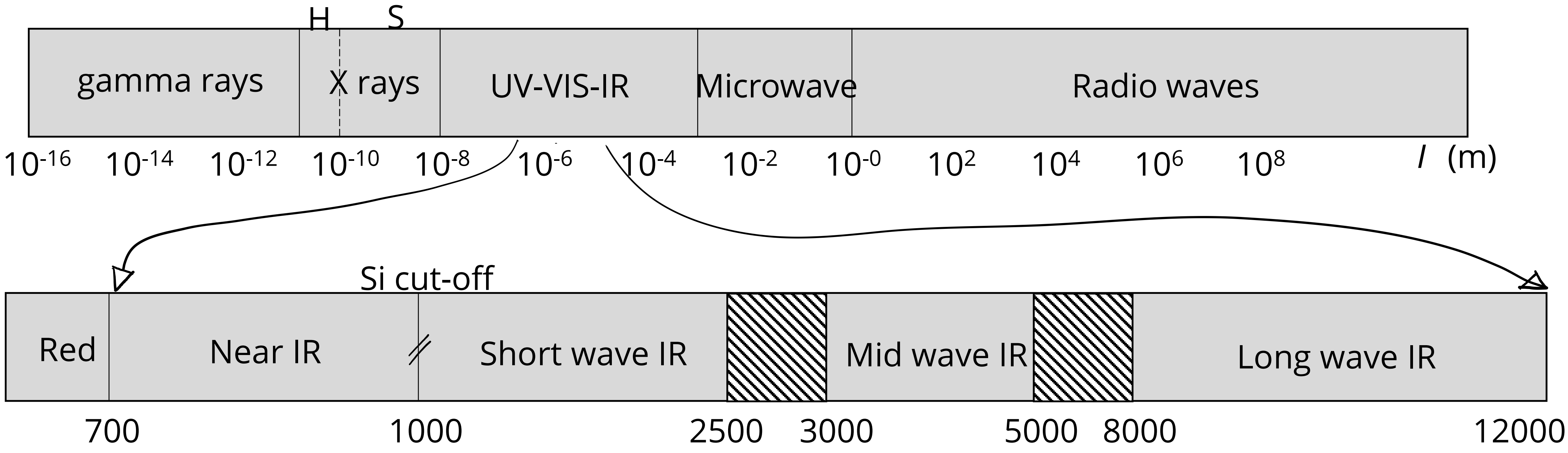
THE INFRARED (IR) SPECTRUM

The infrared (IR) spectrum



- Fiber optic communication
- Sorting

- Security
- Metrology/inspection
- Night vision

- Security (gas detection)
- Surveillance

Reflected light is mainly utilized | Generated (thermal) radiation is mainly utilized

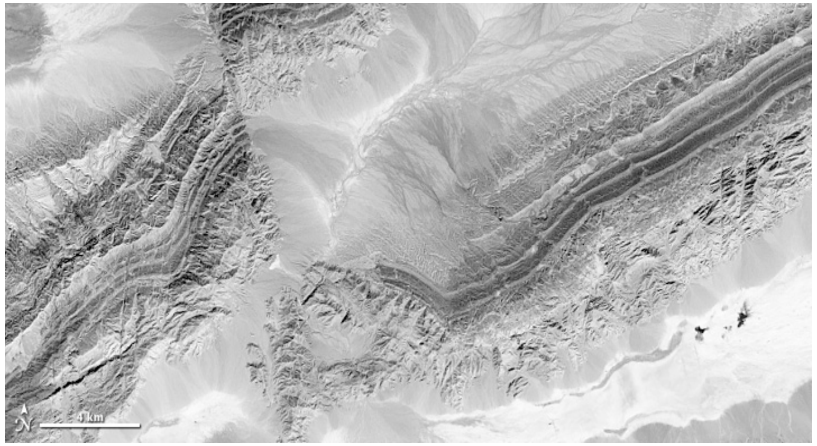
APPLICATIONS OF NIR IMAGING

Images of San Francisco Bay produced by a visible light camera and a SWIR camera.

Image credits: NASA

Advantages:

- See through haze and smoke
- High contrast in difficult illumination situations
- Takes advantage of existing optics
- Good sensitivity
- Effective for identification



NIR view of the Piqiang Fault, China

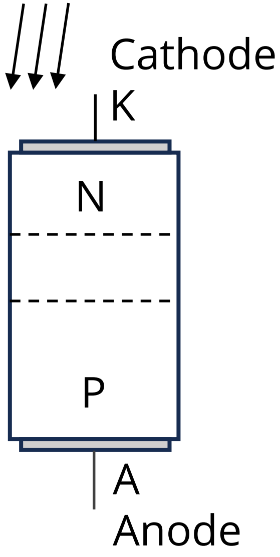
Space applications :

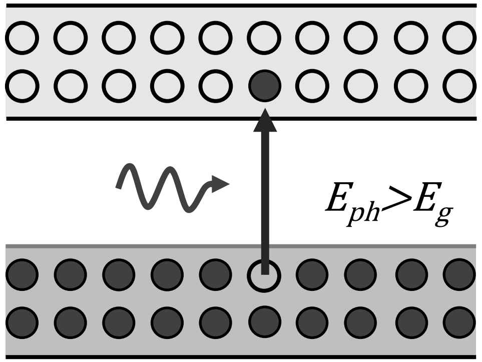
- Earth observation and characterizing special features of ground, environmental mapping, weather and climate monitoring from on board satellites (MIR to VLWIR)

Other major applications of interest:

- Machine vision, healthcare, food sorting, pedestrian detection

ADDRESSING THE IMAGING BEYOND VISIBLE



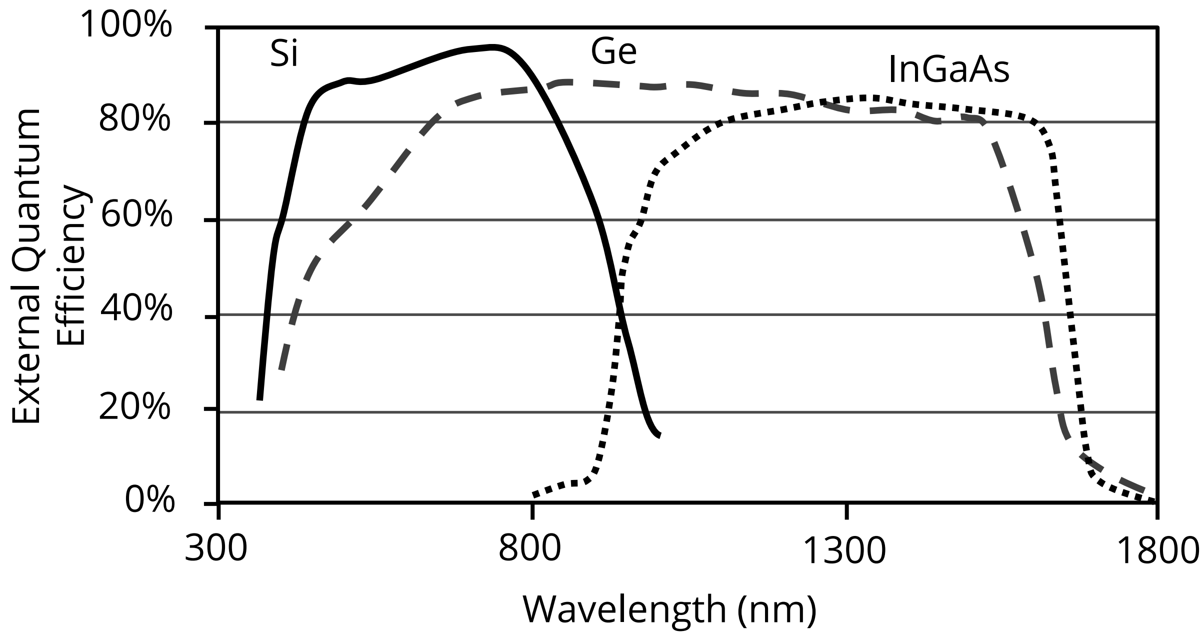


$$\frac{hc}{\lambda} > E_g \Rightarrow \lambda > \frac{1.24}{E_g} = \lambda_c$$

λ – wavelength
λ_c – cut-off wavelength
E_g – band gap energy
h – Planck's constant
c – speed of light

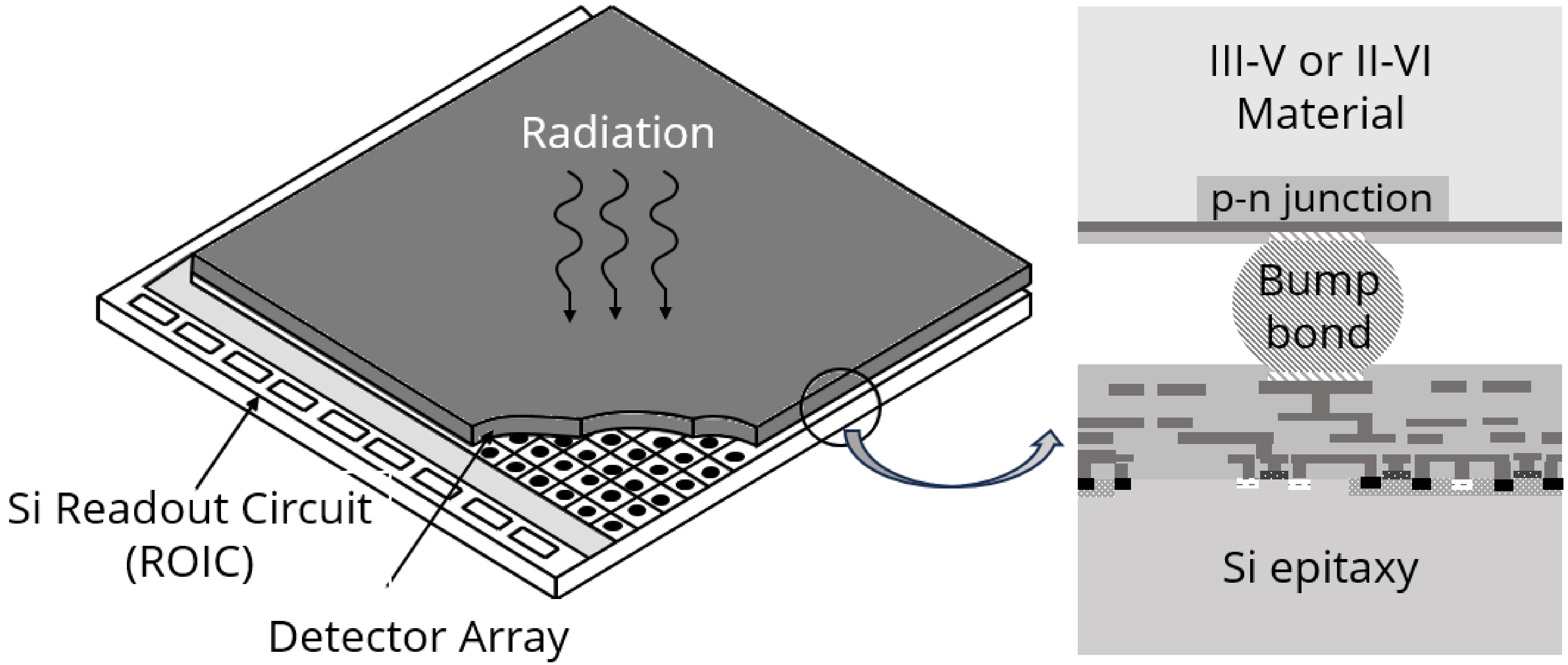
- Image sensors are similar in overall architecture in many domains
- Uses a photodiode to convert incident photons to electrical charges
- Requires that the energy of the photons is larger than the bandgap of the semiconductor

Addressing the Imaging Beyond Visible



Material	Band gap (eV)	Cut-off wavelength (µm)	Suitable range
Silicon	1.12	1.1 (unusable beyond 0.85 µm)	VIS
Germanium	0.66	1.9	SWIR
InGaAs	0.75	1.65	SWIR
InSb	0.225	5.5	MWIR
$Hg_xCd_{(1-x)}Te$(MCT) 0<x<0.8	0.09 - 1.6	0.8 - 14	SWIR - LWIR

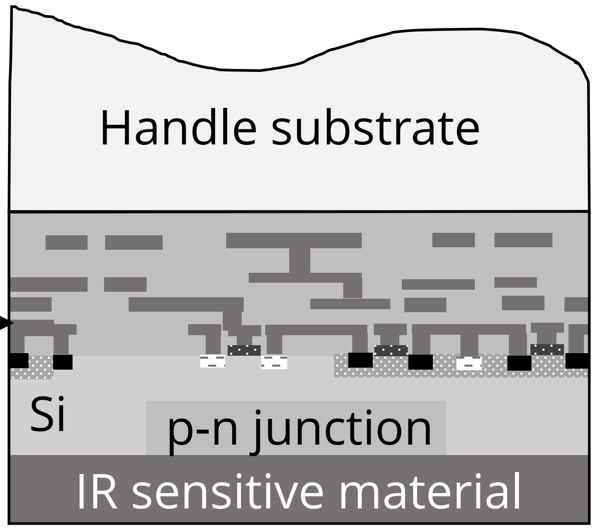
DOMINANT TECHNOLOGIES & DRAWBACKS



- The detector array is separately fabricated and connected at the pixel level by hybridization
- Hybrid/3D integration methods are complex & require specialised foundries and is expensive
- The advantage of CMOS scaling cannot be fully utilised
- Can we achieve IR imaging in a CMOS compatible process?

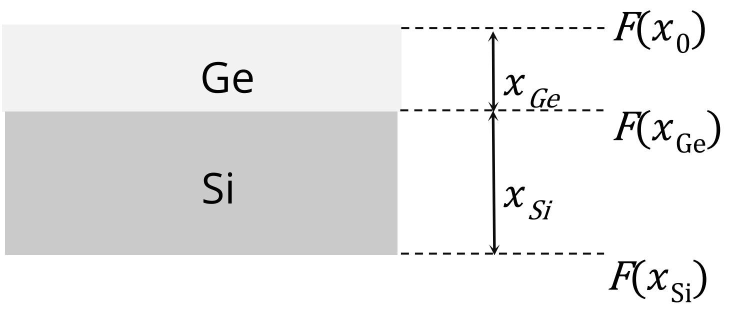
Our Research Towards the Holy Grail

Device physics & process simulations → Design of experiments → Fabrication & processing of test-devices →



- Post-process silicon with NIR/SWIR sensitive materials (e.g., III-V, II-IV or upconverting materials)
- Use low temperature (< 350 °C) techniques such as using Chemical Vapour Deposition (CVD)
- **Advantages**:
  - Makes use of the advantage of CMOS scaling
  - No complex integration techniques, not expensive

Simulation of the Beer Lambert's Law



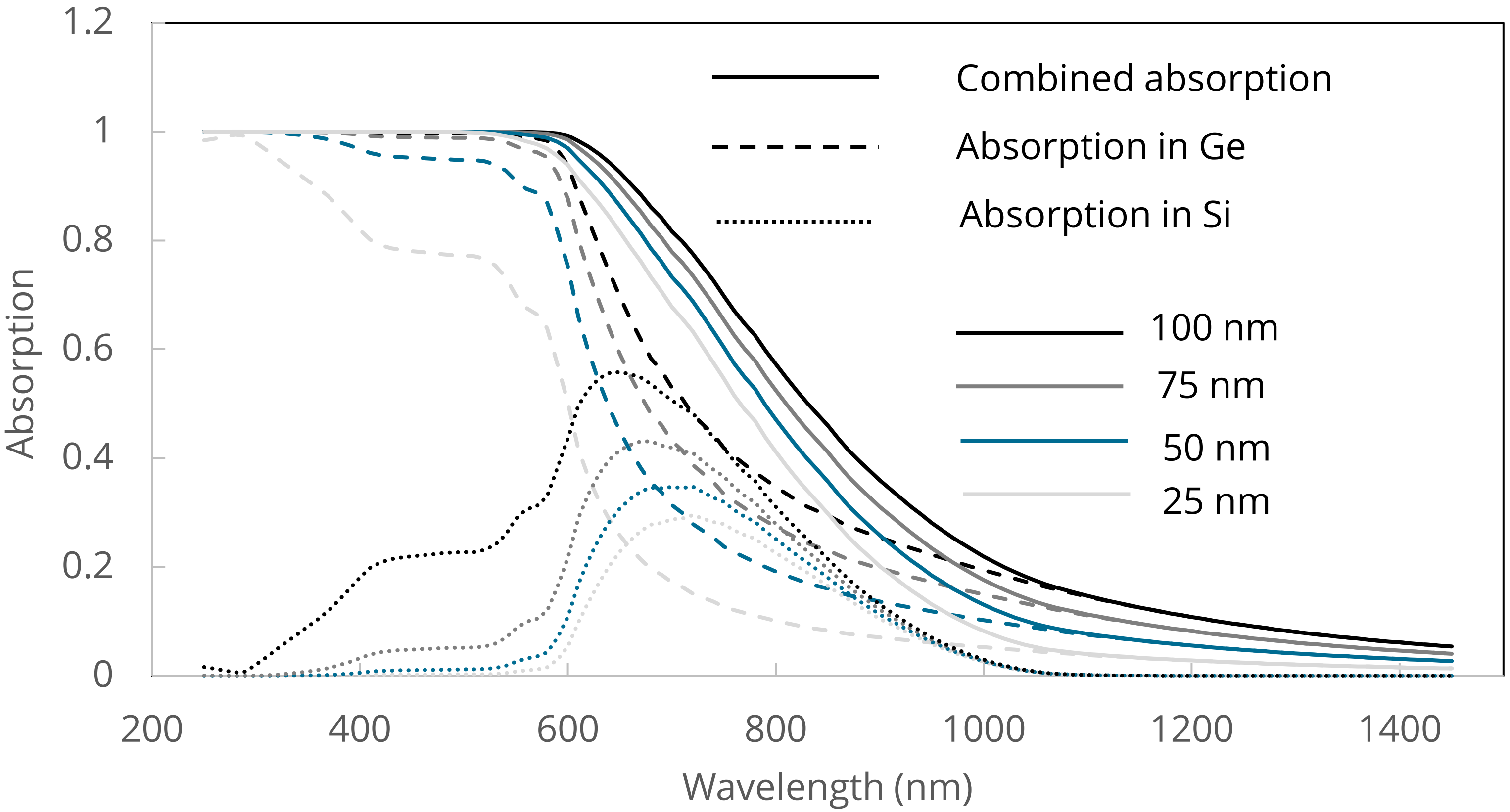
$$F(x_{Ge}) = F(x_0)e^{-\propto_{Ge}x_{Ge}} \quad (1)$$

$$F(x_{Si}) = F(x_{Ge})e^{-\propto_{Si}x_{Si}} \quad (2)$$

Using (1) in (2);

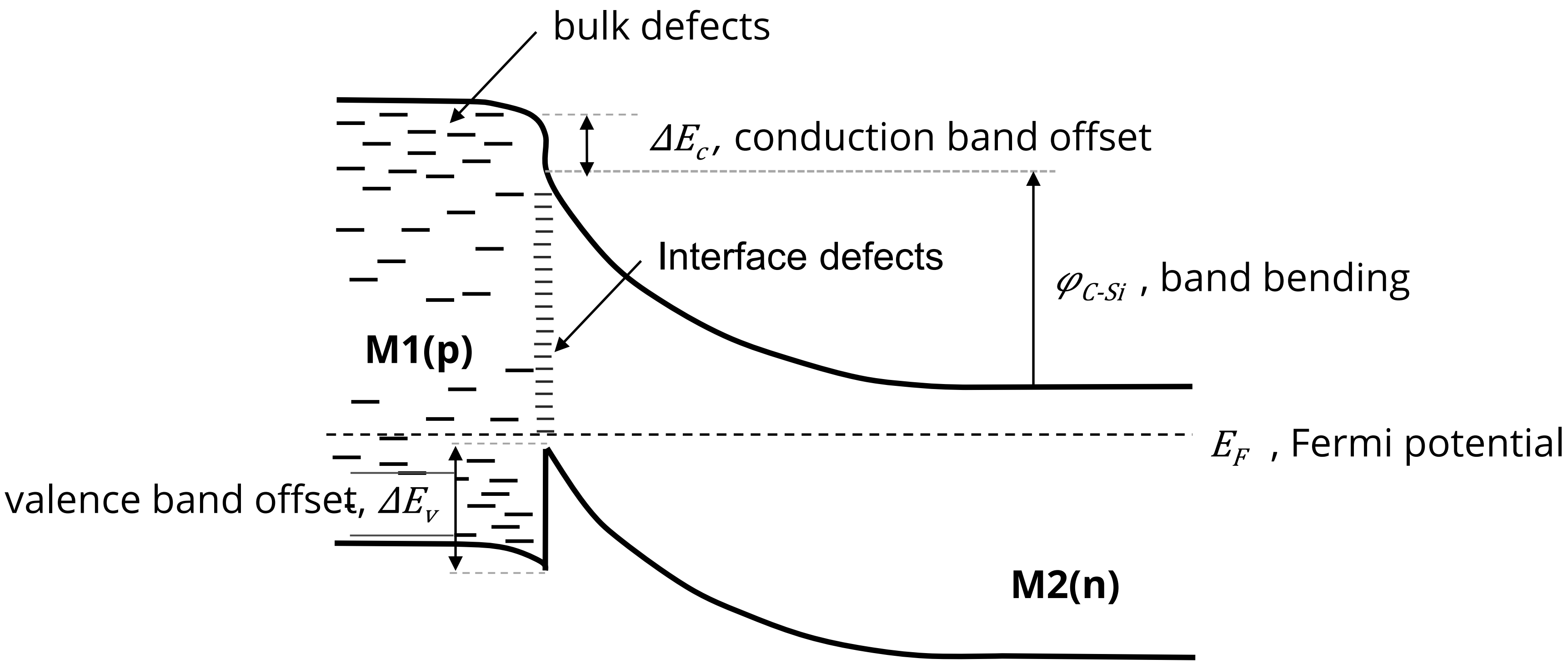
$$F(x_{Si}) = F(x_0)e^{-(\propto_{Ge}x_{Ge}+\propto_{Si}x_{Si})} \quad (3)$$

$$Q.E.\ \alpha\ 1 - F(x_{Si}) \quad (4)$$



x_{Ge} - thickness of Ge
x_{Si} - thickness of Si
α_{Ge} - absorption coefficient of Ge
α_{Si} - absorption coefficient of Si
$F(x_0)$ - photon intensity at the surface
$F(x_{Ge})$ - photon intensity at depth x_{Ge}
$F(x_{Si})$ - photon intensity at depth $x_{Ge} + x_{Si}$

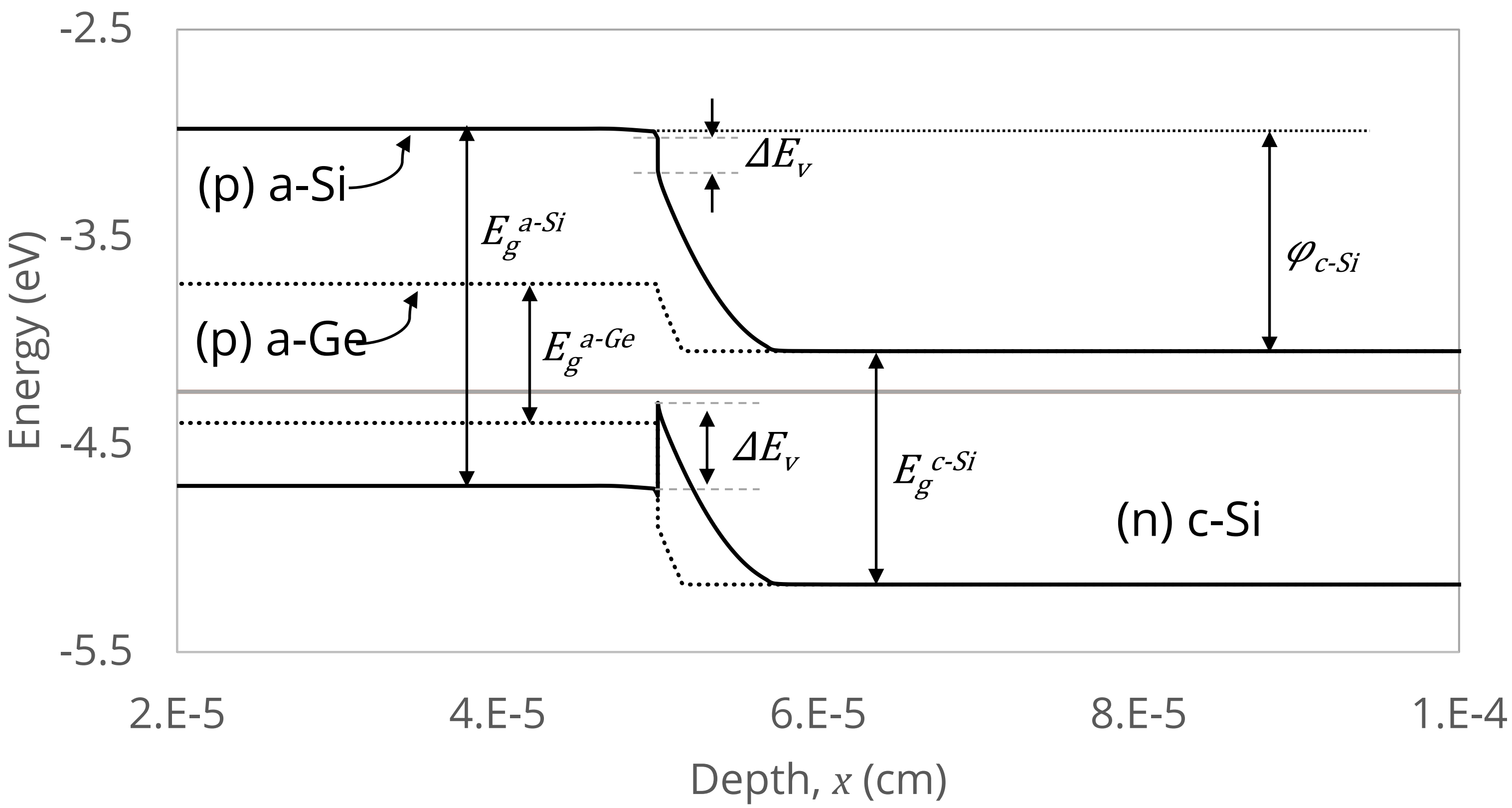
FACTORS AFFECTING THE PERFORMANCE OF A HETEROJUNCTION



Properties of interface that determine the performance of a photodiode

- band offsets between the materials due to the changes in their band gaps and electron affinities,
- interface and bulk defects
- band bending due to Fermi potential alignment

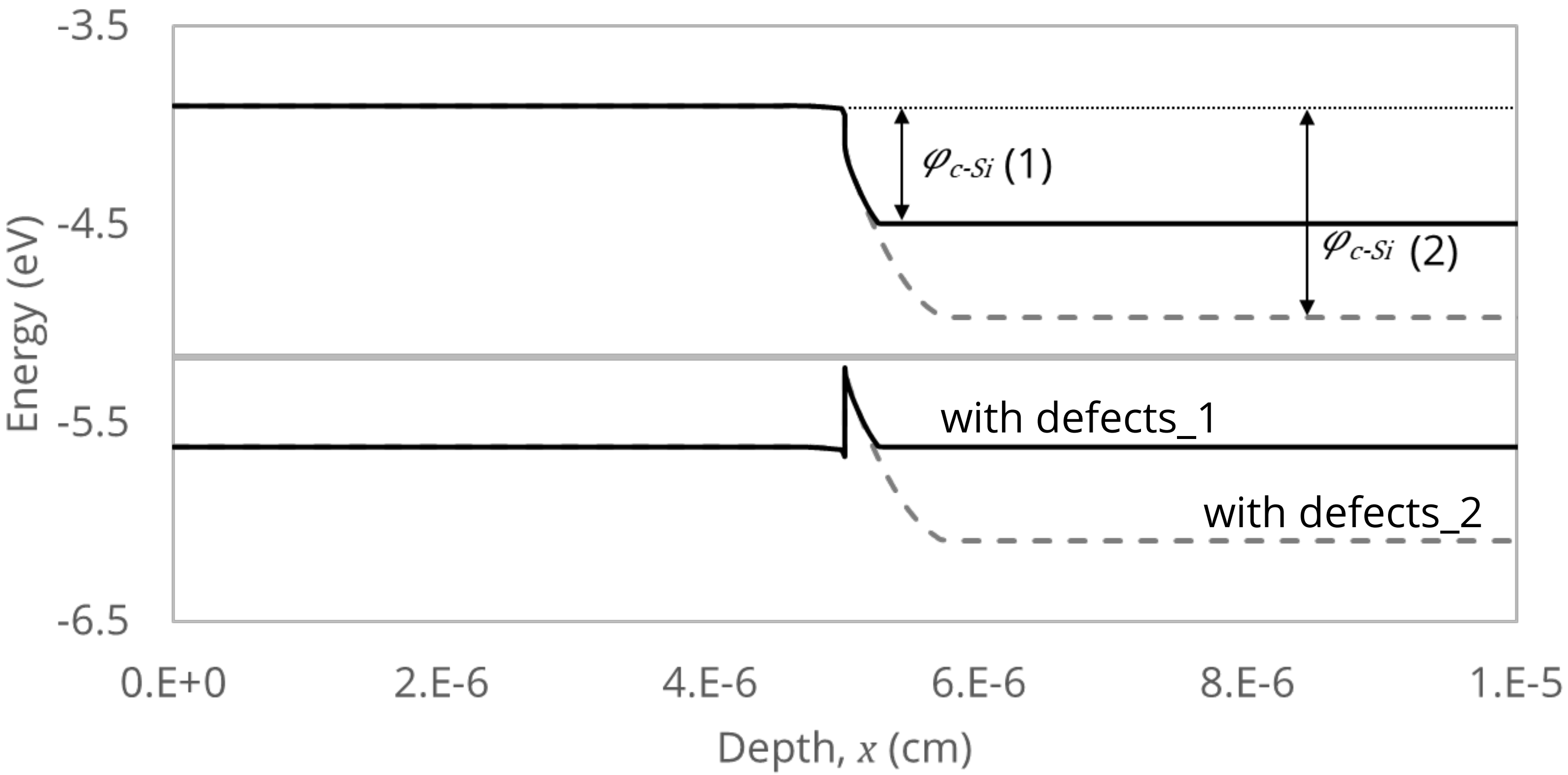
Simulation Results



Material	Thickness (μm)	Band gap	Electron affinity
a-Si	0.5	1.72	3.9
a-Ge	0.5	0.68	4.01
c-Si	300	1.12	4.05

- Used a numerical simulation tool AFORS-HET, automat for simulation of heterostructures
- It allows to simulate different sequence of semiconducting layers and interfaces

SIMULATIONS



$\varphi_{c\text{-}Si}$ – band bending

Material	**Trap densities /cm^{-3}**	
	Defects_1	Defects_2
a-Si	1E18	1E20
interface	1E10	1E20
c-Si	1E10	1E18

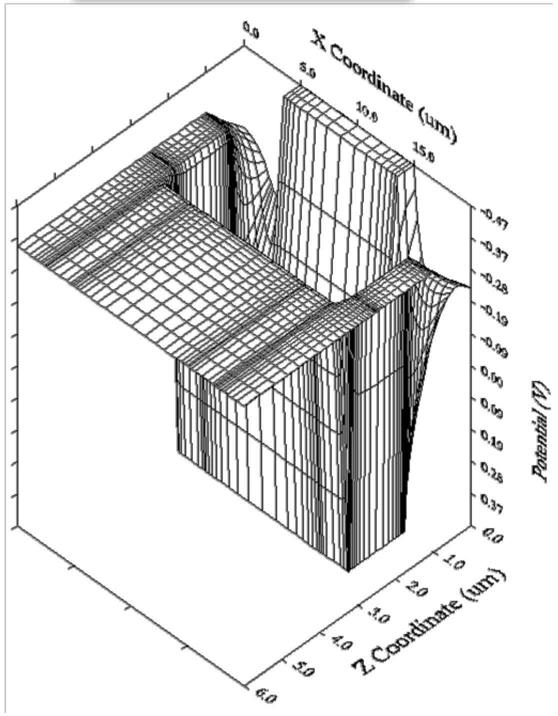
- Band bending increases with increased defect densities

PROCESS FLOW

Experimentation with test devices/layers on Si wafer

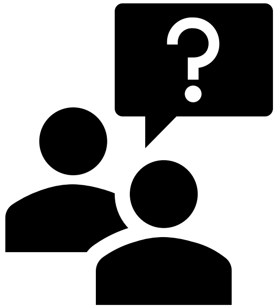
Numerical simulations (e.g. AFORS-HET)

3D Device physics simulations (e.g., Spectra)



Experimentation with real Si based image sensor

For Further Discussion



- We would appreciate your inputs on:
  - Your experiences (if any) with low-temperature (post-) processing of materials on Si or similar
  - Use of device physics simulation/AFORS-HET or similar for tandem cells
  - Impact of our R&D on your own research
  - Options for collaboration

Feel free to have a chat offline!