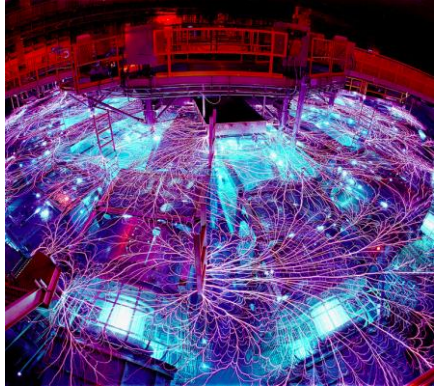
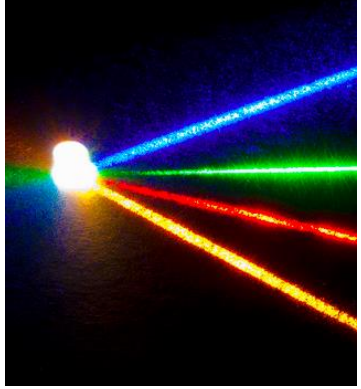
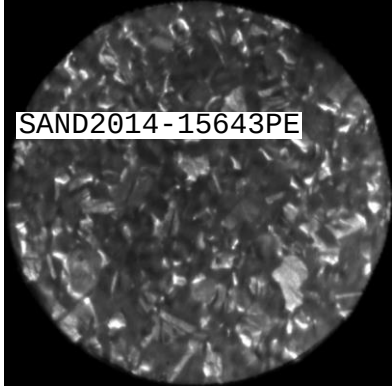





U.S. Department of Energy SunShot Initiative

Bridging Research Interactions through collaborative Development Grants in Energy (BRIDGE)

Spectroscopic Photoemission Electron Microscopy (Spec-PEEM) for Imaging Nanoscale Variations in the Chemical and Electronics States of Thin-Film Photovoltaics

Calvin K. Chan, Sandia National Laboratories
Kannan Ramanathan (Rommel Noufi), NREL
Brian Korgel, The University of Texas at Austin
Taisuke Ohta (Gary Kellogg), Center for Integrated Nanotechnologies
Normand Modine, Center for Integrated Nanotechnologies
Daniel Dwyer, Photovoltaics Manufacturing Consortium

Quarterly Update
07 May 2014

Agreement #25859

BRIDGE Project Overview

- **Objective:** Develop and apply new metrology tool (spec-PEEM) to measure nanoscale chemical and electronic structure of PV materials and devices.
- **Collaborative Research Team**

Sandia National Laboratories

Calvin Chan (PI), Senior Research Staff
C. Bogdan Diaconescu, Post-doc
Low-energy and photoemission electron microscopy, electron spectroscopy, electronic/chemical structure, interfaces, materials/device physics

The Center for Integrated Nanotechnologies

Taisuke Ohta (formerly Gary Kellogg), Senior Research Staff
Normand Modine, Brian Swartzentruber, Principle Research Staff
Low-energy electron microscopy, theory and simulation of nanoscale phenomena, nanoscale electronic transport, nanomanipulation

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Kannan Ramanathan (formerly Rommel Noufi), Group Manager
Lorelle Mansfield, Scientist
Thin-film PV materials and devices, record-setting vacuum-deposited CIGS

THE UNIVERSITY OF TEXAS AT AUSTIN

Brian Korgel, Professor, Chemical Engineering
Doug Pernik, Taylor Harvey, C. Jackson Stolle, Graduate Students
Solution-deposited thin-film PV materials and devices, nanoparticle synthesis

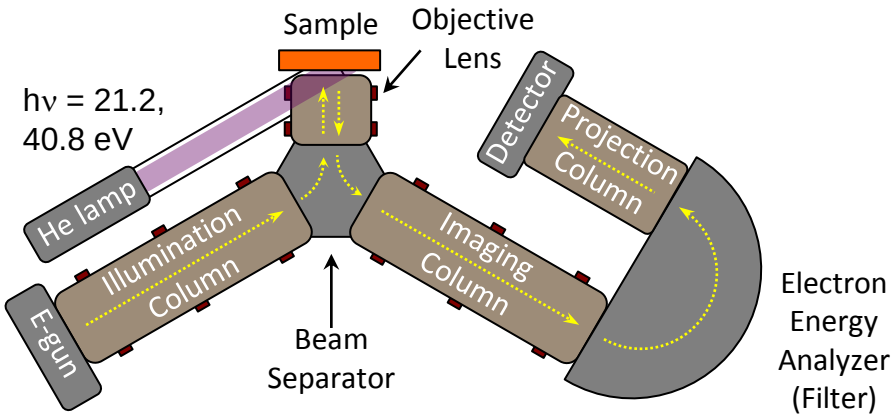
U.S. PHOTOVOLTAIC MANUFACTURING CONSORTIUM PVMC

Daniel Dwyer, Senior Process Engineer
CIGS pilot line, commercialization

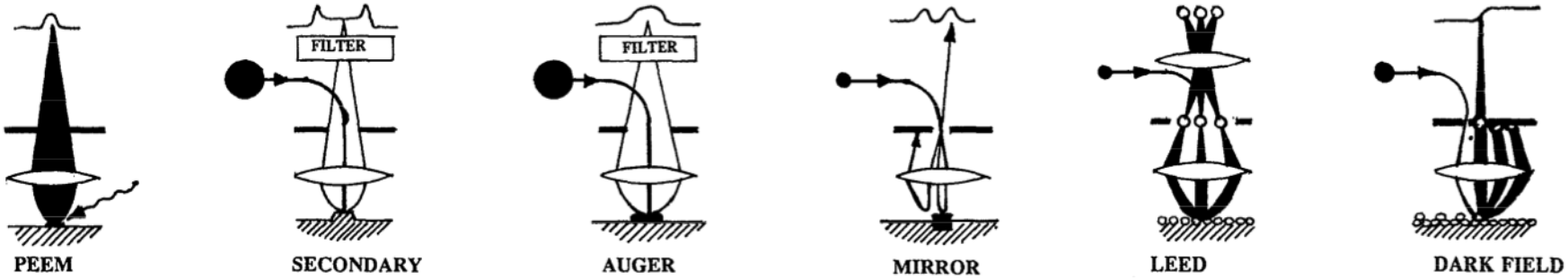
Technical Approach: Spectros. PEEM/LEEM

- **Developing and Applying Photoemission / Low Energy Electron Microscopies (PEEM / LEEM) to Photovoltaic Materials and Devices**

Spatially-resolved electronic and chemical structure (PES, EELS, AES, SES, LEED, etc.)



- **5-10 nm spatial resolution**
- **50-100 meV spectral resolution**
- **Live-time imaging of:**
  - Surface topology and crystallography
  - Electronic and chemical structure
  - Carrier/field distribution
  - Fermi-level/surface
  - Interfacial band alignment



Veneklasen, *Rev. Sci. Instrum.* **63**:5513 (1992).

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Project Updates and Proposed Revisions

- **Timeline and Budget**

  Extend Project by 2 Quarters:

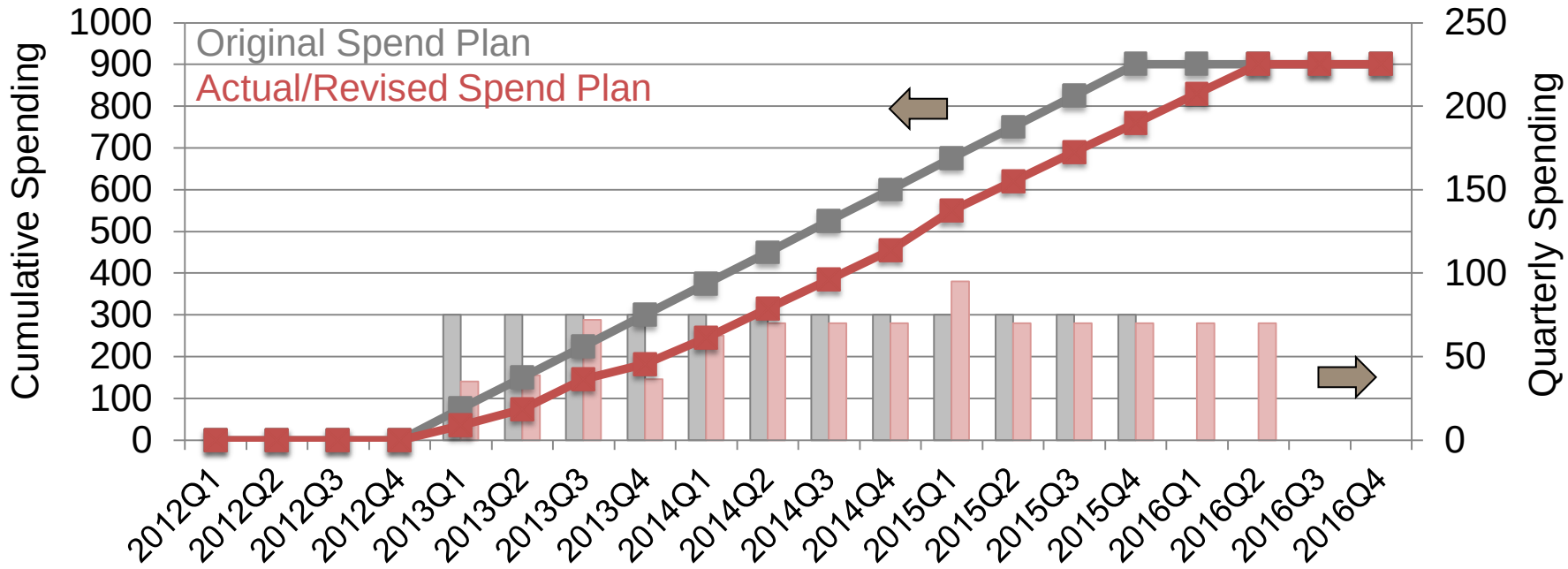
  - **Budget Period 1** (January 2013 – ~~June 2014~~): **$450k**

    December 2014 $245k spent (54% spent over 83% BP1)

  - **Budget Period 2** (~~July 2014 – December 2015~~): **$450k**

    January 2015 – June 2016

  - See next slide for added task.



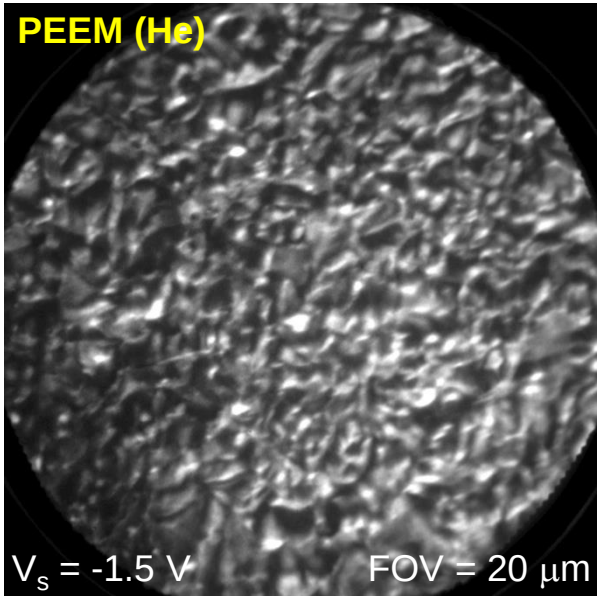
Project Updates and Proposed Revisions

- **Summary of Budget Period 1 Milestones**

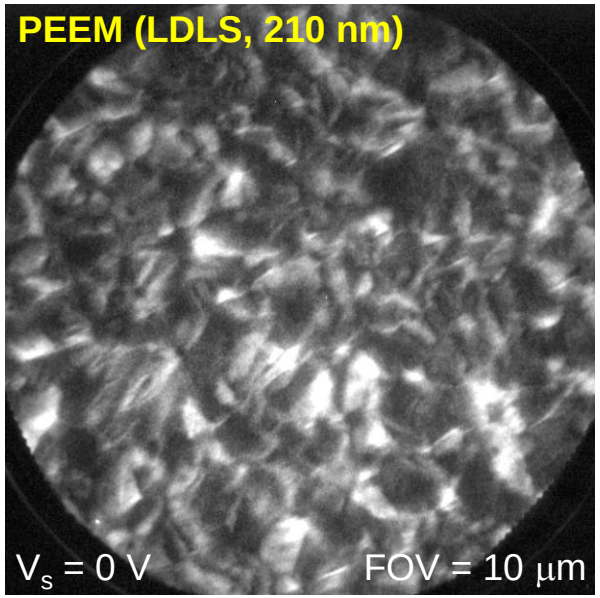
Date	Task/Milestone	Status
12/2013	**M (ST-3.4).** Demonstrate nm-resolved chemical/electronic states in NP-CIGS films.	**Completed 12/2013.**
06/2014	**M (ST-3.5).** Observe mesoscale Cu segregation at PVD-CIGS grain boundaries.	**Completed 09/2013.**
~~06/2014~~ 12/2014	**M (T-3).** Demonstrate nm-resolved chemical/ electronic states of PVD-CIGS.	**On-track.** Electronic states demonstrated. Chemical states TBD.
12/2014	**ST-3.6.** Add and evaluate sample cleaning capabilities, e.g. sputter gun, H_2 cracker.	**On-track.** ST added 2013 Q4. Installed and prelim. studies begin.
12/2014	**ST-3.7.** Add and evaluate high intensity monochromated laser-driven light source.	**On-track.** ST added 2013 Q4. Unit installed. Prelim. studies begun.
12/2014	**ST-3.8.** Develop image analysis software to perform statistical analysis of data.	Not yet started. ST added 2014 Q1. See next slides for details.
~~06/2014~~ 12/2014	**G/NG-1** Dynamic growth studies feasible?	**On-track.** Preliminary data on grain ripening observed, pending analysis.
06/2014	Identify industrial partner.	**At-risk.** Landscape changing quickly. Will continue efforts at meetings.
06/2014	Compute band structure of CIGS GB	**At-risk.** Lack of personnel. Previous efforts by Yan. Will discuss with Yan.

Progress Report for CY14 Q1

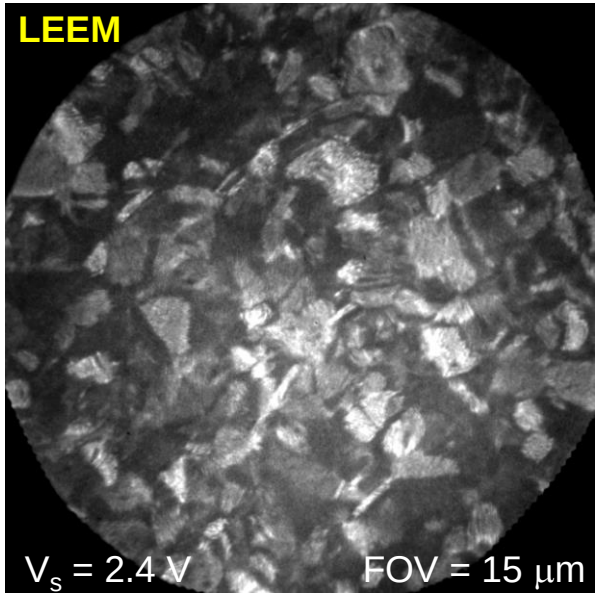
- **Comparison of Results Using New Laser-Driven Xenon Plasma Lamp System**
  - ~10x higher intensity for Laser-Driven Light Source (LDLS, hν = 6 eV) vs He lamp (He I, hν = 21.2 eV).



FOV = 20 µm
V_{MCP} = 1.5 kV
t_{exp} = 5 sec
Avg Counts = 1000



FOV = 10 µm
V_{MCP} = 1.4 kV
t_{exp} = 0.5 sec
Avg Counts = 300

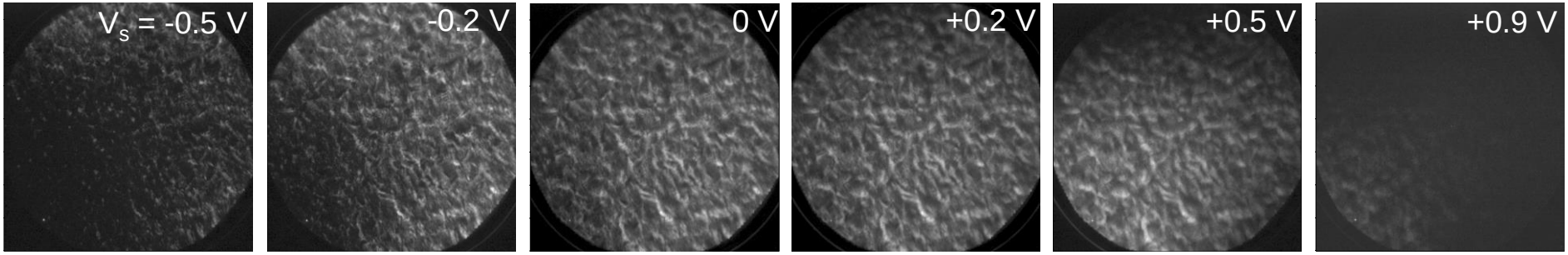


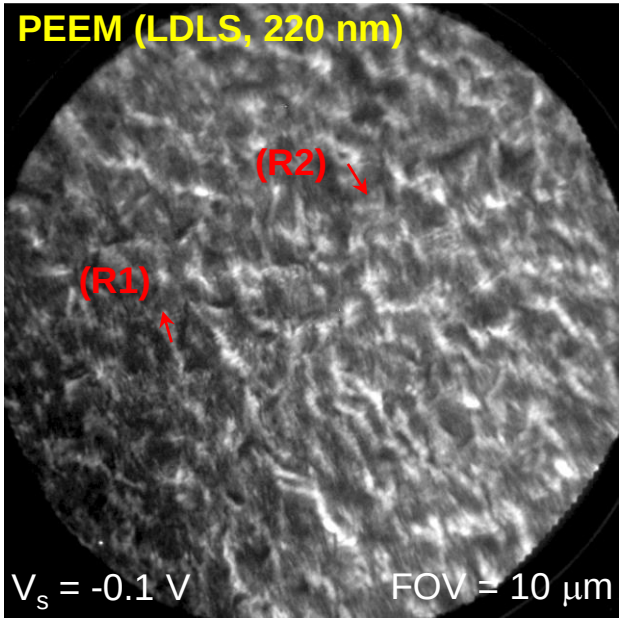
FOV = 15 µm
V_{MCP} = 1.35 kV
t_{exp} = 0.1 sec
Avg Counts =1000

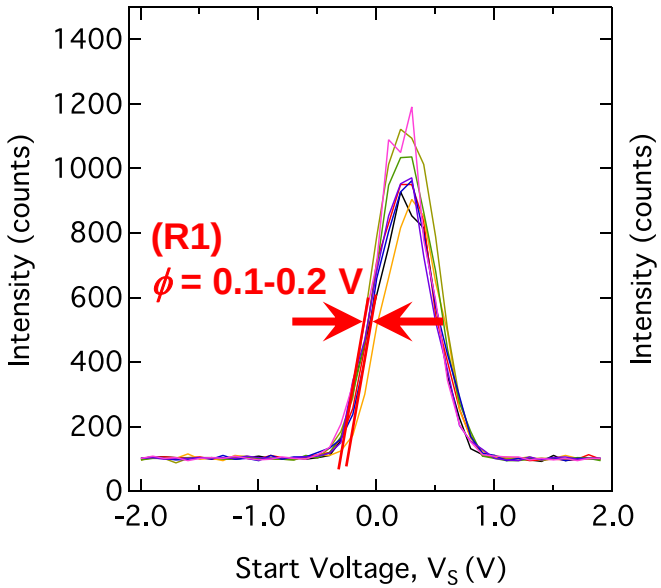
New light source provides higher resolution, more stable imaging.
PEEM with LDLS resolution approaching parity with LEEM.

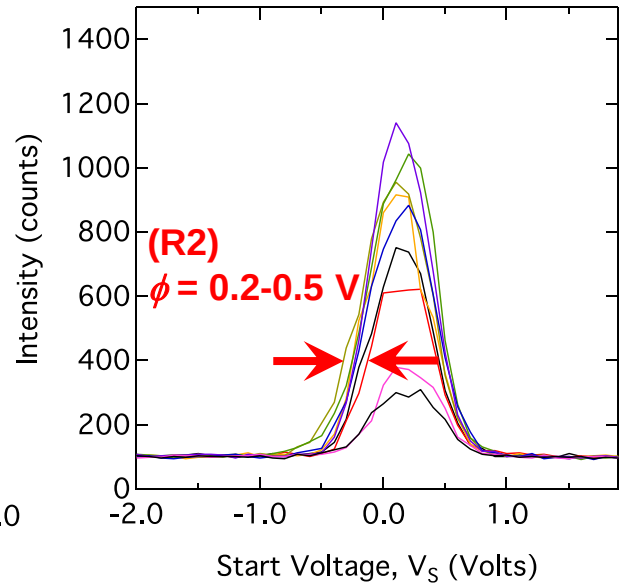
Progress Report for CY14 Q1

- **Determining changes in local work function using PEEM-IV with new LDLS.**





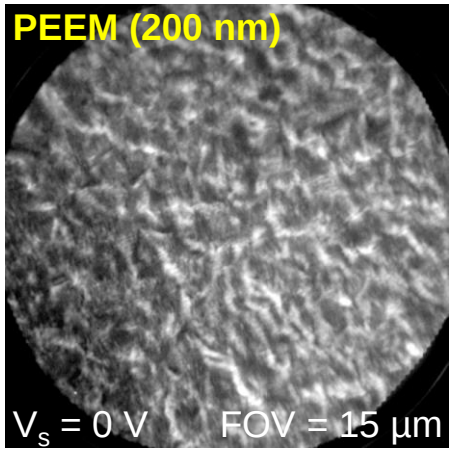


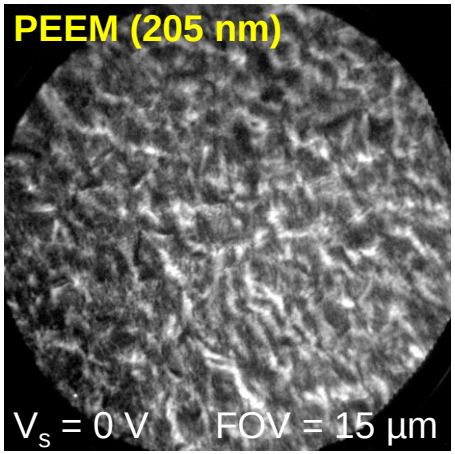


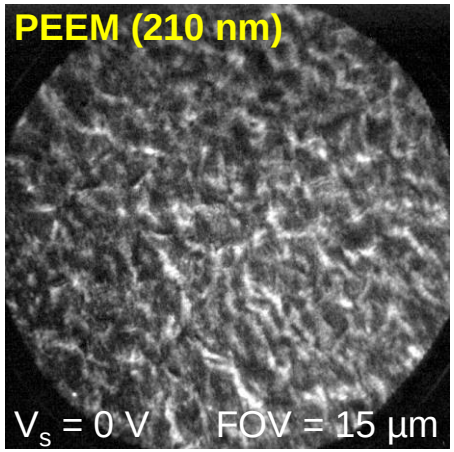
Despite fine structure detail in grains, "internal" variations (R1) show no ϕ. G-GB variations (R2) show ϕ = 0.5 V.

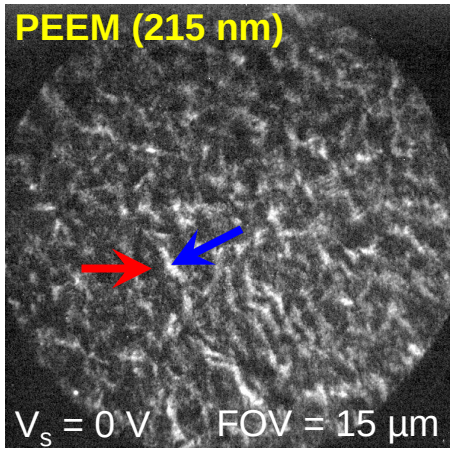
Progress Report for CY14 Q1

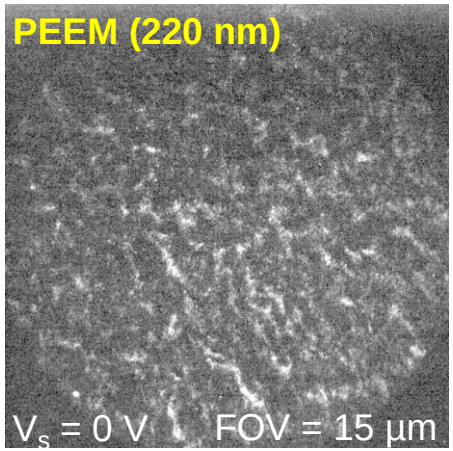
- **Local work function determined with PEEM using variable wavelength LDLS.**

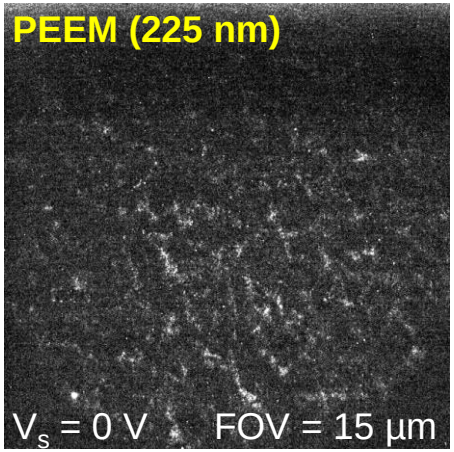


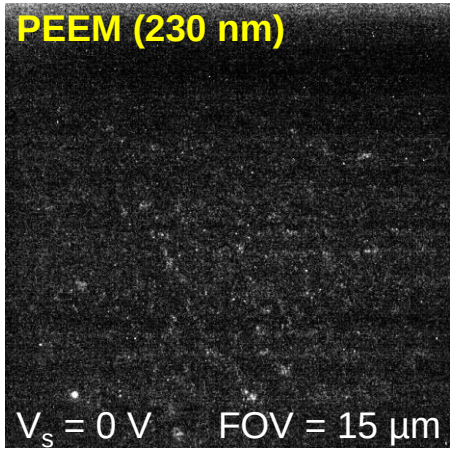


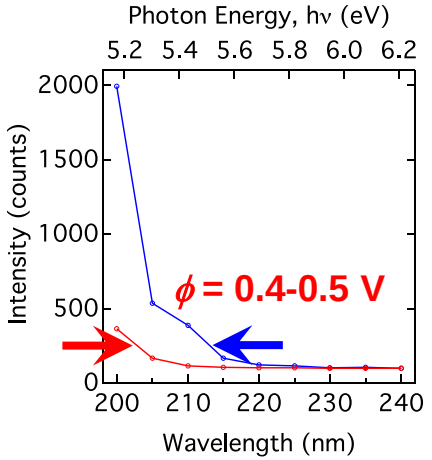








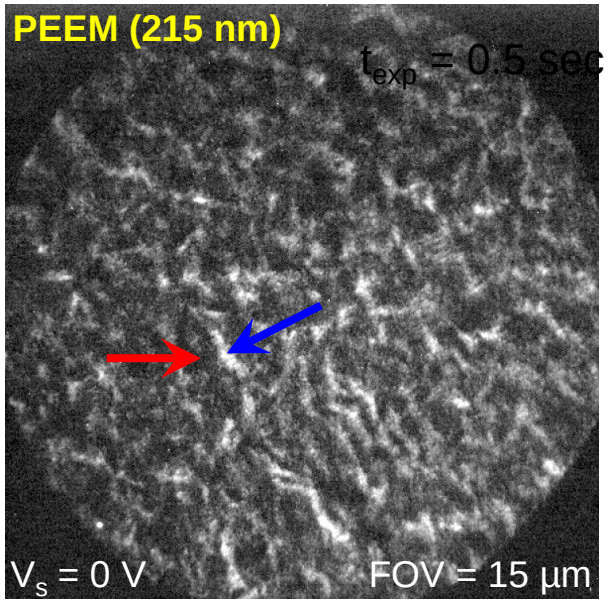


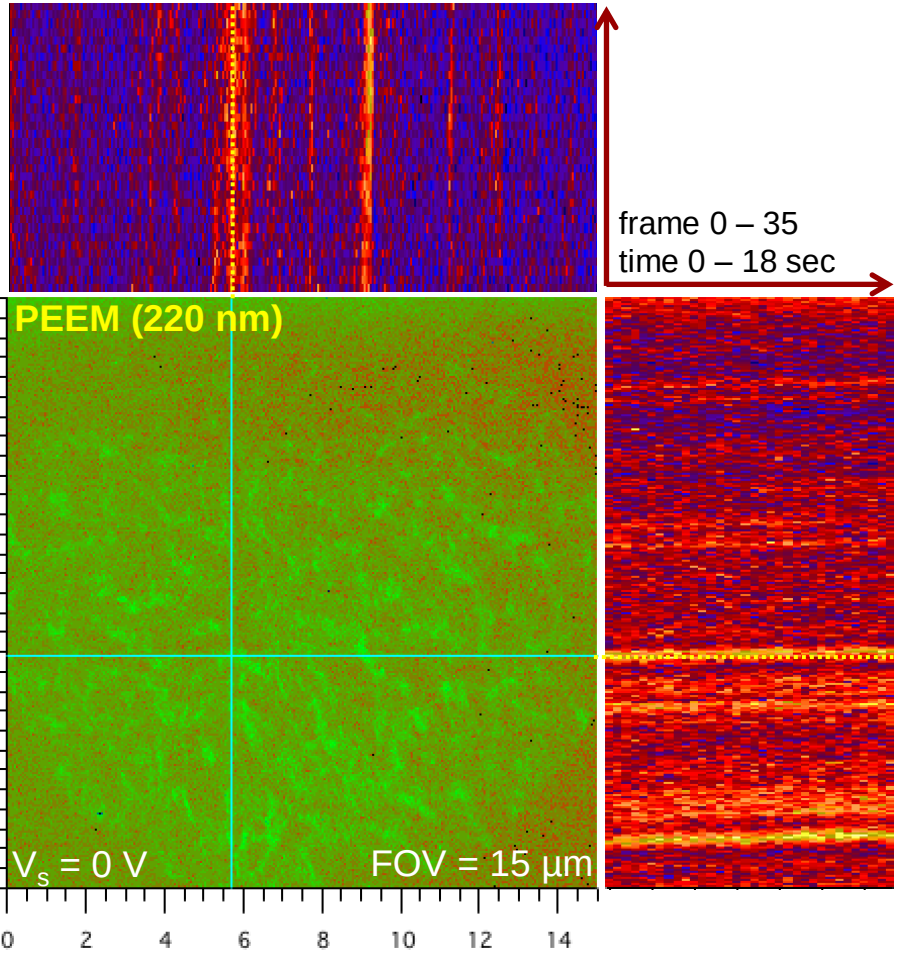


Observe photoemission onset/cutoff by varying incident photon energy.
G-GB work function difference ~0.5 V.

Progress Report for CY14 Q1

- **Can we get better images/data by increasing acquisition time?**
  Higher t_{exp}?
  Higher frame averaging?
- Perform PEEM at 220 nm.
  Take 35 images using t_{exp} = 0.5 sec,
  16 frame average.





Noticeable drift is observed over ~5 min (35 images @ 0.5 sec, 16 frames each).
Need autocorrelation and thresholding algorithms.

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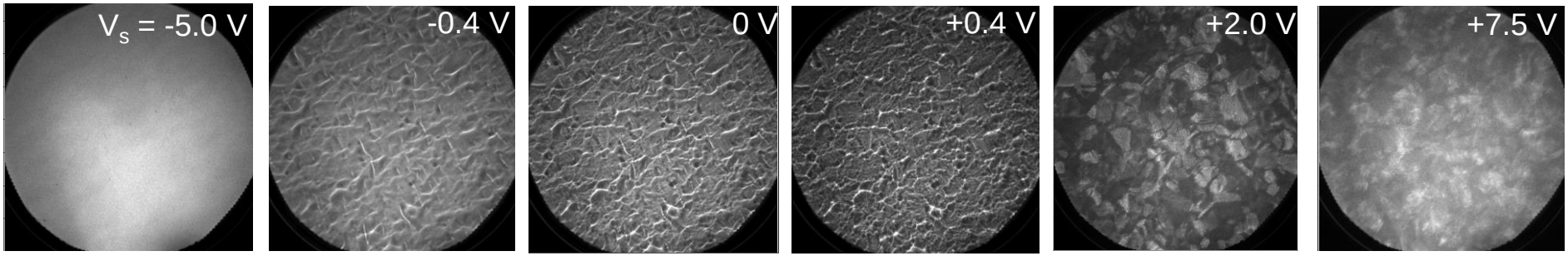
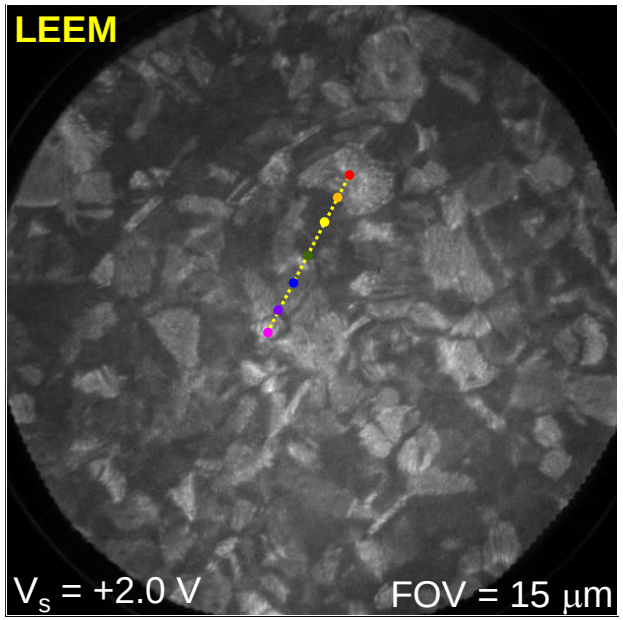
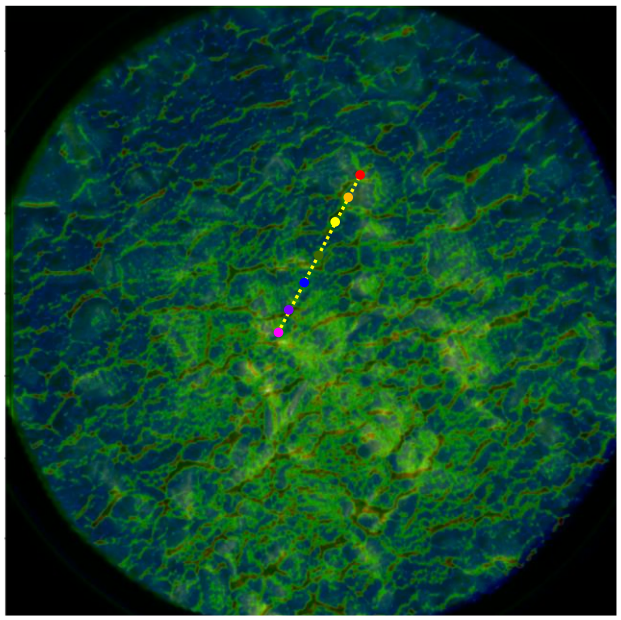
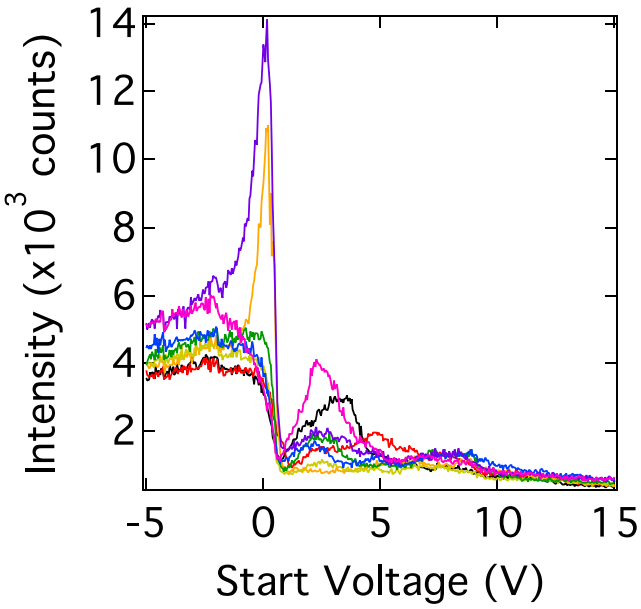
Progress Report for CY14 Q1

- **Determining changes in local work function using LEEM-IV.**









G-GB variations show ϕ = 0.5 V.

Origins of the fine details in the LEEM-iv spectra?