Recent Progress toward Robust Photocathodes
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Why robust photocathodes?

• Ideal case: photoemitter operates well in poor vacuum

• Practical: improved performance always desired

• RF gun environment still tough on photoemitters
  - gun improvements (better pumping) help

• High polarization photoemitters need UHV - ILC RF gun?

• High average current operation - ion damage

Past and current work supported by United States Department of Energy SBIR grants
DE-FG02-06ER84475 (Advanced Accel. Concepts) and DE-FG02-07ER84832 (ILC) and
United States Navy SBIR grant N65538-08-M-0126 (a-Si_{1-x}Ge_x for FEL)
Consider the issues in two parts

• Chemical reactions
  - Background gas main source
  - Electron beam induced desorption problematic
  - CO₂, H₂O, O₂, etc. bad for NEA lifetime

• Charged particle sensitivity, primarily ions
  - Low energy (RF guns) displacements near surface
    + Can affect activation layer
    + Damage may be annealed
    + Polarization and yield affected
  - High energy (DC guns) many displacements per particle
    + Damage widespread
    + Damage may not anneal
    + Polarization and yield affected
High polarization photoemitters

- Crystalline, single layer or superlattice

- NEA activation layer

- Attack chemical reactivity first - many papers on decay process
  - Interesting story how current work started
    + 1992 J. Clendenin (SLAC) visit to Los Alamos
    Bob Springer comment on CsK₂Sb - K for GaAs?
    + R. Kirby and G. Mulhollan (SLAC) observe F (XPS) on activated surface - too much! Finger in the dike
    + Li as replacement for Cs in final stage of activation - diminish the drop in polarization when over-cesiate?
    + We attempt bi-alkali activation of bulk GaAs
CO$_2$ as archetype of ‘bad’ gas

Normalized quantum yield decay for Cs activated photocathode using our standard exposure schedule.
Everyone knows…

Single alkali activation of bulk GaAs using Na and Cs
Sure enough…

Normalized quantum yield decay for photocathodes activated in the usual fashion but for the addition of the indicated second alkali in the final stages of the process. The dual alkali photoemitter yields were all lower than those with Cs alone. Decay properties were not enhanced?
With persistence…

Comparison of yield decay at 633 nm for Cs only and Cs + Li activated bulk GaAs.
Activation record
Near bandgap (850 nm)

Bulk GaAs

100 nm MBE
What about the yield?

Quantum yield as a function of wavelength for Cs, Cs + Li and Cs + Na activations on bulk GaAs.
What do we know?
• It works
• XPS on Cs + Na activated shows near equal Na and Cs coverage
  R. Kirby (SLAC)

Next phases?
• Other gas reactivity/immunity
• How affects polarization (T. Maruyama/SLAC and R. Kirby)
• Structure of activation layer when Cs + Li used
  (P. Pianetta/SSRL and R. Kirby)
• Alternate photoemitting layer...next slide please
Amorphous Si$_{(1-x)}$Ge$_x$ photoemitters as candidates for FEL sources

- *Ex situ* growth
- Substrate flexibility
- Reflection or transmission mode
- Size scales
- Pre-insertion preparation rapid
- Standard activations
- Re-activates
- Lower gas/ion sensitivity than GaAs
- Shelf life excellent
- Bandgap shift easy
- Vacuum tube source demonstrated
Background

- FEL injectors can use DC or RF guns
  DC: time structure via laser or buncher/chopper
  Best vacuum; cathode energy ions at photoemitter
  RF: time structure via laser + RF
  Vacuum higher; few kV ions at photoemitter

- Examples
  DC: JLab FEL (ERL), 120 pC/bunch in 90 ps
  RF: SLAC LCLS, 1 nC in 7 ps

- Machine utilization determines photoemitter life requirement
  Physics machine: High luminosity, runs 24/7
  Weapons machine: Runs on demand, failures undesirable
• Photoemitters

Metal (easy, low QE), PEA (high QE, in situ growth), NEA (highest QE, ex situ growth), Field emitter (tough to control), SE multiplier (new technology, requires photoemitter), etc.

Simplified band structure for a metal, direct band gap semiconductor and indirect band gap semiconductor. The indirect gap semiconductor requires the addition of momentum ($dk$) for the transition to the conduction band to occur.

Best yields from copper reach only 0.1% at ~100 nm from the emission edge$^\dagger$.

$^\dagger$1D. T. Palmer, R.E Kirby and F.K. King, Quantum Efficiency and Topography of Heated and Plasma-Cleaned Copper Photocathode Surfaces, PAC05 Particle Accelerator Conference, Knoxville, Tennessee, USA, May 16-20.
• Photoemitter robustness
  Ion
  Crystalline structures most sensitive
  Low energy near surface damage—may anneal out
  High energy damage more extensive—irreversible

Neutral
  Gas reactivity poisons surfaces

Electron
  Electrons can crack molecules; assist in contamination
  Very high energies cause dislocations
Amorphous $\text{Si}_{(1-x)}\text{Ge}_x$ properties

- **Structure**
  - Local tetrahedral bonding
  - Local coordination distance (1st nn) same as crystalline silicon
  - Direct band gap
  - Disorder reduces carrier mobility
  - Substrate compliant
  - Mobility edge rather than band edge

- **Hydrogen**
  - Required to satisfy dangling bonds (fewer defects)
  - Allows a-Si to be doped, $n$-type (P) and $p$-type (B)

- **Radiation (proton) hardness**
  - Good compared to microcrystalline-Si

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†J. Kuendig et al., Effect of Proton Irradiation on the Characteristics of Different Types of Thin-Film Silicon Solar Cells, 16th EPVSEC, 2000, 986.
Growth

- Sputter

DC magnetron
Hydrogen pressure (1.5 milliTorr)
Argon pressure (7 milliTorr)
T ~ 200°C
a-Si on Ta with glass witness piece
Various amorphous silicon samples grown on glass for relative conductivity measurements. From top left clockwise they are: highly doped, low doped thick, plain glass and low doped thin
- RF PECVD

- Gas sources and controls

- Load chamber

- Isolation valve

- 13.56 MHz

- Heated electrode

- Electrode

- RF PECVD chamber

- Turbo pump

- Backing pump, scrubber, etc.
Plasma discharge in the RF PECVD system with the heated stage in use. The discharge is well-shaped and stable in this configuration. The plasma is very uniform over the substrate diameter.

<table>
<thead>
<tr>
<th>Pressure (milliTorr)</th>
<th>Power Density (mW/cm²)</th>
<th>Heater Temperature (°C)</th>
<th>Electrode spacing (cm)</th>
<th>Active gas flow (sccm/cm²)</th>
<th>Hydrogen Dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>~100</td>
<td>180</td>
<td>2.5</td>
<td>~0.04</td>
<td>19</td>
</tr>
</tbody>
</table>
Preparation

- Samples are stored in a nitrogen purged dry cabinet
- 2% hydrofluoric acid dip at room temperature for 1-1/2 minutes
- DI water rinse in a beaker with running water for 2 minutes
  Very highly boron doped a-Si is only moderately hydrophobic
- Dry with static-neutralized, filtered N₂ from LN₂ tank boiloff
- Mount in the holder and install into the loadlock
- Pumpdown within 5 minutes using molecular drag dry pump system
- Loadlock chamber pumps overnight before sample transfer
Activation

- Reflection mode
- Ta substrate (have used Ta, Ta coated Cu and glass)
- Cs and Oxygen
- Light source 455 nm LED
Re-activation of a-Si using Cs and O$_2$ after moving to loadlock and allowing to decay for several hours to near zero photoyield.
Gas and ion reactivity

The output current was monitored and the standard $e$-fold lifetime given by

$$I(t) = I_0 \exp \frac{-t}{\tau}.$$  

- Photocathode Decay with Beam Induced Desorption
  Current to chamber walls with 36 eV bias

<table>
<thead>
<tr>
<th>Sample</th>
<th>Start current (µA)</th>
<th>$e$-fold lifetime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>α-Si</td>
<td>2.4</td>
<td>100</td>
</tr>
<tr>
<td>GaAs</td>
<td>2.2</td>
<td>19</td>
</tr>
</tbody>
</table>

- Photocathode decay with NEG heater induced pressure rise

<table>
<thead>
<tr>
<th>Sample</th>
<th>Start current (µA)</th>
<th>$e$-fold lifetime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>α-Si</td>
<td>0.35</td>
<td>28</td>
</tr>
<tr>
<td>GaAs</td>
<td>0.15</td>
<td>7</td>
</tr>
</tbody>
</table>
• Hydrogen background gas and ion lifetime change for activated a-Si and GaAs

<table>
<thead>
<tr>
<th>Sample</th>
<th>Beam on/H$_2$ 2x10$^{-6}$ lifetime (hrs)</th>
<th>Beam off/H$_2$ 2x10$^{-6}$ lifetime (hrs)</th>
<th>Beam off/no gas lifetime (hrs)</th>
<th>Beam on/no gas lifetime (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a-Si</td>
<td>19</td>
<td>longest</td>
<td>longest</td>
<td>32</td>
</tr>
<tr>
<td>GaAs</td>
<td>2.4</td>
<td>long</td>
<td>long</td>
<td>5.9</td>
</tr>
</tbody>
</table>

1. Sink current to the chamber walls with the background pressure raised to 2x10$^{-6}$ Torr of hydrogen and measure the $e$-fold lifetime. For the currents used (~1 microAmp). Assuming full ion capture, this gives picoamps of H$^+$ on the cathode. The accelerating potential was 1.7 kV.

2. Measure the lifetime with the light source blocked but for short intervals to determine the photoyield decay due only to the presence of the hydrogen.

3. Measure the lifetime as in 2, but with the chamber evacuated and

4. Measure the lifetime as in 1, but with the chamber evacuated.
Flexibility

- Example: wavelength shift
  Shift the bandgap of a-Si with germane: $a$-Si$_{(1-x)}$Ge$_x$
  Red shift in the overall spectrum
Current and future work

- Emission characteristics: angle, charge density
- Use robust a-Si on GaAs as photoemitting layer
- Growth temperature
- Optimal thickness
- Substrate compatibility
- Lower temperature cleaning
- Atomic hydrogen implanting
- Alternate activation methods

Cs and Rb activated Si(100) photoresponse. Yield was somewhat greater for the Rb activated surface.
Use in vacuum tubes (un-funded)

Heat Cleaning of a-Si in stand-alone tube
Activation of a-Si in stand-alone vacuum tube
Characteristic curve of photo-triode a-Si vacuum tube
- grid very coarse -
Appendix: Saxet Surface Science Facilities

Silicon cathode test system
GaAs cathode test system
Sputter deposition system
RF PECVD deposition system
Auger system
Tube bake and test system
Optical Microscopes and IR/VIS Spectrometer
Laminar flow clean bench
Vacuum leak checker
Electronics work bench