Overview of Photocathode Physics & Plans

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SSL:
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WASHU:
James Buckley, Daniel Leopold
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(ν) 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

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

<table>
<thead>
<tr>
<th>Suffix</th>
<th>Photocathode</th>
<th>Input Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>-71</td>
<td>GaAs</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-73</td>
<td>Enhanced Red GaAsP</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-74</td>
<td>GaAsP</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>-76</td>
<td>InGaAs</td>
<td>Borosilicate Glass</td>
</tr>
<tr>
<td>Non</td>
<td>Multalkali</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-01</td>
<td>Enhanced Red Multi</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-02</td>
<td>Bialkali</td>
<td>Synthetic Silica</td>
</tr>
<tr>
<td>-03</td>
<td>Cs–Te</td>
<td>Synthetic Silica</td>
</tr>
</tbody>
</table>

### Why are we Planning a Large Cathode Effort?

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

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

<table>
<thead>
<tr>
<th>Photocathode Properties</th>
<th>Multi-Alkali</th>
<th>GaAs-based</th>
<th>GaN-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength response (typical)</td>
<td>150nm-500nm</td>
<td>450nm-850nm</td>
<td>100nm-350nm</td>
</tr>
<tr>
<td>Typical efficiency</td>
<td>20%</td>
<td>20%</td>
<td>30-40%</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>50%</td>
<td>60%</td>
<td>80%</td>
</tr>
<tr>
<td>Wavelength tunability</td>
<td>low</td>
<td>large</td>
<td>Very high</td>
</tr>
<tr>
<td>Dark current</td>
<td>~100cps/cm²</td>
<td>~10000cps/cm²</td>
<td>~100cps/cm²</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Growth properties</th>
<th>Single crystal substrate</th>
<th>Multilayer</th>
<th>GaN-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Easy scalable</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Large production volume possible</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Prefabrication possible</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature sensitive</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Existing Industry</td>
<td>No (besides night vision / small area)</td>
<td>Yes (foundries available)</td>
<td>Yes (foundries available)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Basic Physics</th>
<th>Good understanding</th>
<th>GaAs-based</th>
<th>GaN-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microscopic understanding of growth</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2-D Fabrication tools</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>3-D Fabrication tools</td>
<td>No</td>
<td>Yes</td>
<td>Some</td>
</tr>
<tr>
<td>Theoretical description</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Band-structure engineering</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Not Clear which will be the best for the project
The Concept of the Photocathode Project

Photocathode Project

SSL
Basic Design
- Small Production Volume
- Moderate Specs
- Fully Integrated in Detector
- Future Production of One-of-a-Kind

ANL/WashU/UIUC
Theory Inspired Design
- Development of Novel Materials and Design Concepts
- Applying Principles of Modern Semiconductor Development
- Basis for Future Detector Development

ANL
Industrial Production
- Addressing Large Production Volume Issues
- Prototyping of Production Facilities
- Industry Contacts
- Compatibility with Assembly Process

Know-How and Lab Infrastructure of Four Institutions
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)

Enabler: Tools provided by ANL

- User Facilities
  - Center for Nano-scale Materials Electron Microscopy Center
- ALD Group
- Theory & Simulation
- Characterization Static
- Characterization Time Domaine

Space Science Laboratory

Argonne National Laboratory

Window–Cathode Interface

Multi–Alkali
Goal: Fabrication of 8"x8"
Leader: Siegmund

Multi–Alkali
Goal: Implementation of known design concepts & Basic understanding
Leader: Yusof

III–V GaAs–based
Goal: Basic understanding & development of design concepts
Leader: Attenkofer & Li (UIUC)

Nano–Structures
Goal: Easy to fabricate Cathode

III–V GaN–based
Goal: Basic understanding & development of design concepts
Leader: Buckley

Wash University

LAPPD: Second Collaboration Meeting 2010
The Design Concept of the Photocathode Itself

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

As-rich

(2x4)/c(2x8)

(4x2)/c(8x2)

Ga-rich

0.5 ML Cs

560°C

450°C

The Activation and Dark Current

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

**References**

- LAPPD: Second Collaboration Meeting 2010
Where We are Now?

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 flexibility 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 ex situ 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