Overview of Photocathode Physics & Plans

ANL:

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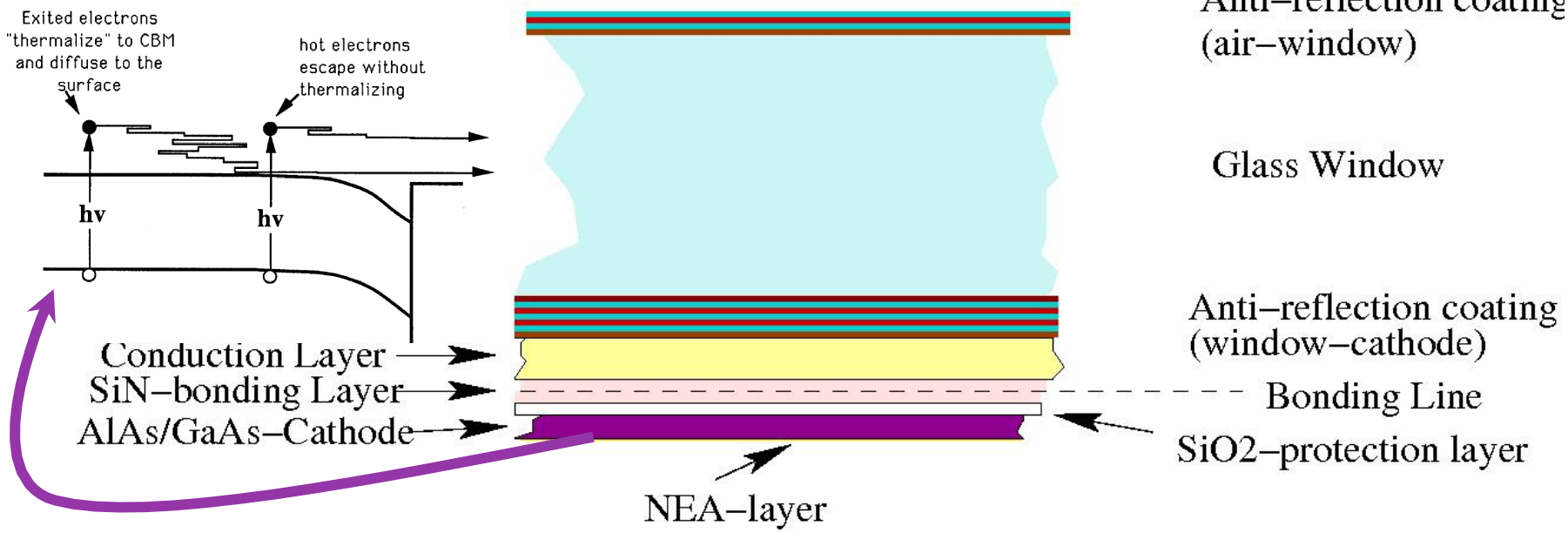
Overview

- Motivation and description of the challenge
- The program and who is involved
- Theory inspired device design: GaAs, a specific example
  - Wavelength optimization
  - Properties of photoelectrons
  - Kinetic energy and NEA-surface
  - Dark current and surface states
- Conclusions

What is a Photocathode



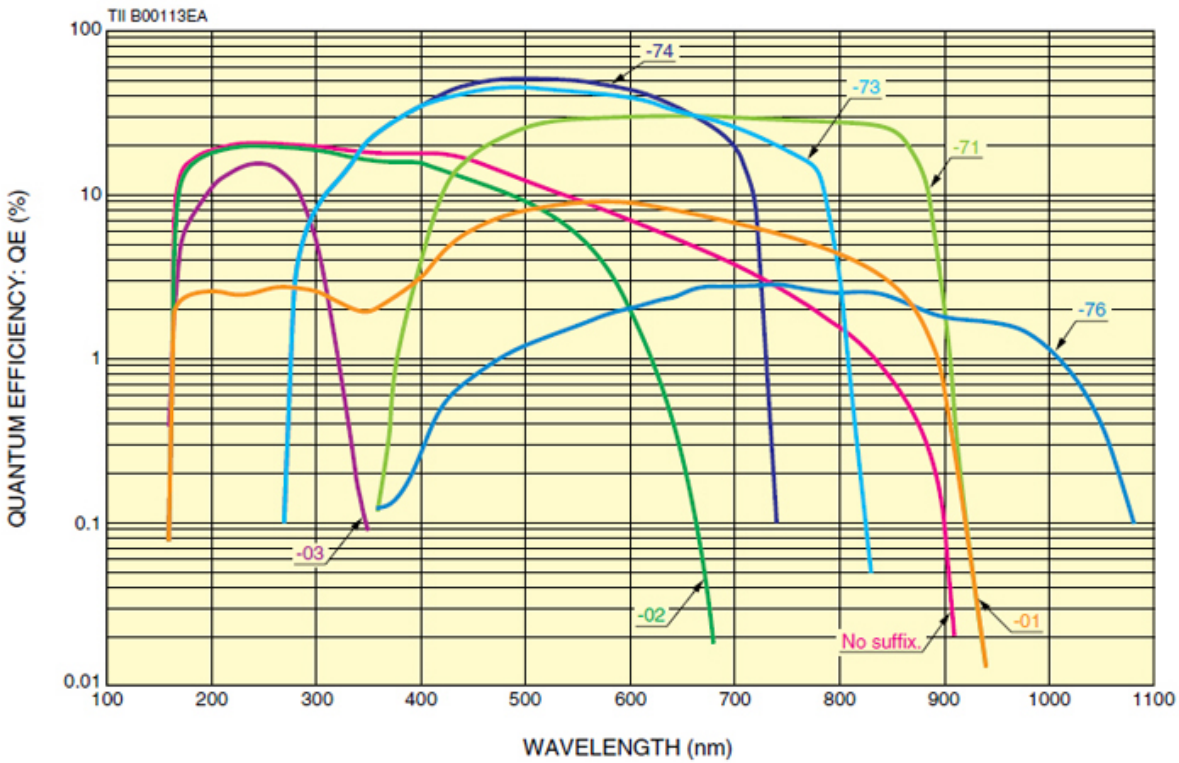
- Transmission Cathode is a complex heterogeneous structure with many functionality layers
- Cathode (Photon-Electron Conversion Layer) is described in three step model.
- QE(v) depends on reflection losses of photons, absorption efficiency of cathode layer, electron transport and recombination properties of cathode, and emission properties of surface
- Noise behavior depends on surface states of photocathode:
  1 out of 10^{23}!

What do We Expect from a Good Photocathode (Especially for the LAPPD-Project)

- Physical Properties:
  - High quantum efficiency in defined wavelength range (possibility of tailoring)
  - Low dark-count probability (noise)
  - Robust structure resulting in long lifetime
  - Specific for application
    - High count rate capability
    - Ultrafast response
    - Extreme wavelength response (x-rays/gamma rays)
- Production Needs:
  - Compatible with industrial large scale process technology (Production has to be similar to solar panel production …….)
  - Good production yield (with low sigma)
  - Cathode has to be process compatible (Sealing technology)
  - Production must tolerate large production-volume changes (10.000m2 =

The Photocathode Families

Hamamatsu: http://jp.hamamatsu.com/products/sensor-etd/pd014/index_en.html



Suffix	Photocathode	Input Window
-71	GaAs	Borosilicate Glass
-73	Enhanced Red GaAsP	Borosilicate Glass
-74	GaAsP	Borosilicate Glass
-76	InGaAs	Borosilicate Glass
Non	Multialkali	Synthetic Silica
-01	Enhanced Red Multialkali	Synthetic Silica
-02	Bialkali	Synthetic Silica
-03	Cs-Te	Synthetic Silica

- Required spectral response still not clear (main application)
- Future applications (combination with scintillators) will require response optimization

Why are we Planning a Large Cathode Effort?

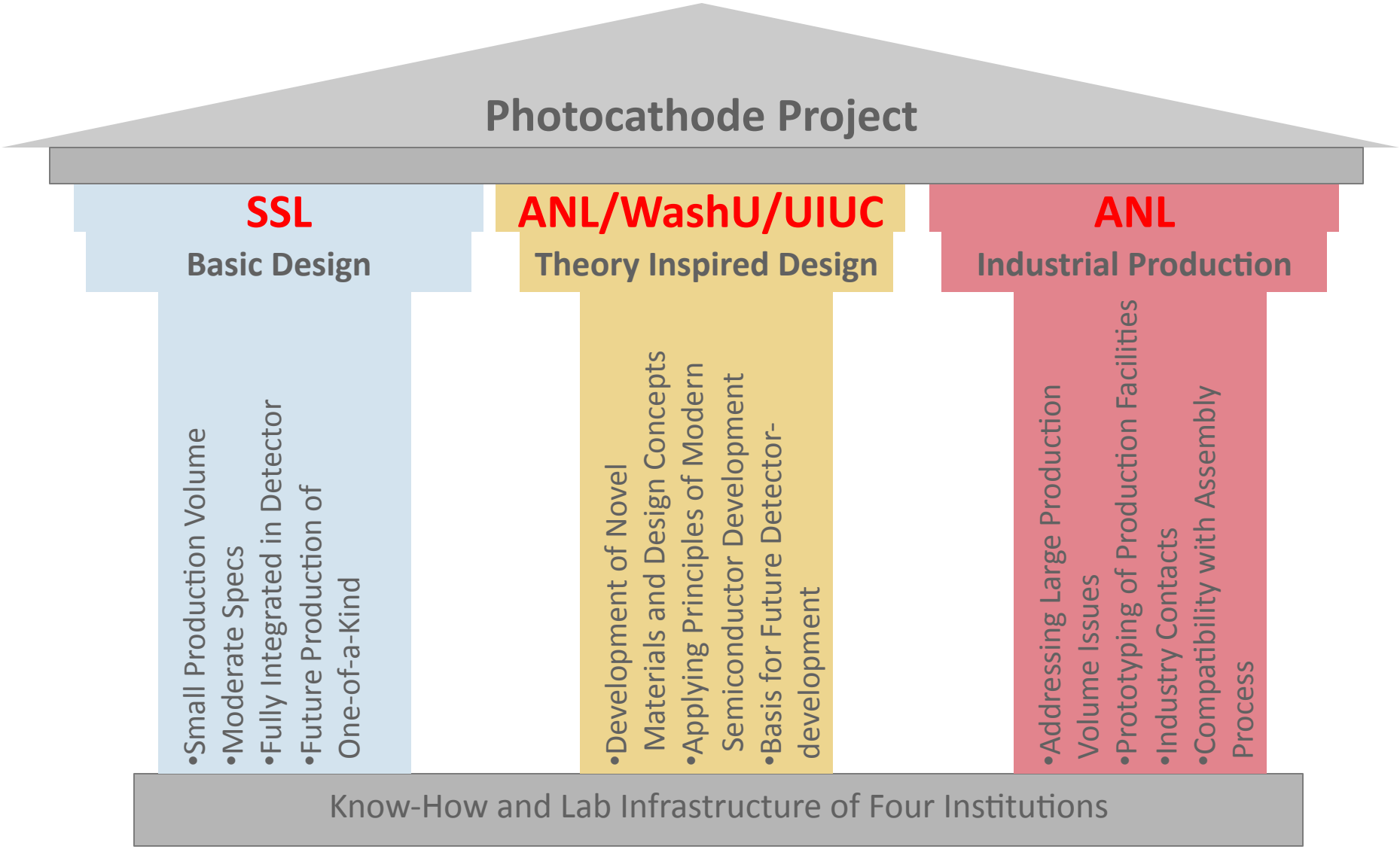
- **Multi-Alkali seems to have perfect cathode properties**
- But
  - Little understanding
  - Small community
  - No developed Industry
  - **Problems with mass-production**

- **Existing III-V cathode have not the right properties**
- But
  - Excellent understanding
  - Large community
  - Excellent developed Industry
  - Easy mass-production

	Property	Multi-Alkali	GaAs-based	GaN-based
Photocathode Properties	Wavelength response (typical)	150nm-500nm	450nm-850nm	100nm-350nm
	Typical efficiency	20%	20%	30-40%
	Maximum efficiency	50%	60%	80%
	Wavelength tunability	low	large	Very high
	Dark current	~100cps/cm2	~10000cps/cm2	~100cps/cm2
Growth properties	Single crystal substrate	no	yes	yes
	Easy scalable	No	yes	yes
	Large production volume possible	No	Yes	Yes
	Prefabrication possible	No	Yes	Yes
	Temperature sensitive	High	Medium	Medium
	Existing Industry	No (besides night vision / small area)	Yes (foundries available)	Yes (foundries available)
Basic Physics	Good understanding	No	Yes	Yes
	Microscopic understanding of growth	No	Yes	Yes
	2-D Fabrication tools	No	Yes	Yes
	3-D Fabrication tools	No	Yes	Some
	Theoretical description	No	Yes	Yes
	Band-structure engineering	No	Yes	Yes

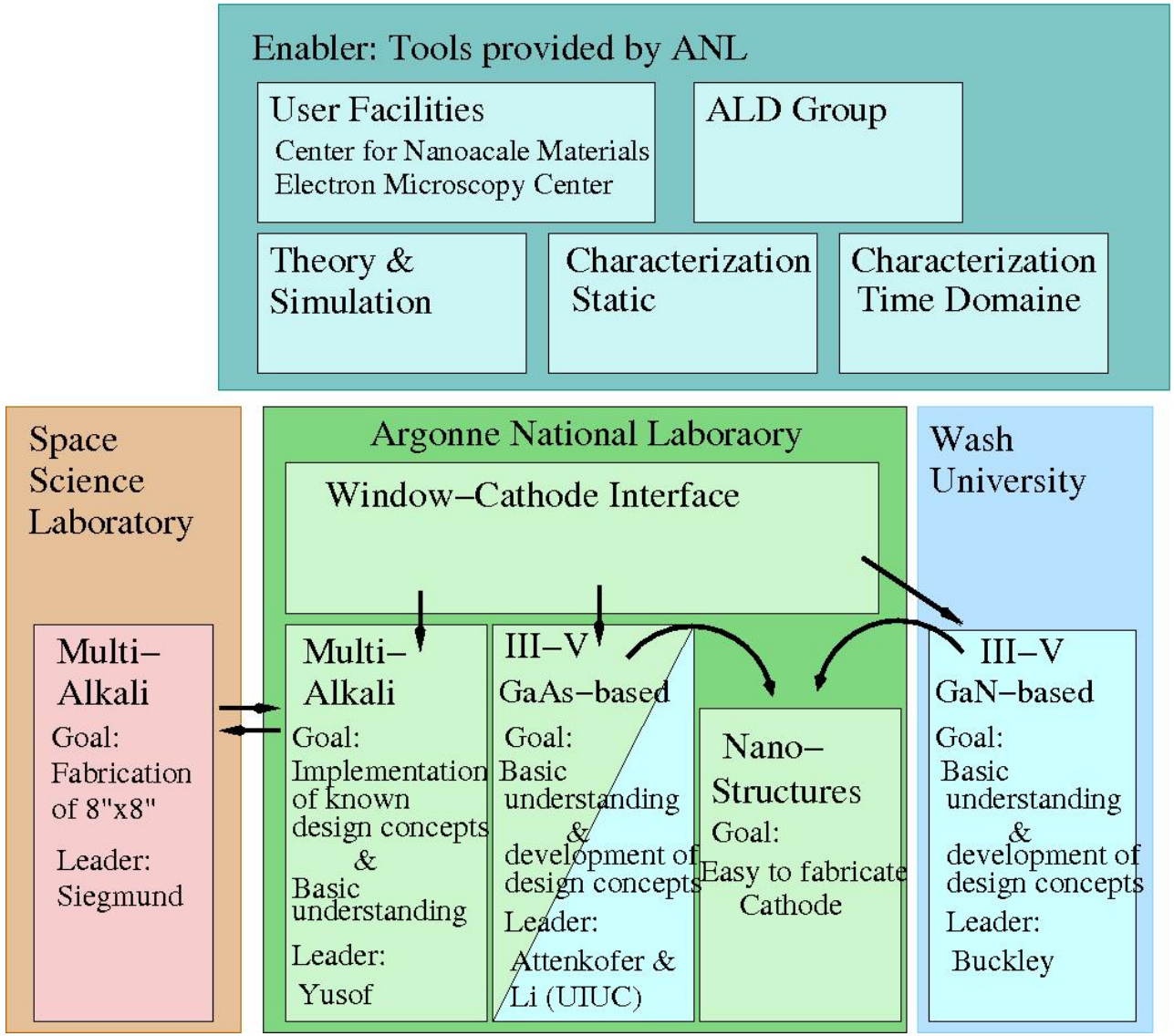
Not Clear which will be the best for the project

The Concept of the Photocathode Project

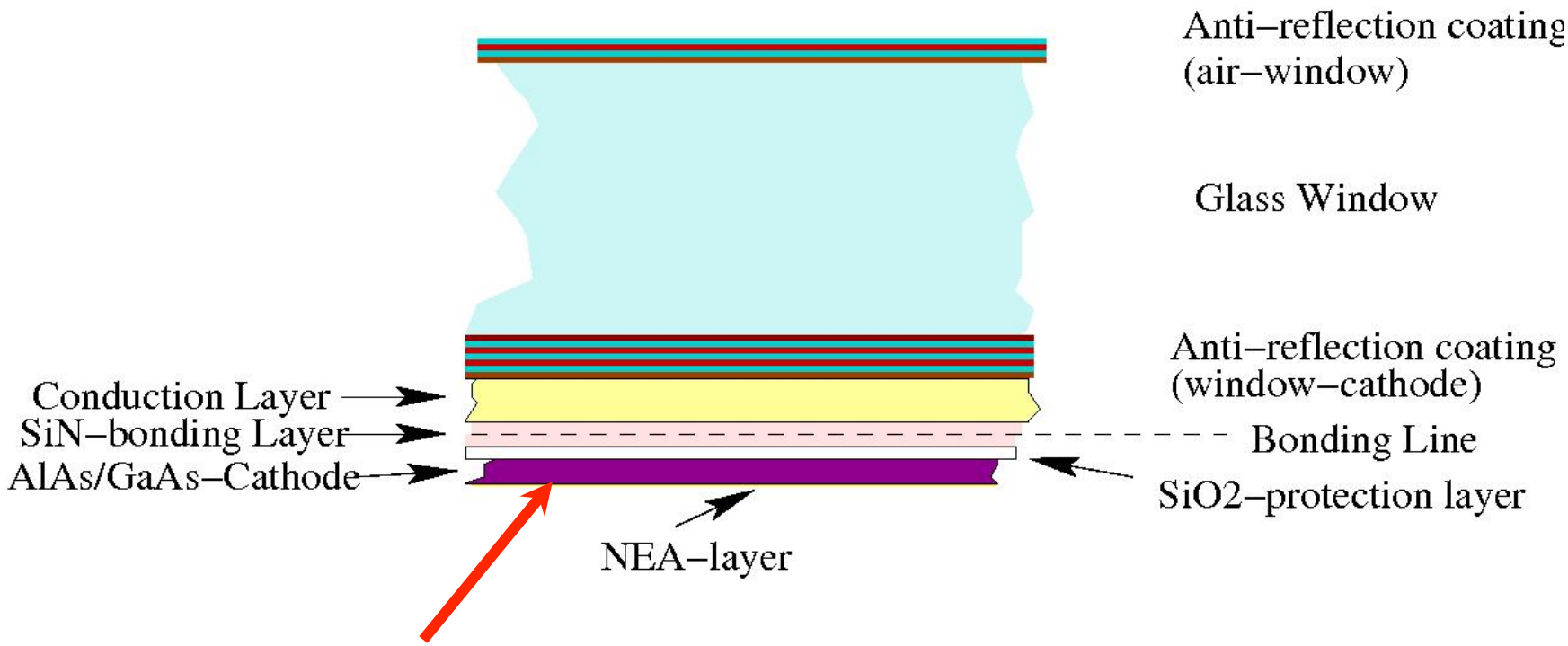


The People and Places

- Integration of 4 partners
- Collaboration partners bring:
  - Growth expertise (III-V and multi-alkali)
  - World class growth facilities
  - Standard and unique characterization tools
  - Connection to industry
  - Connection to science community (future funding)
- Unique effort for cathodes
  - Size
  - Completeness (growth, macroscopic and microscopic characterization, theory/ simulation)



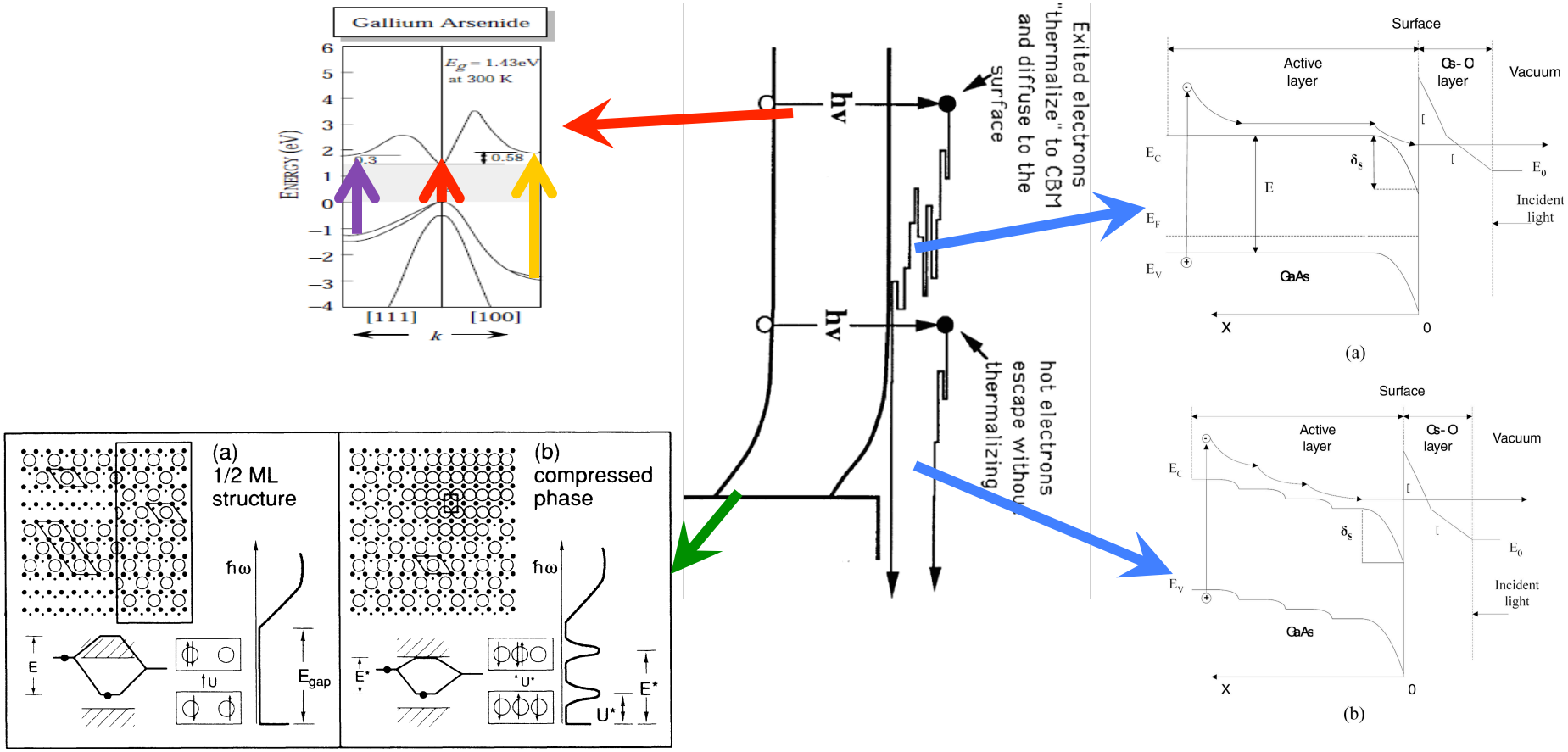
The Design Concept of the Photocathode Itself



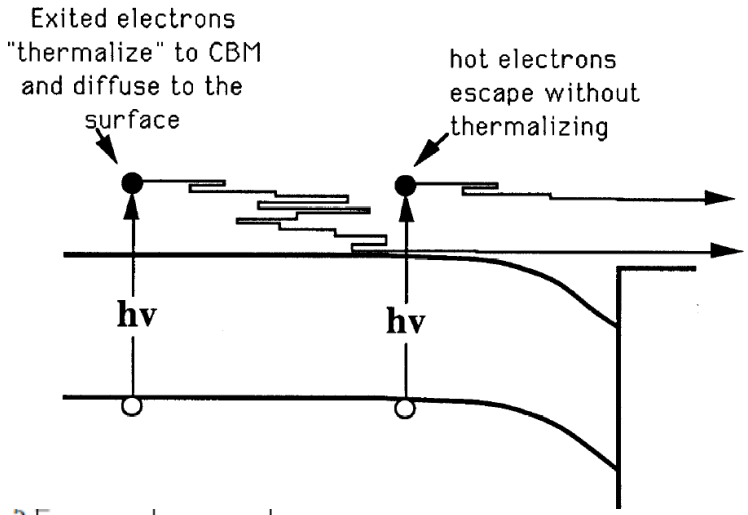
We will only discuss this part (Bonding of GaAs is discussed by Ryan)

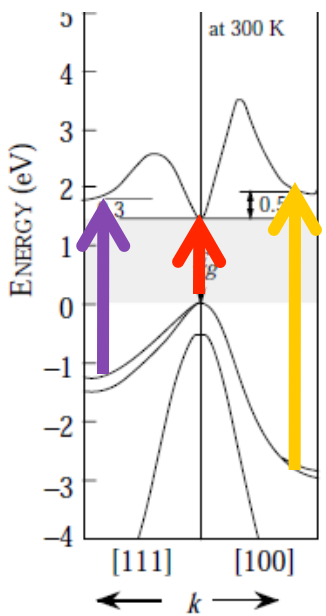
Theory Inspired Design of Devices

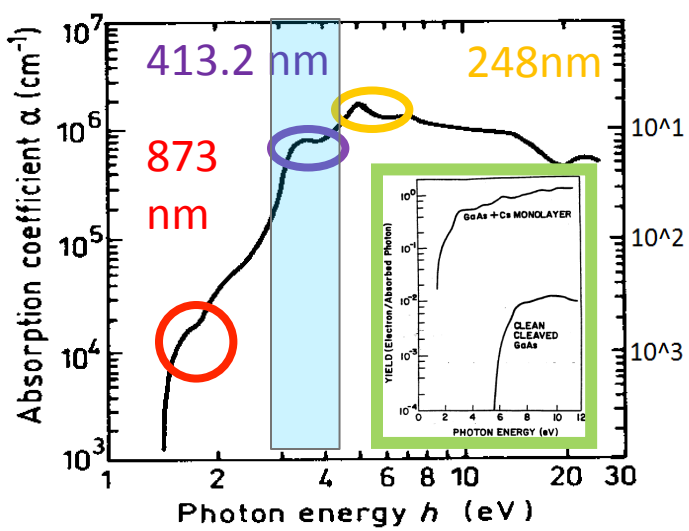
Basic Energy Sciences (BES) supports **fundamental research** to understand, predict, and **ultimately control matter and energy at the electronic, atomic, and molecular levels** in order to provide the foundations for new energy technologies and to support DOE missions in energy, environment, and national security.



Wavelength Optimization of Layer Thickness: The Optimization Criteria

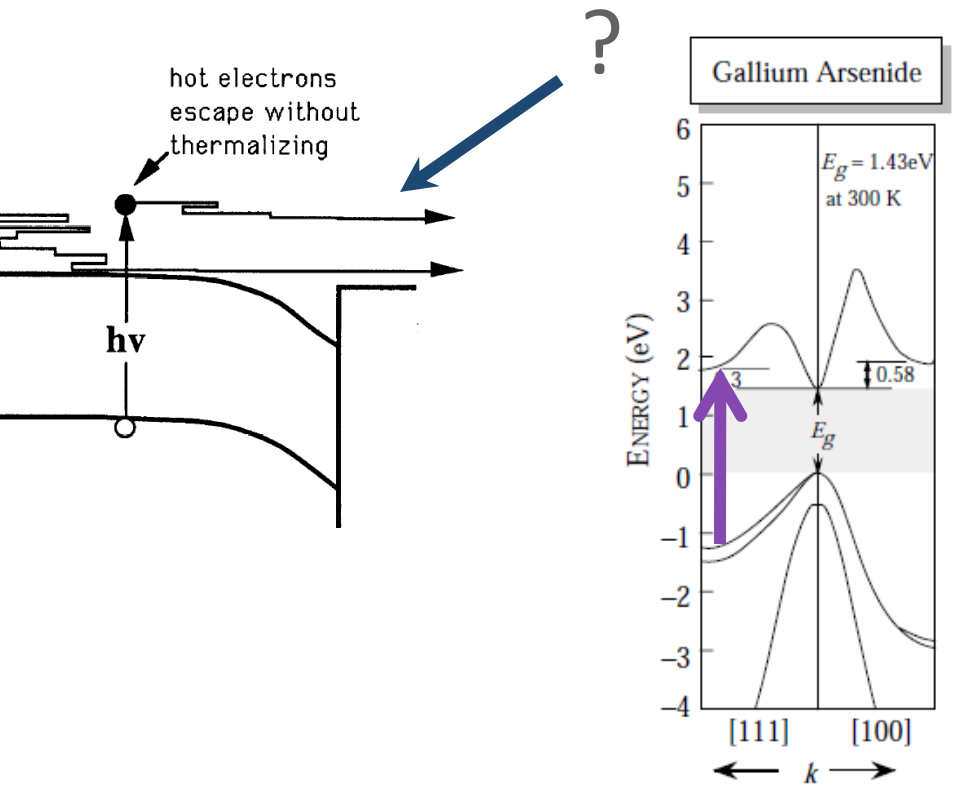






- Efficiency depends on
  - Probability to absorb photon
  - Probability to reach surface
  - (Probability to escape from surface is thickness independent)
- Case GaAs (only an example)
  - Direct bandgap in IR (typical application)
  - Typical absorption length for IR: 1µm
  - Absorption length for 400nm: **30nm-100nm**
- Consequences:
  - Cathode has to be by a factor 10 thinner!
  - Photoelectron has defined kinetic energy
  - Thickness is thinner than mean free path-length
  - Crystallographic direction matters
  - Defect density, strain, …. at the interface between cathode and window matters!

What Happens in a 100nm Thick GaAs Cathode (400nm Photon)



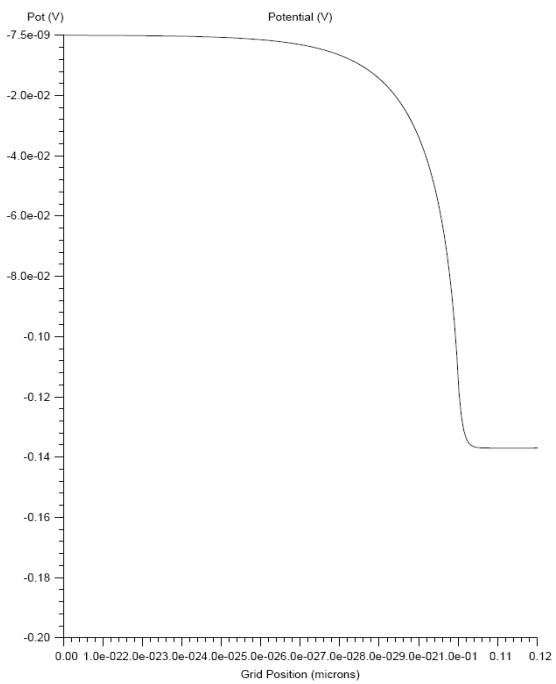
- Answer: **NO**
  - Creation of hot electron
  - Momentum in cathode plane! (electron will not reach surface if not scattered)
- Result:
  - Low QE
  - Very slow
- Solution:
  - Increasing scattering probability (can be done: tuning band structure to phonon distribution)
  - Better: creating internal electric field gradient
    - By doping gradient (what we have done)
    - Or by external electric Field.

The Doping Profile: The First Steps

Active layer with doping profile

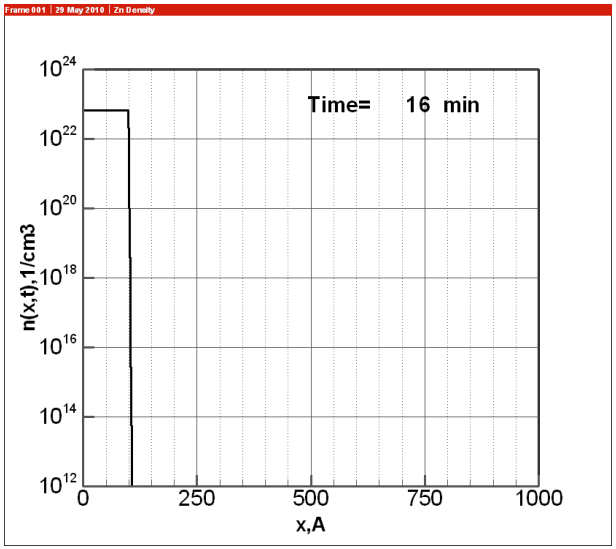
Buffer layer

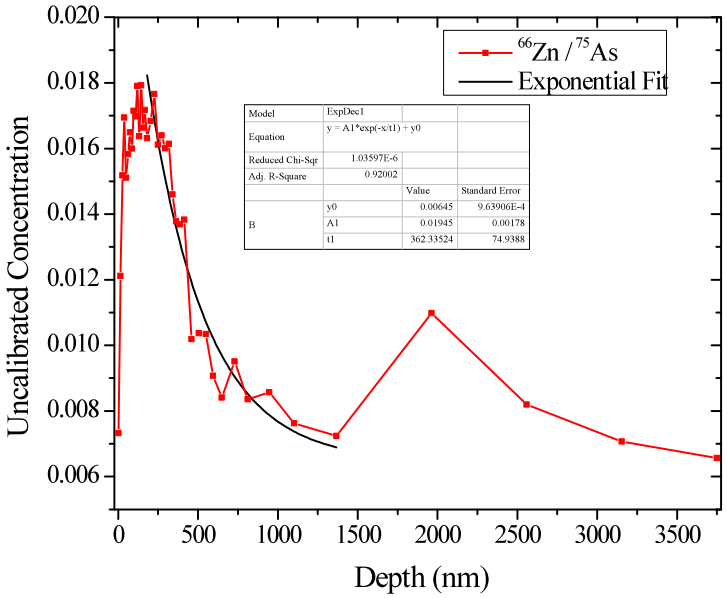
GaAs substrate
(100)



- Doping profile
  - Electric field distribution can be calculated by commercial simulation programs
  - Typical potential difference 0.1-0.2eV
- Influence on timing behavior
  - Theoretical potential possible which allows transient time independent from absorption position!
  - Optimization possible even for very hard x-rays?

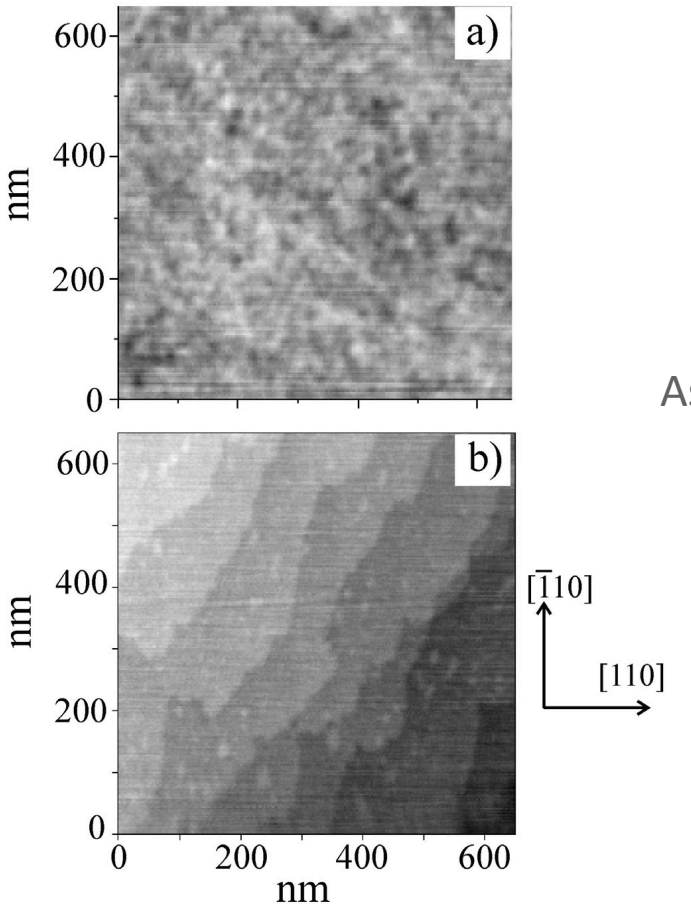
Is the Doping Profile Stable During Processing

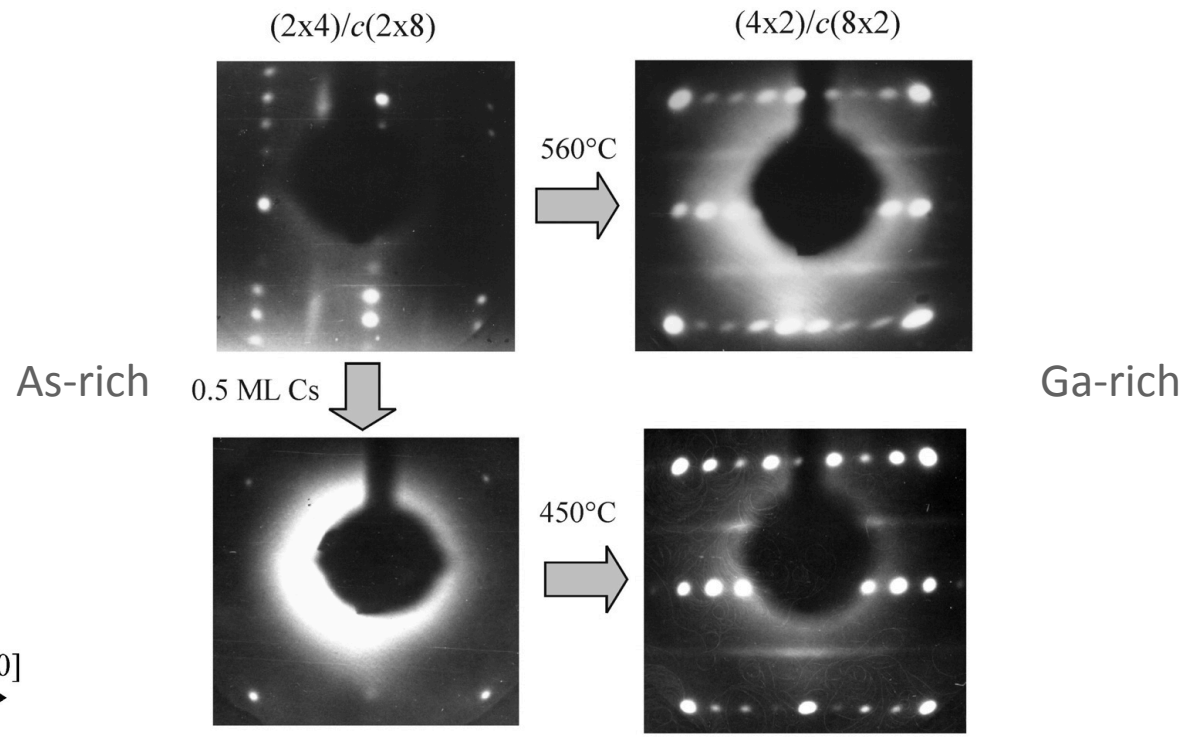




- Approach:
  - Minimizing process temperature
  - Using simulations to predict doping profile after processing
  - Calibrating simulations with selected samples using SIMS (Igor & Slade)
- Status:
  - First simulations done by Zeke Insepov
  - In the process of creating SIMS measurements

The Emission Layer:
The Standard Cleaning and Activation of GaAs





e-J. Surf. Sci. Nanotech. Vol. 5 (2007) 80-88

The Activation and Dark Current

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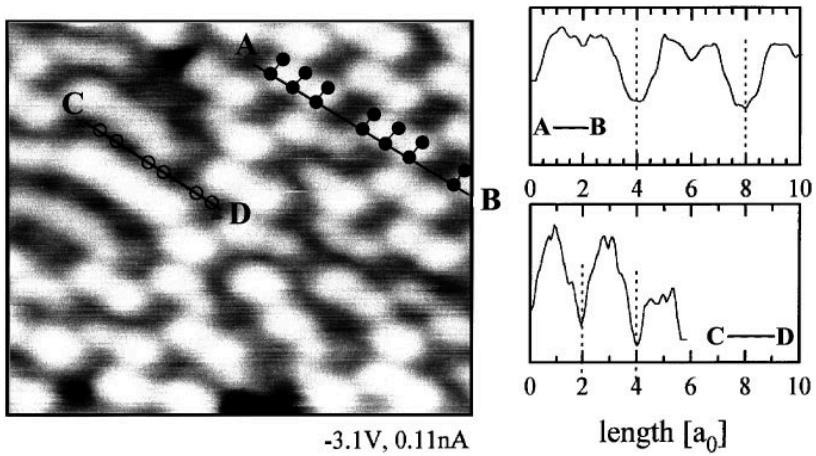
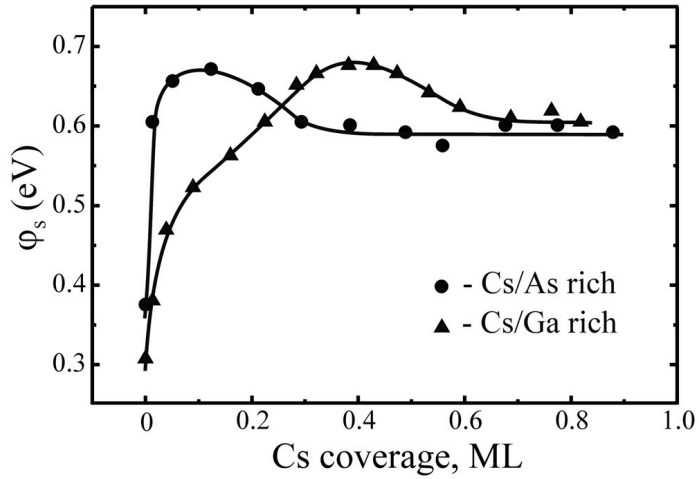
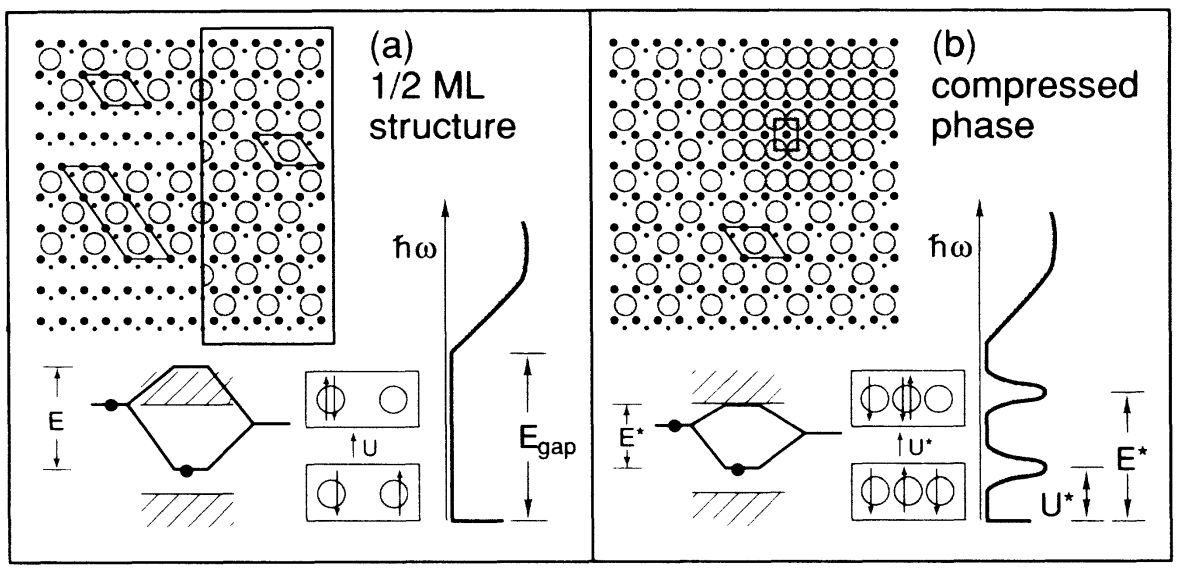


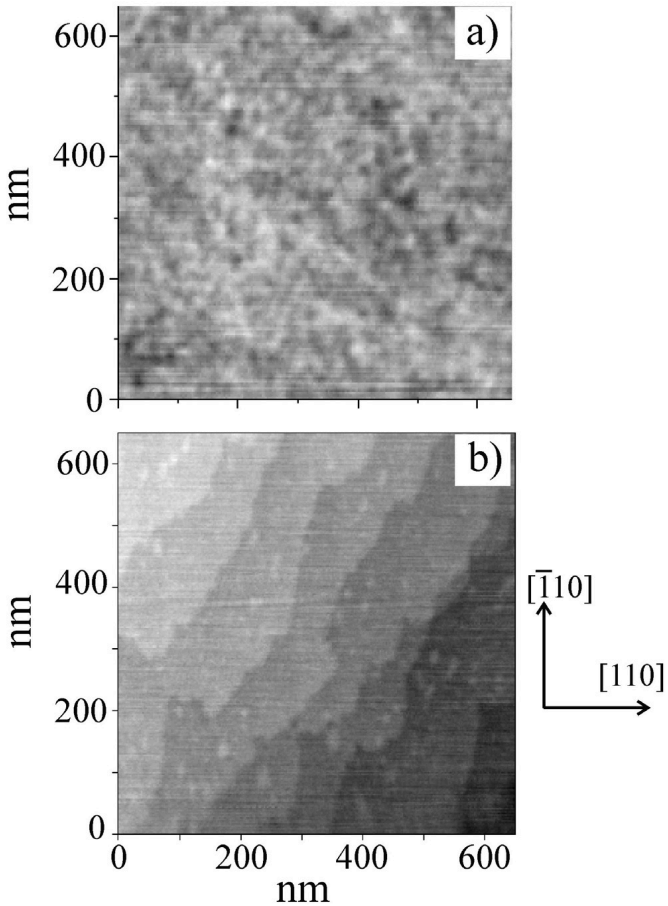




Phys. Rev. Lett. 81, 721–724 (1998)

- Exact details of surface and Cs contribution determines electronic states of activation layer
- Dark counts are highly effected by these details
- Effects of morphology unknown
- Long term stability depends on exact composition

Where We are Now?



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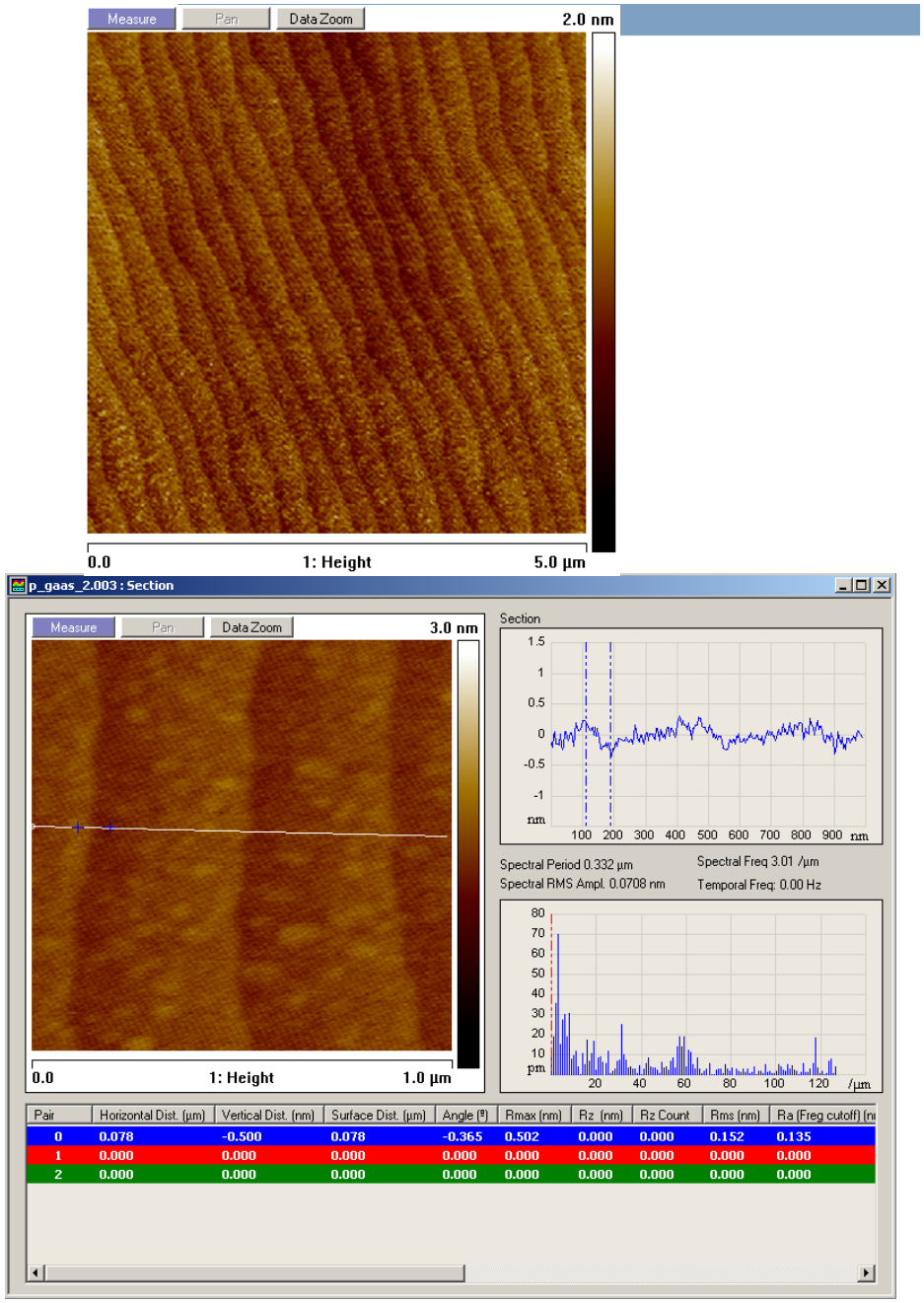
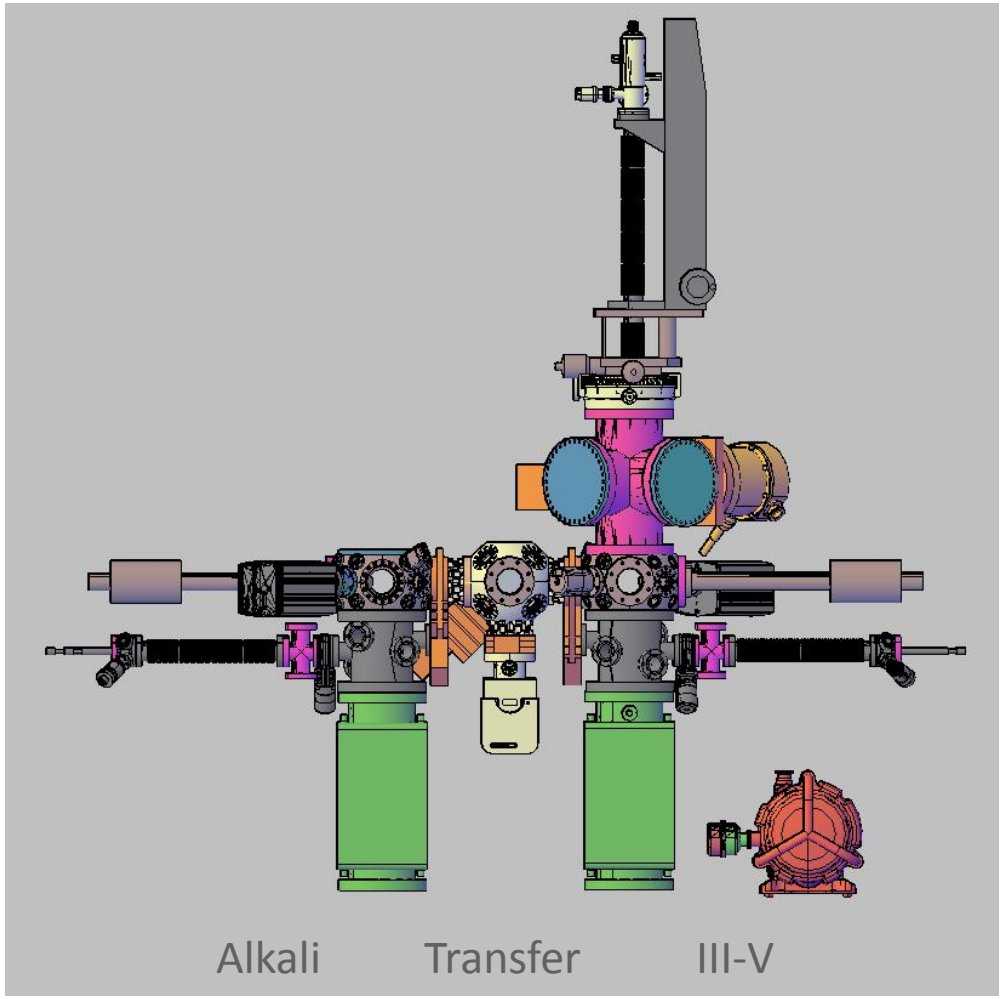


The Next Steps:
The Growth and Activation Chamber



- Status of Chamber
  - Chamber is in design
  - First parts have arrived
  - Key components are designed
- Characteristics
  - Small footprint
  - “easy” integration of optical and electrical insitu characterization
  - Large felxibility to adapt various growth and characterization recipes
  - Minimum structural characterization (LEED)

Conclusion

- Program is established
  - Build on three columns: Conservative approach, theory inspired design, large scale industrial aspects
  - Builds on expertise and infrastructure at different Laboratories and Universities
  - Theory inspired design was first focused on GaAs samples
    - Basic understanding of cathode physics and materials sciences aspects
    - First samples grown and first exsitu experiments performed and compared with simulations
    - Hardware is designed and currently build
- Large potential to overcome significant limitations of existing cathodes possible
  - New concepts of wavelength optimization
  - Employing of device design simulation tools
  - Starting to understand dark current/surface composition correlation
- Requires strong interaction between growth, characterization, and simulation