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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
    - CO_2, H_2O, O_2, etc. bad for NEA lifetime

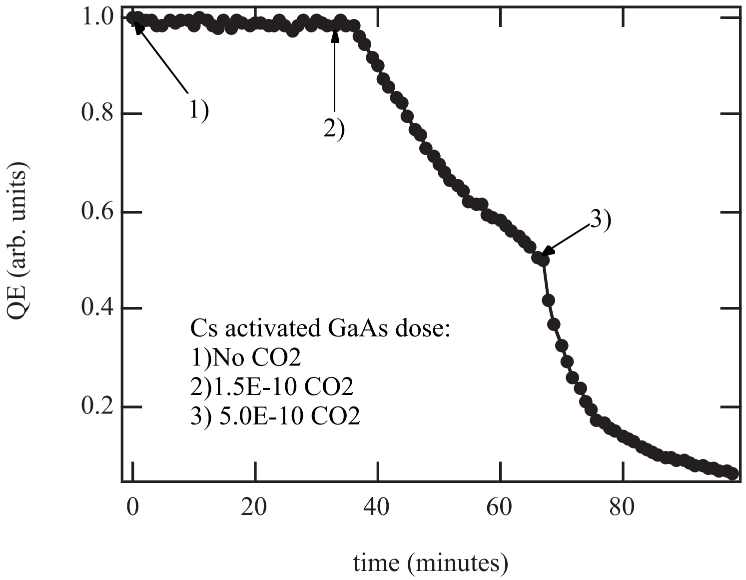
- Charged particle sensitivity, primarily ions
    - Low energy (RF guns) displacements near surface
        + Can affect activation layer
        + Damage may be annealed
        + Polarization and yield affected

    - High energy (DC guns) many displacements per particle
        + Damage widespread
        + Damage may not anneal
        + Polarization and yield affected

High polarization photoemitters

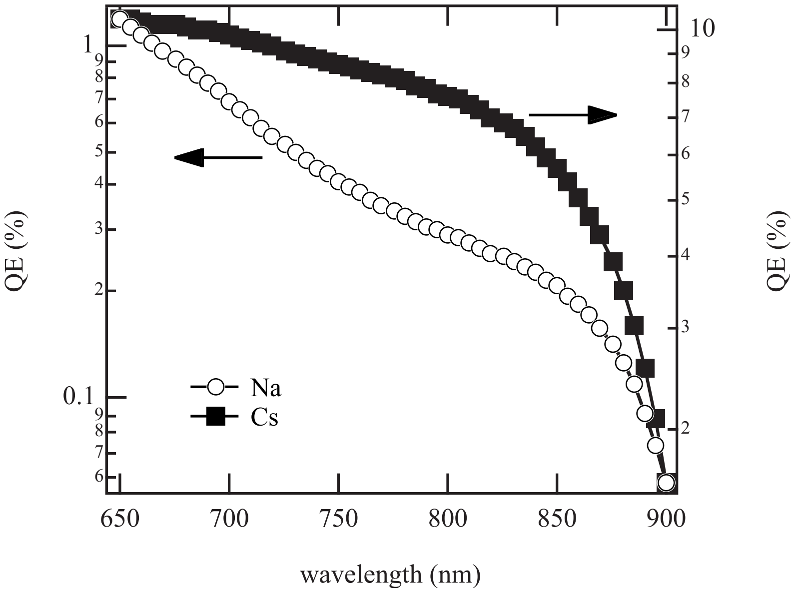
- Crystalline, single layer or superlattice
- NEA activation layer
- Attack chemical reactivity first - many papers on decay process
  - Interesting story how current work started
    - + 1992 J. Clendenin (SLAC) visit to Los Alamos Bob Springer comment on CsK_2Sb - K for GaAs?
    - + R. Kirby and G. 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



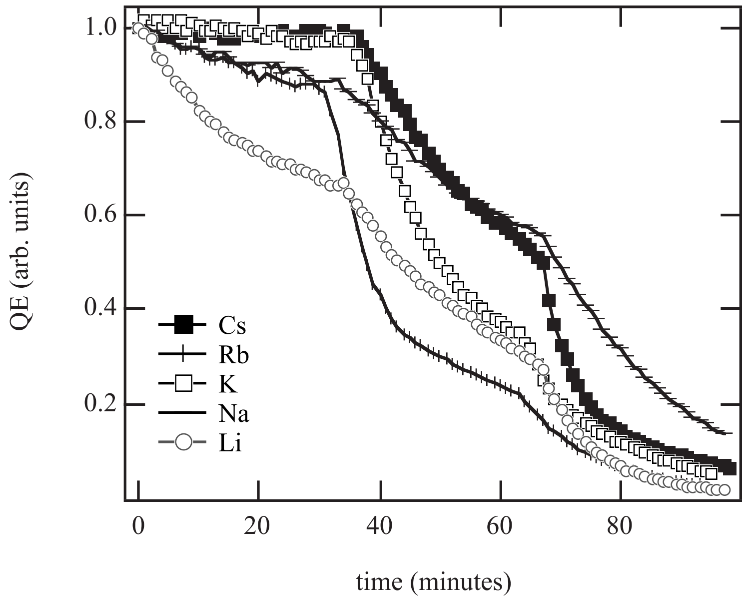
Normalized quantum yield decay for Cs activated photocathode using our standard exposure schedule.

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?

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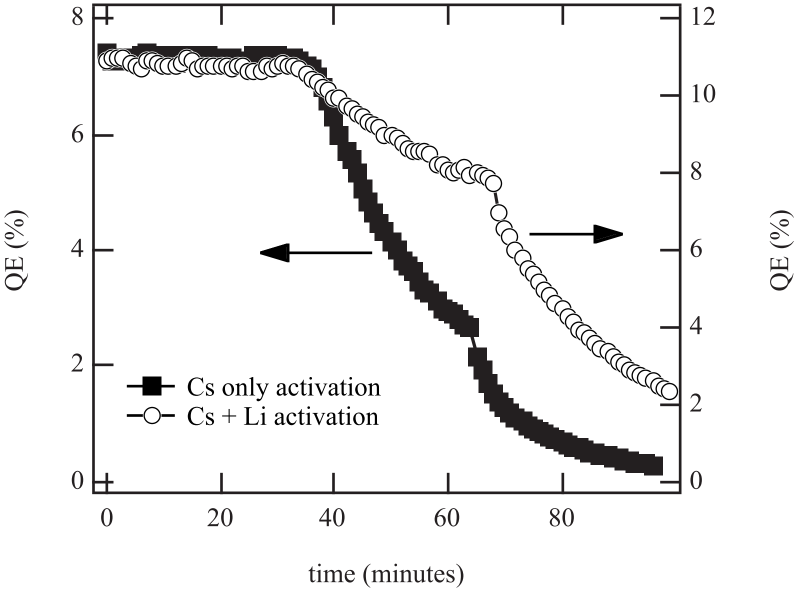
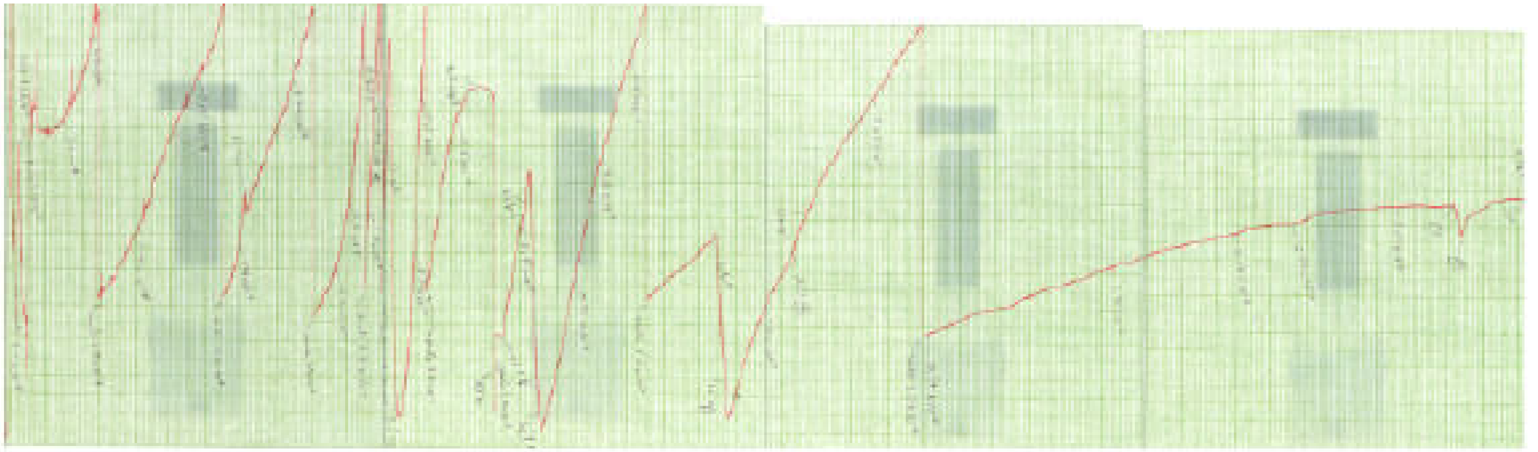
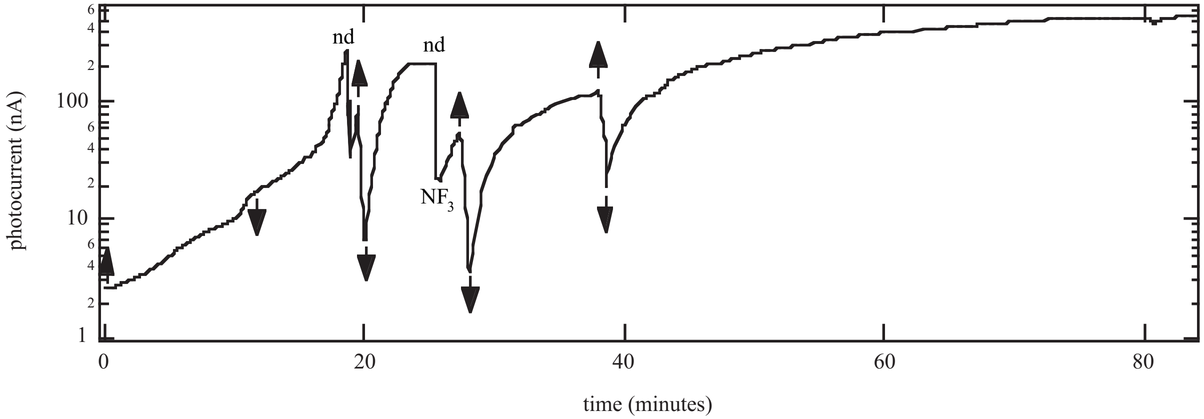
With persistence…



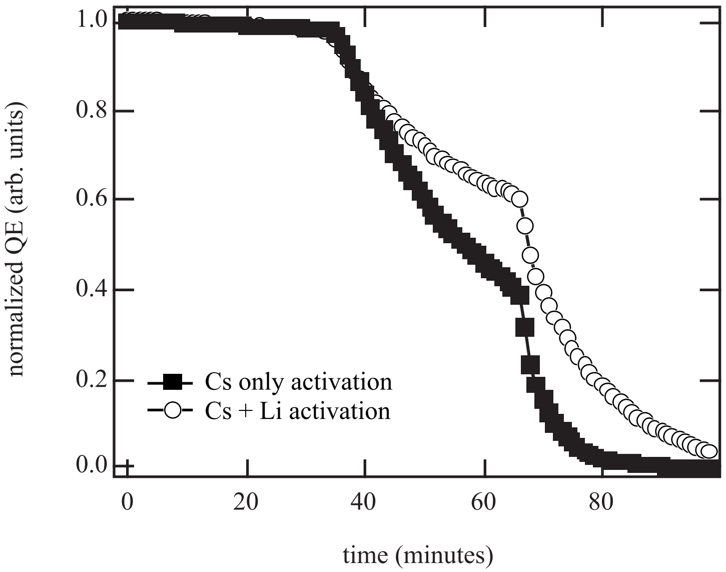
Comparison of yield decay at 633 nm for Cs only and Cs + Li activated bulk GaAs.

Activation record

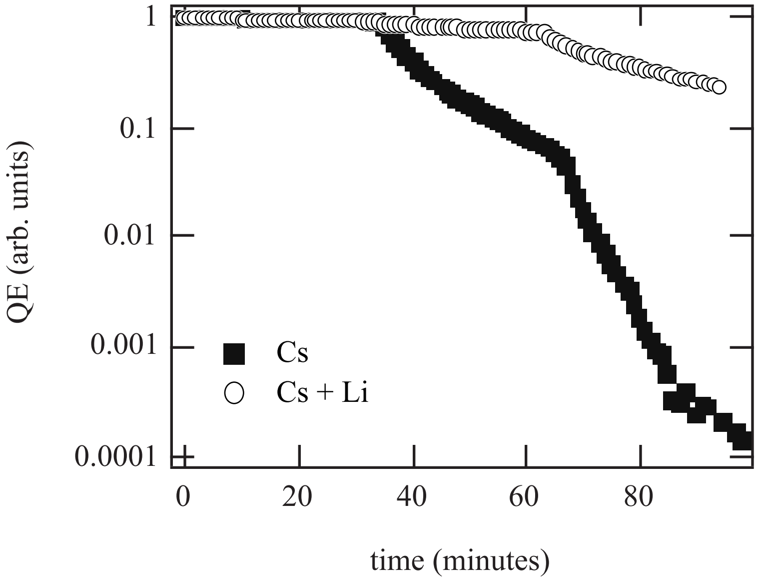




Near bandgap (850 nm)

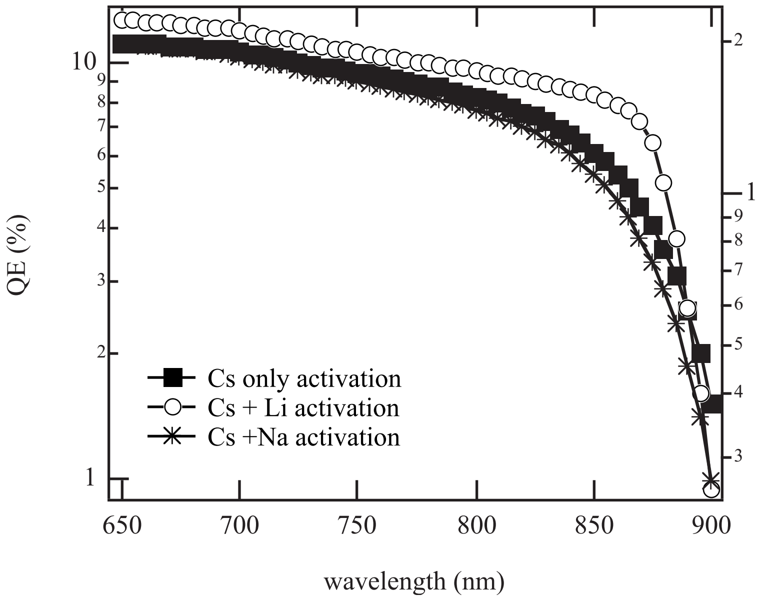


Bulk GaAs



100 nm MBE

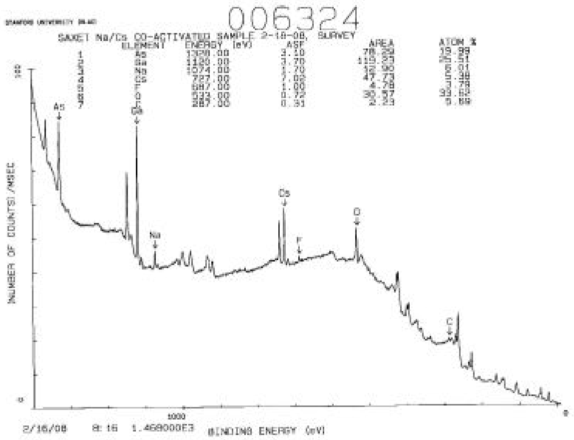
What about the yield?



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

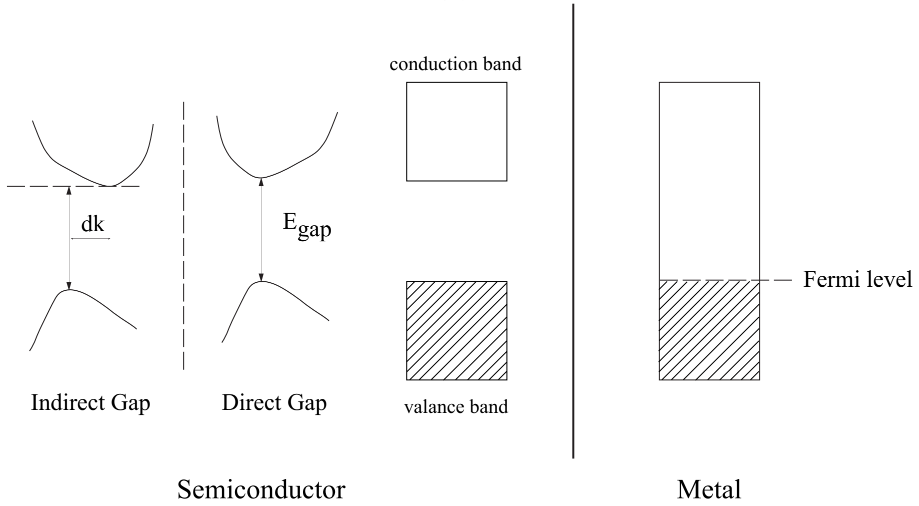
- FEL injectors can use DC or RF guns
    - DC: time structure via laser or buncher/chopper
        - Best vacuum; cathode energy ions at photoemitter
    - RF: time structure via laser + RF
        - Vacuum higher; few kV ions at photoemitter

- 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.

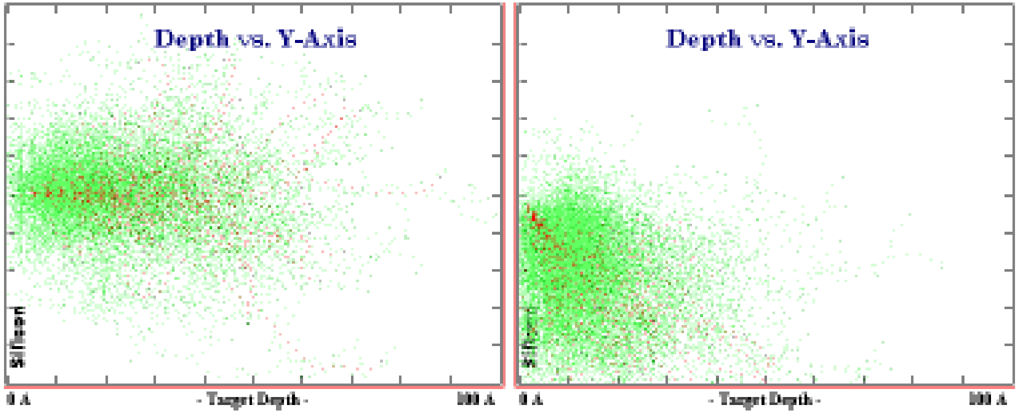


Simplified band structure for a metal, direct band gap semiconductor and indirect band gap semiconductor. The indirect gap semiconductor requires the addition of momentum (*dk*) for the transition to the conduction band to occur.

Best yields from copper reach only 0.1% at ~100 nm from the emission edge[†].

[†] 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 Si$_{(1-x)}$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[†]

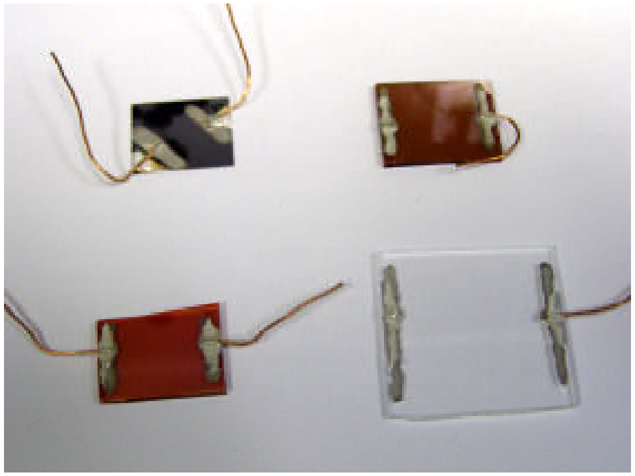
[†] J. Kuendig et al., Effect of Proton Irradiation on the Characteristics of Different Types of Thin-Film Silicon Solar Cells, 16th EPVSEC, 2000, 986.

Growth

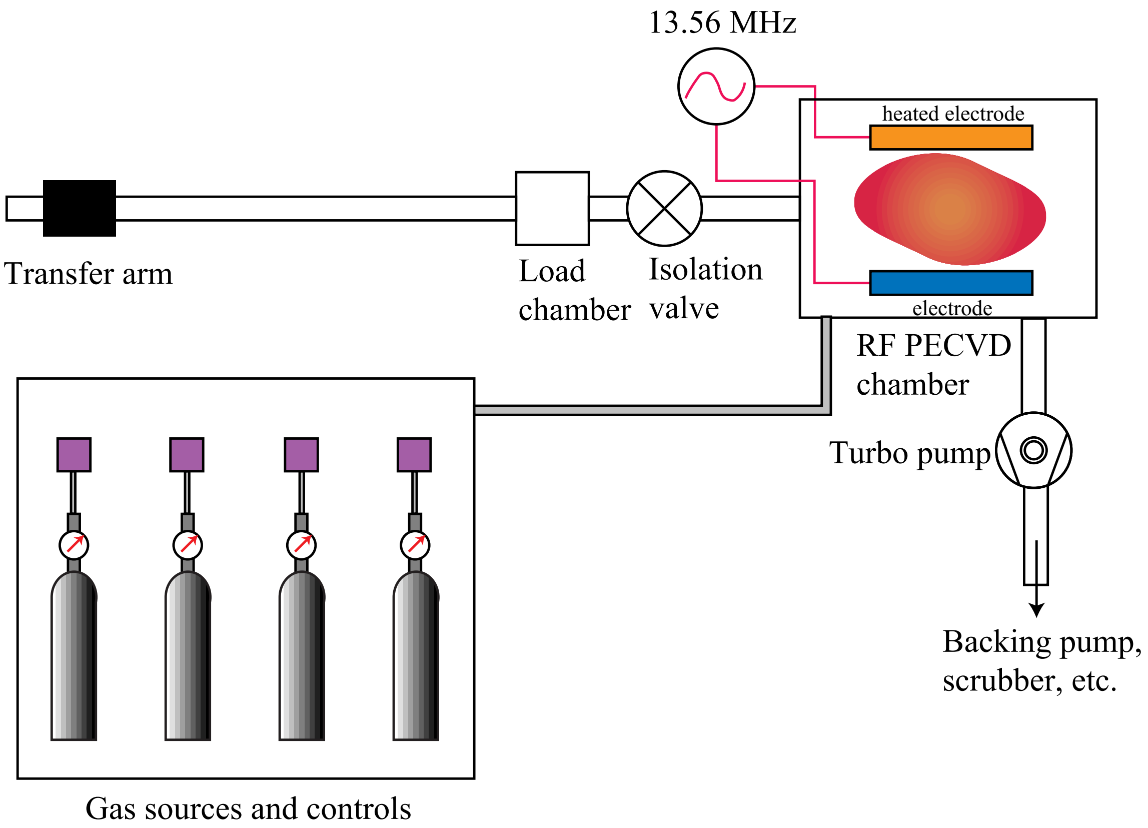
- Sputter

DC magnetron
Hydrogen pressure (1.5 milliTorr)
Argon pressure (7 milliTorr)
T ~ 200°C
a-Si on Ta with glass witness piece

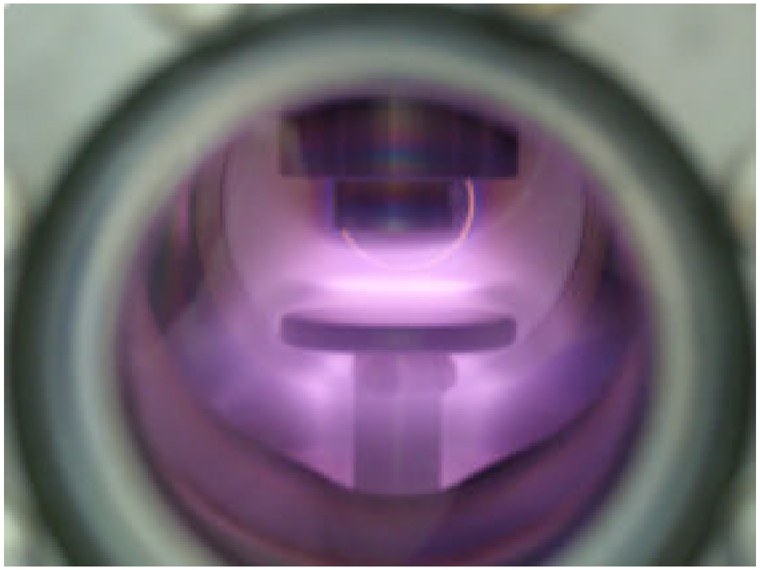
Various amorphous silicon samples grown on glass for relative conductivity measurements. From top left clockwise they are: highly doped, low doped thick, plain glass and low doped thin



- RF PECVD

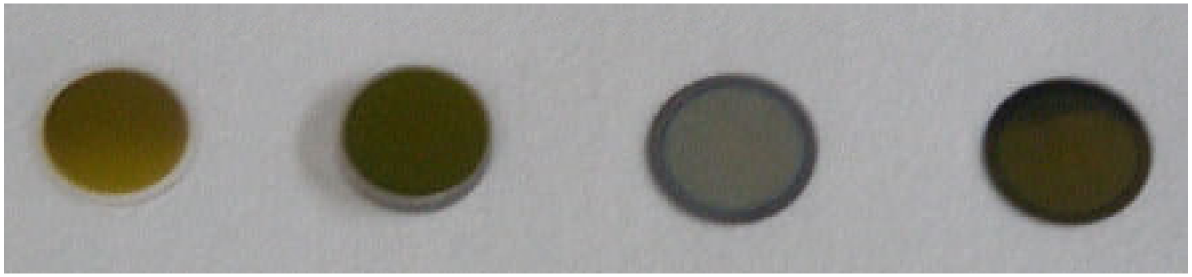

13.56 MHz
heated electrode
electrode
Transfer arm
Load chamber
Isolation valve
RF PECVD chamber
Turbo pump
Backing pump, scrubber, etc.
Gas sources and controls

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.



Pressure (milliTorr)	Power Density (mW/cm^2)	Heater Temperature (°C)	Electrode spacing (cm)	Active gas flow (sccm/cm^2)	Hydrogen Dilution
250	~100	180	2.5	~0.04	19

Preparation

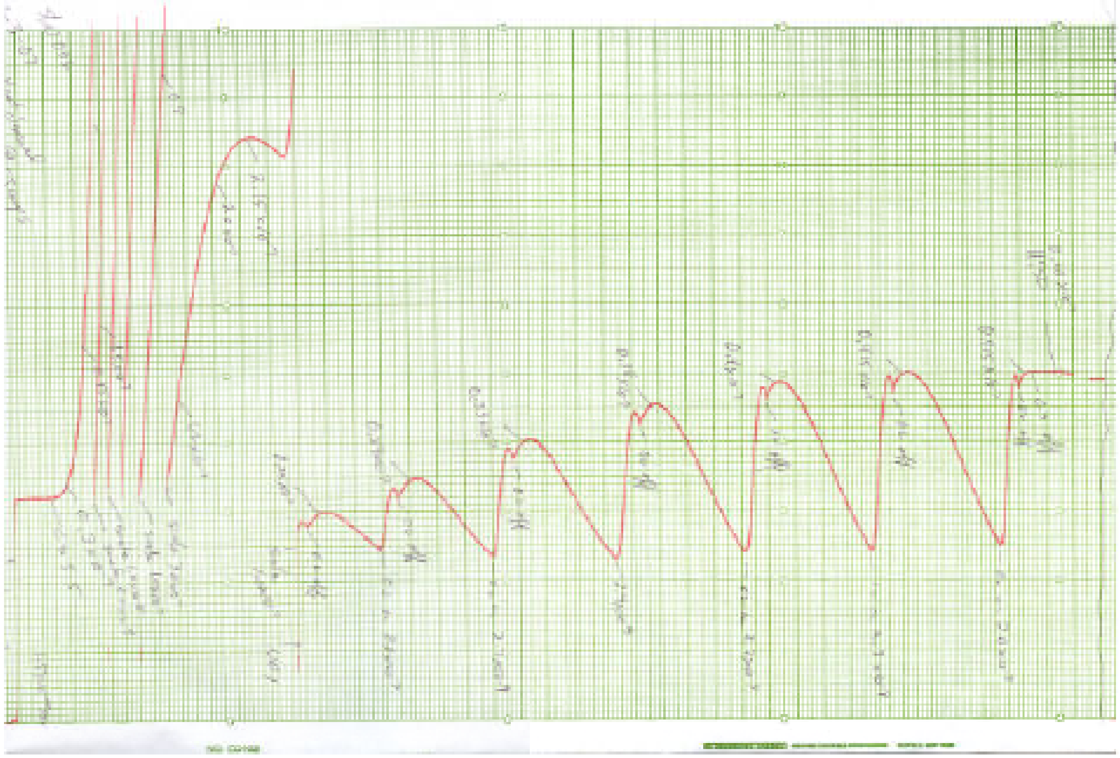


- Samples are stored in a nitrogen purged dry cabinet
- 2% hydrofluoric acid dip at room temperature for 1-$^{1}/_{2}$ minutes
- DI water rinse in a beaker with running water for 2 minutes

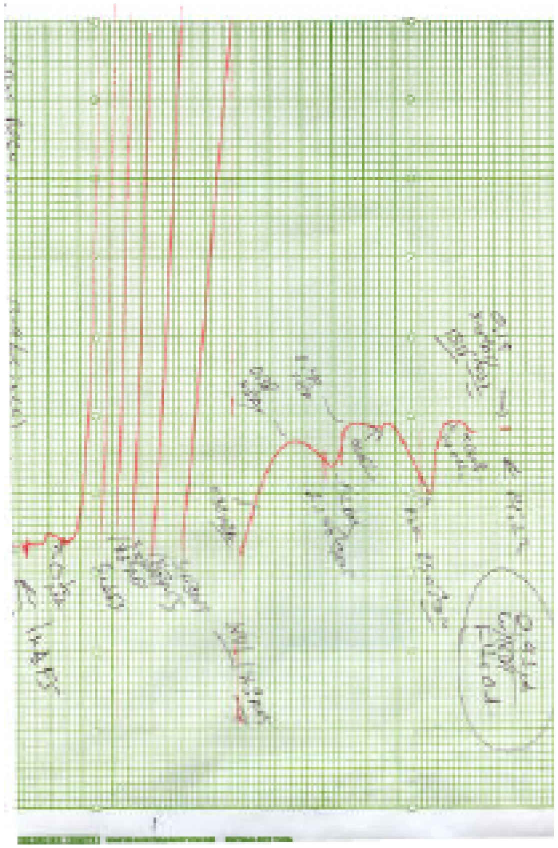
  Very highly boron doped a-Si is only moderately hydrophobic
- Dry with static-neutralized, filtered N_2 from LN_2 tank boiloff
- Mount in the holder and install into the loadlock
- Pumpdown within 5 minutes using molecular drag dry pump system
- Loadlock chamber pumps overnight before sample transfer

Activation

- Reflection mode
- Ta substrate (have used Ta, Ta coated Cu and glass)
- Cs and Oxygen
- Light source 455 nm LED



Re-activation



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

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

- Photocathode Decay with Beam Induced Desorption

  Current to chamber walls with 36 eV bias

Sample	**Start current (μA)**	***e*-fold lifetime (hrs)**
α-Si	2.4	100
GaAs	2.2	19

- Photocathode decay with NEG heater induced pressure rise

Sample	**Start current (μA)**	***e*-fold lifetime (hrs)**
α-Si	0.35	28
GaAs	0.15	7

- Hydrogen background gas and ion lifetime change for activated a-Si and GaAs

Sample	**Beam on/H_2 $2x10^{-6}$ lifetime (hrs)**	**Beam off/H_2 $2x10^{-6}$ lifetime (hrs)**	**Beam off/no gas lifetime (hrs)**	**Beam on/no gas lifetime (hrs)**
a-Si	19	longest	longest	32
GaAs	2.4	long	long	5.9

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

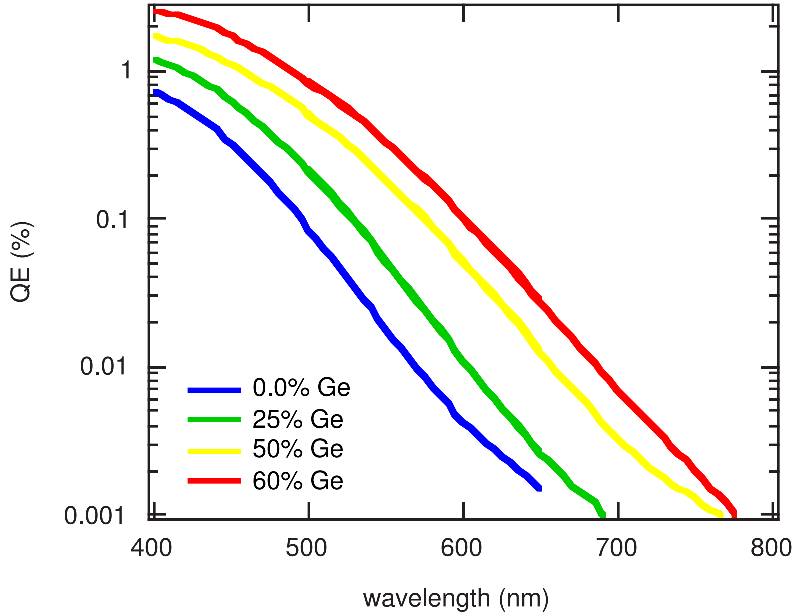
4. Measure the lifetime as in 1, but with the chamber evacuated.

Flexibility

- Example: wavelength shift

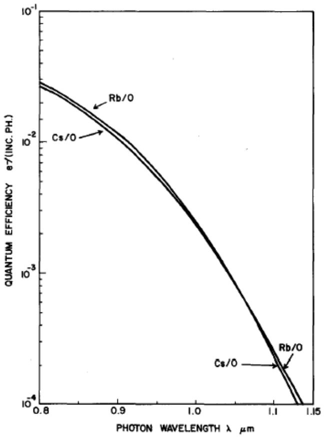
  Shift the bandgap of a-Si with germane: a-$Si_{(1-x)}Ge_x$

  Red shift in the overall spectrum



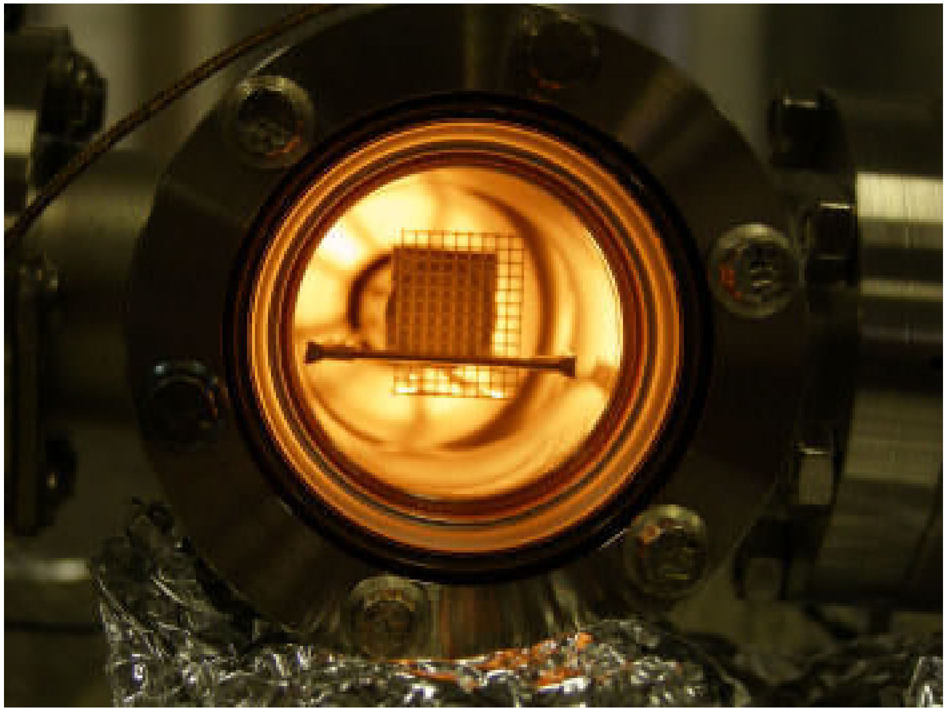
Current and future work

- 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

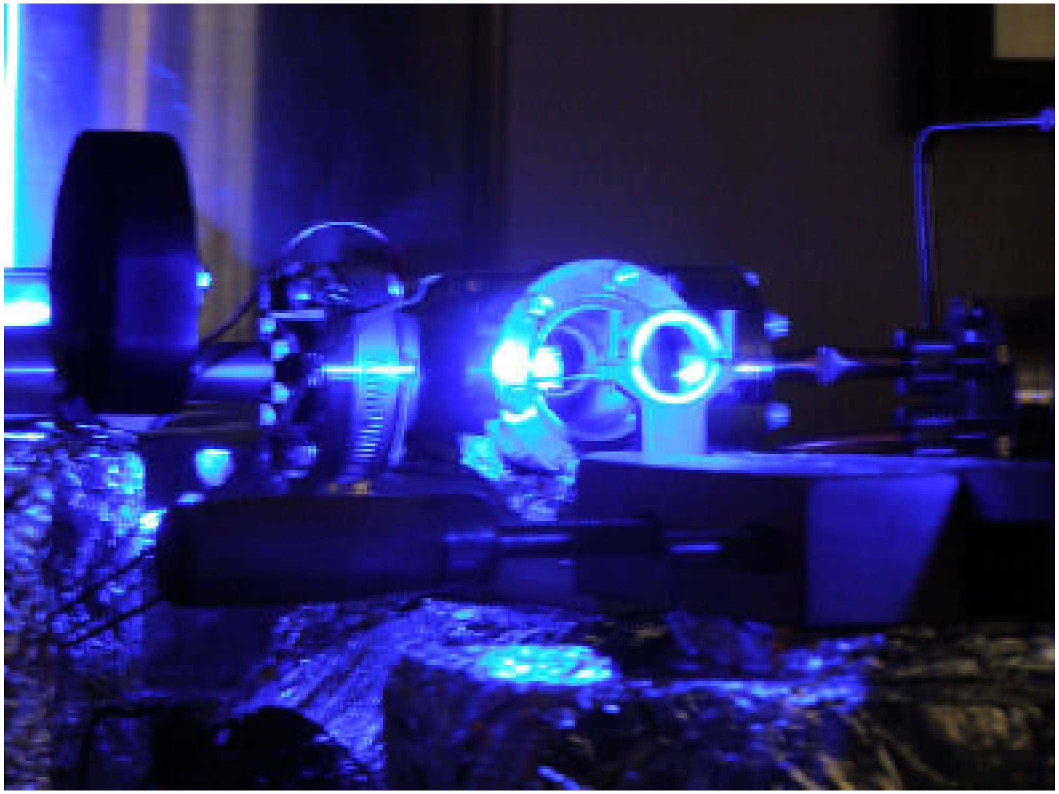


Cs and Rb activated Si(100) photoresponse. Yield was somewhat greater for the Rb activated surface.

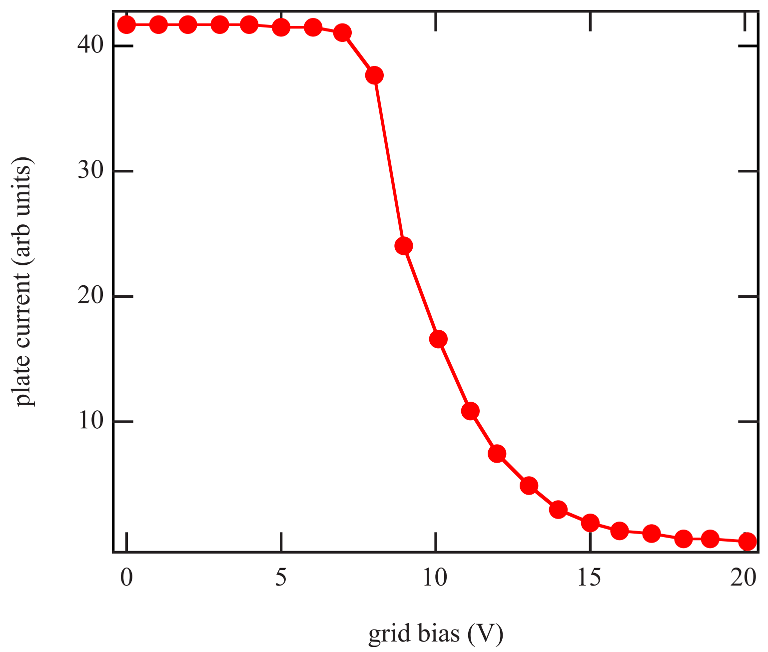
Use in vacuum tubes (un-funded)



Heat Cleaning of a-Si in stand-alone tube

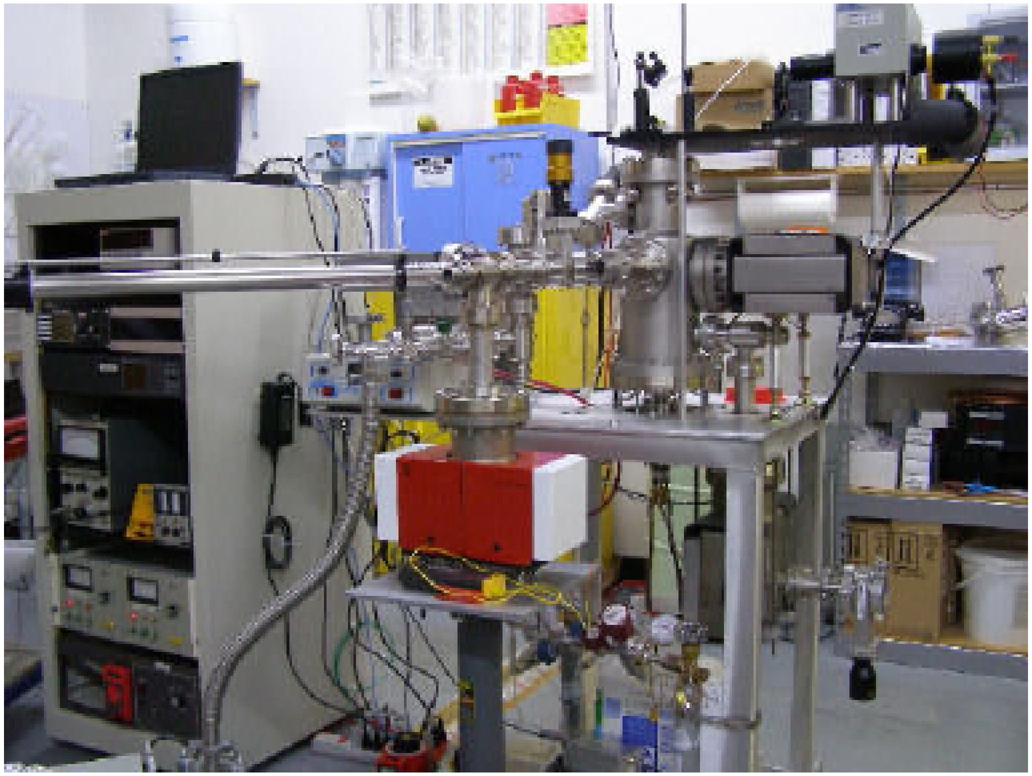


Activation of a-Si in stand-alone vacuum tube



Characteristic curve of photo-triode a-Si vacuum tube
- grid very coarse -

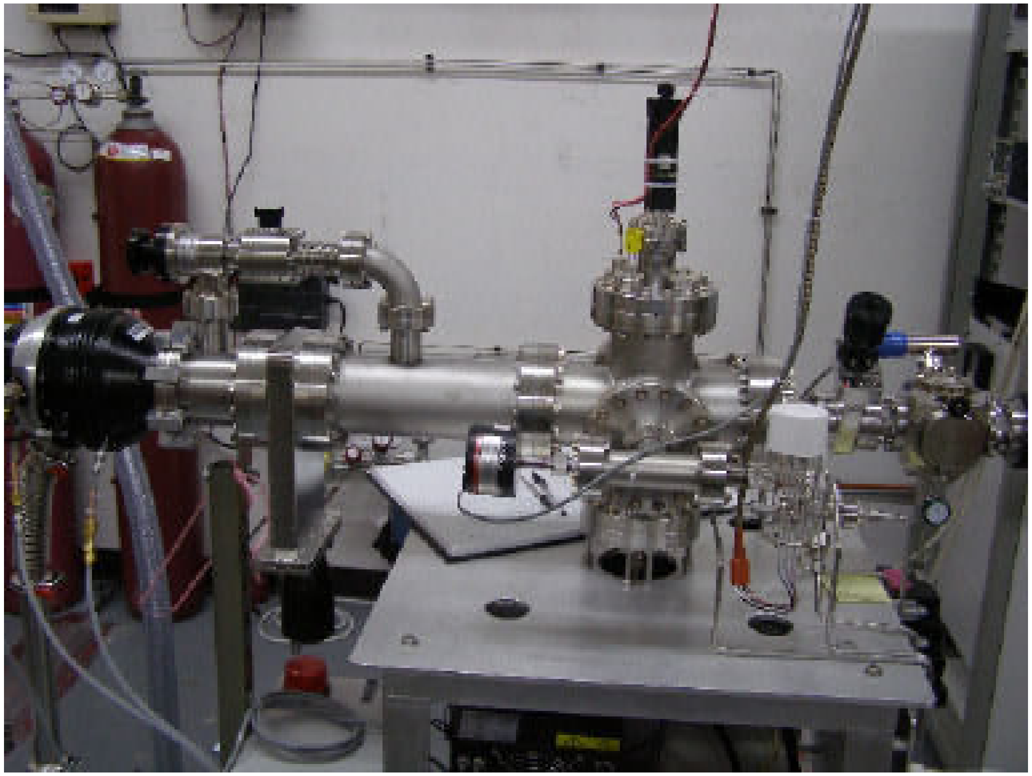
Appendix: Saxet Surface Science Facilities



Silicon cathode test system

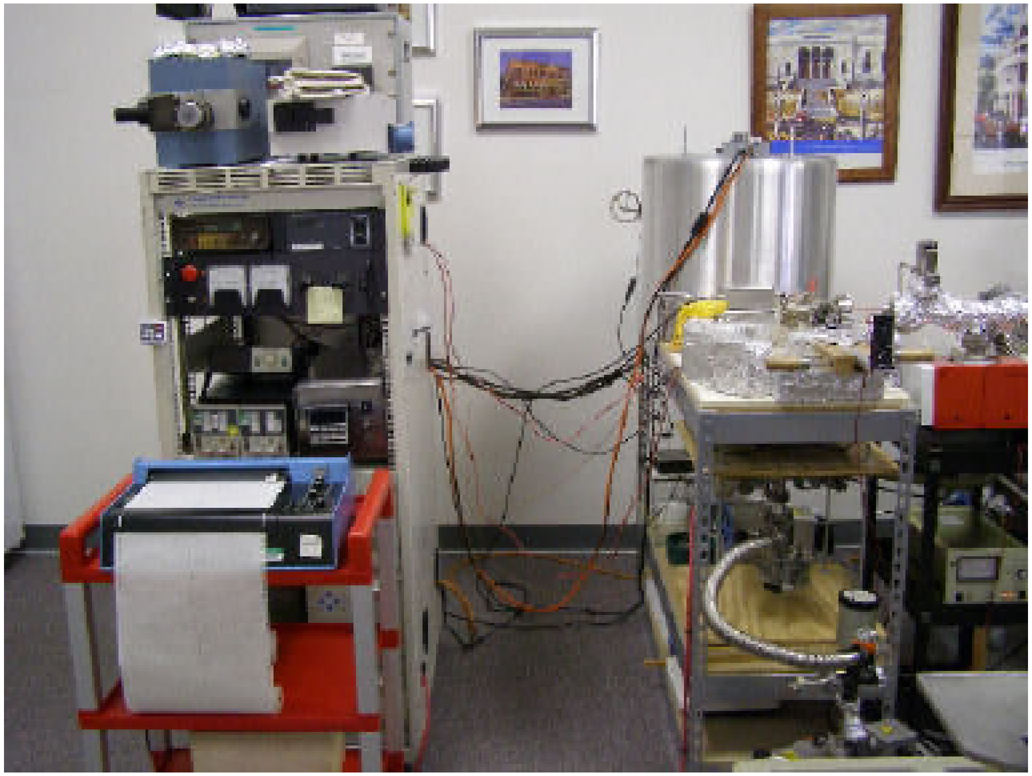
GaAs cathode test system

Sputter deposition system



RF PECVD deposition system

Auger system



Tube bake and test system

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Optical Microscopes and IR/VIS Spectrometer

Laminar flow clean bench

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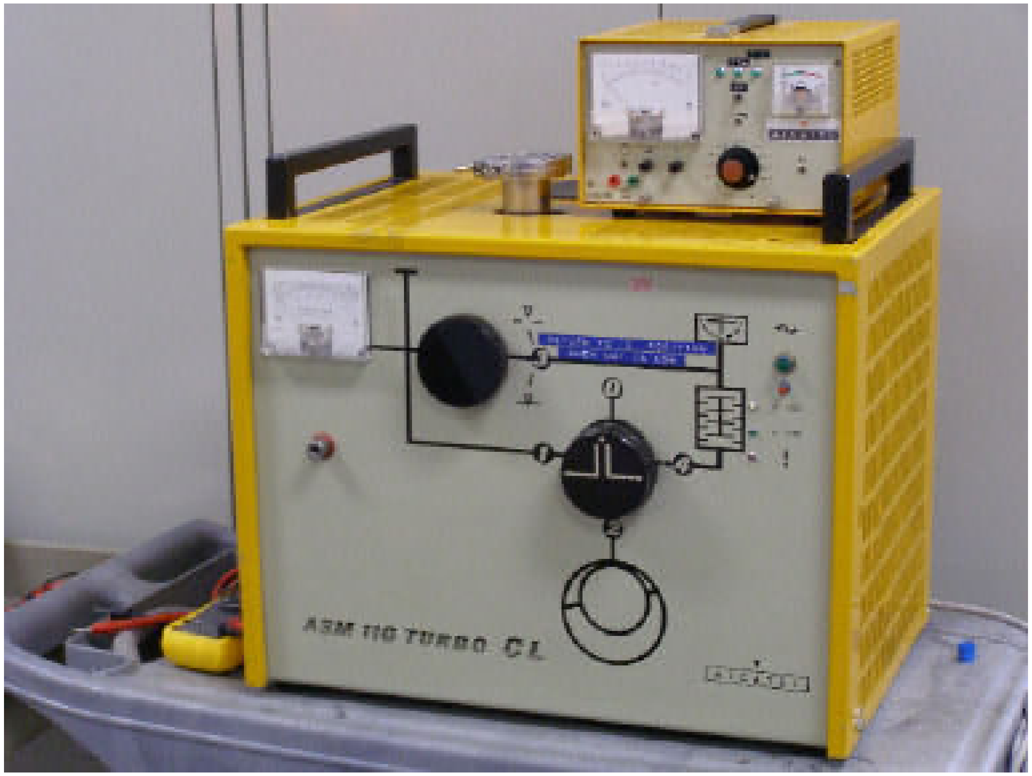

Vacuum leak checker

Electronics work bench