

Vector Potential Photoelectron Microscopy: Overview

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Vector potential photoelectron microscopy ^[1] (VPPEM) is a new spectroscopic microscopy that provides information about the elemental composition, and chemistry of materials surfaces. VPPEM was developed to image a wide range of real world samples, including samples with high aspect ratio topography, uneven or poor conductivity, magnetic materials, and fibers. The VPPEM technique is based on photoelectron spectroscopy (PES). VPPEM uses a strong immersion magnetic field at the sample to create a full field electron emission image. The full field image is energy analyzed using a concentric hemispherical analyzer (CHA), and projected onto an image detector. A spectroscopic image series is created by changing both the energies of the photons, and the detected electrons. The vector potential imaging technique is unique in microscopy allowing images to be made of very low energy photoelectrons, down to tenths of an electron volt, with submicron spatial resolution, on uneven surfaces. A schematic of the VPPEM instrument is shown in Fig. 1.

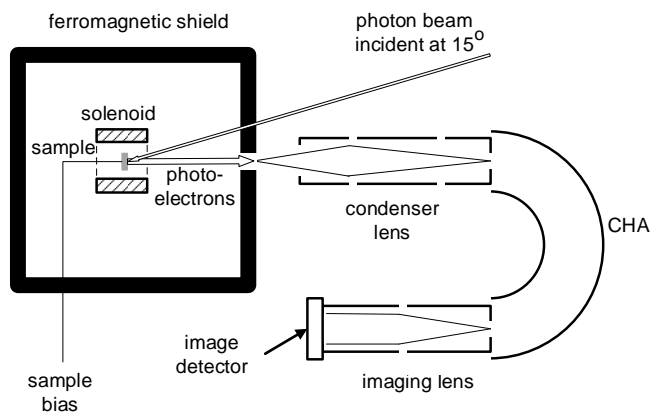


Fig. 1 Schematic of the VPPEM instrument

A magnet with a uniform field region, such as a solenoid, is used to create a cylindrically symmetric vector potential field. The microscope uses the magnetic vector potential field as a spatially resolved reference for image formation. The sample sits in the middle of this field, and is irradiated with photons. Photoelectrons are emitted into the field, and travel down magnetic field lines to an aperture in a ferromagnetic shield where the field is terminated. Because the momentum electrons have in the vector potential field is conserved when the field is terminated, the photoelectrons diverge into an angular image. The resultant angular photoelectron image is energy analyzed using a concentric hemispherical analyzer (CHA). The energy analyzed angular image is projected onto an image plane detector using electrostatic lenses. A high depth of focus results from the vector potential being a cylindrical shape along the magnet axis. In the case of the present instrument the depth of focus is very large, of the order of millimeters.

As the photoelectrons are entrained in a strong magnetic field, the image field shape, is not sensitive to differential surface charging, surface topography, magnetic substrate effects, or sample bias. In particular the spatial resolution is not dependent on the surface topography in contrast to cathode lens-based photo emission electron microscopy (PEEM) ^[2]. However, the VPPEM image contrast is sensitive to many of these effects. In the current instrument the photon beam is at 15° to the optic axis, therefore there will be some illumination, and emission shadowing on a rough surface. Roughness will also generate changes in the effective penetration depth of the x-rays with variations in the local angle of incidence to the sample surface normal.

The energy of the imaged photoelectrons is changed by biasing the sample. In the strong part of the field, photoelectrons from the sample can be accelerated, and decelerated without distorting the image, or altering the magnification. The electrostatic focusing, and energy analysis is set to a fixed energy so that the transmission, and the magnification of the electrostatic optical system is also constant. The energy of the imaged electrons can thus be changed by simply biasing the sample. Because they are entrained along the magnetic field lines while being accelerated very low energy electrons can be imaged. The advantage of very low energy electrons for imaging with VPPEM is they have the highest spatial resolution ^[3].

The imaging signal is derived from both near edge x-ray absorption fine structure (NEXAFS), and x-ray photoelectron spectroscopy (XPS). The signal not only includes elemental and chemical contrast, but the information depth is also tunable. In combination with a synchrotron x-ray beam line, the VPPEM image is a full field image hyperspectral stack with two spectral dimensions of photon energy, and photoelectron energy.

Fig. 2 illustrates the sources of the VPPEM signal in a schematic photoelectron emission energy level diagram

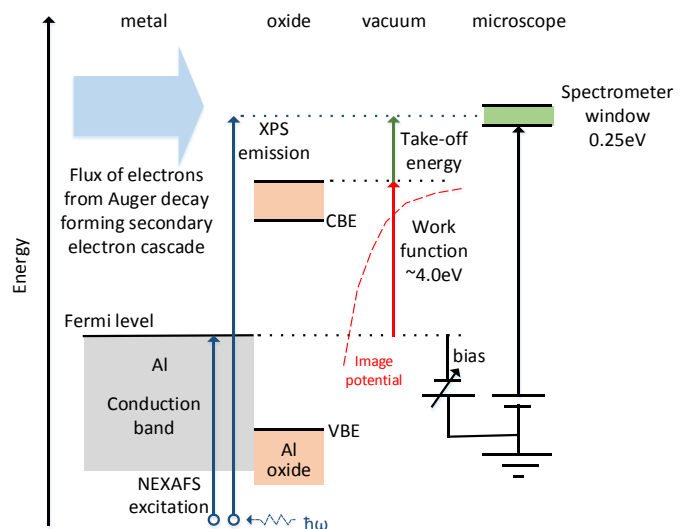


Fig. 2 Energy level diagram of the VPPEM signals from an oxidized aluminum surface

In Fig. 2 the vertical direction is energy, and the horizontal direction represents distance out of the sample surface. Fig. 2 illustrates the case of an aluminum sample with an oxidized surface. The metal is on the left, and the microscope is on the right. The sample is irradiated by x-ray photons, and if a photon, $\hbar\omega$, has sufficient energy it can create a core hole in the metal by removing an electron in a core state to an empty state above the Fermi level. In the case of an insulating oxide, the core electron is removed to the conduction band edge (CBE).

The photoelectron transitions in Fig. 2 are indicated by the blue vertical arrows beginning with a circle to represent the core hole remaining. Only the aluminum metal transitions have been shown. We expect the Fermi level in the oxide to be midway between the conduction band edge, and the top of the valence band (VBE) [4]. After the initial photoelectron event, the remaining core hole is filled with an electron from a higher energy level, and this initiates an Auger cascade. The Auger cascade creates a flux of inelastically scattered electrons over a wide energy range. These electrons form the secondary electron distribution when they leave the sample. The increase in the number of secondary electrons as the photon energy is swept from a low energy up across the core absorption energy is detected by the spectrometer as the NEXAFS signal.

As the photon energy is raised to several eV above the core absorption energy, the XPS electron ejected from the aluminum metal core hole can escape the surface directly. The directly emitted electron must have a kinetic energy in the solid that is greater than the workfunction. For an aluminum metal XPS electron, it also has to travel through the oxide overlayer without being absorbed. If the potential bias of the sample has been set so that the energy of the XPS electron in the vacuum coincides with the energy window of the spectrometer, then the electron is detected. If the sample bias is fixed, and the photon energy is increased, the XPS signal will move through the spectrometer window to produce a peak in the spectrometer signal. This XPS signal will be superimposed on the background secondary electron signal. By changing the sample bias, the energy of the detected electrons (the take-off energy) can be changed from zero to thousands of electron volts. The XPS signal will appear at different photon energies depending on the take-off energy. For VPPEM, we are most interested in the very low energy electrons, 0-10 eV because low energy electrons give the highest spatial resolution [3]. The highest spatial resolutions available are at the secondary electron cut-off region of a few tenths of an electron volt.

Fig. 3 shows a VPPEM spectrum from an aluminum sample taken from an image series with photon energies from 72.5 eV to 85.0 eV in 0.5 eV steps with a take-off energy of 0.5 eV and a 0.25 eV energy resolution [5].

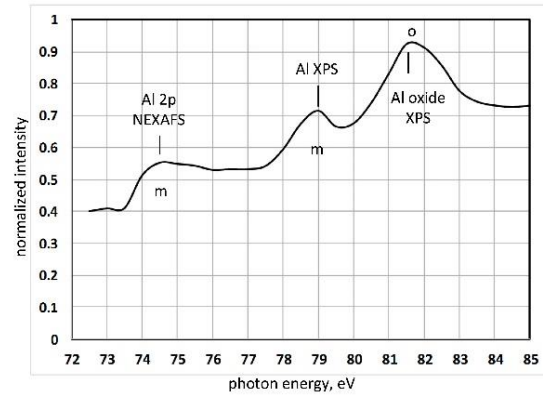


Fig. 3 VPPEM spectrum from oxidized aluminum

The spectrum of Fig. 3 is different from both a conventional partial emission yield (PEY) NEXAFS spectrum, and a typical XPS spectrum. The VPPEM spectrum is in effect a binding energy spectrum, because, except for the 0.5 eV take-off energy offset, the change in electron yield represents the binding energy of the excitation processes. The 2p Al metallic NEXAFS feature appears at 74.5 eV, and the 2p Al metallic XPS feature would be then be expected to appear at a 4.5 eV higher energy at 79.0 eV. The extra 4.5 eV binding energy is the sum of the 4.0 eV workfunction [6], and the 0.5 eV electron take-off energy. In Fig. 3 a third peak can be seen at 81.5 eV. This is the 2p Aluminum oxide XPS peak which is 2.5 eV higher than the metal peak

A major aim of the VPPEM technique is to extract high spatial resolution image information from the spectral image set. This entails several steps which we will just outline here.

First, we need to understand that the spatial resolution of the VPPEM is complex. The VPPEM spatial resolution depends on the maximum cyclotron radius, r_{\max} , of the photoelectrons as they are emitted into the vacuum [3]. With a field B and the energy of the imaged electrons E :

$$r_{\max} = \frac{\sqrt{2mE}}{eB}$$

The current prototype VPPEM instrument uses a 2.0 T field, and for a 1.0 eV electron in a 2.0 T field emitted at 90° to the normal r_{\max} is 1.7 μ . The standard method to determine spatial resolution uses a line scan across an edge [7]. A close approximation to the 20-80% edge resolution in microns for the VPPEM is $3\sqrt{E}/B$ with E in electron volts, and B in Tesla [3], implying a XPS feature just appearing 1.0 eV above the vacuum level, gives a base edge spatial resolution of 1.5 micron at 2 T. However, the edge resolution significantly underestimates the information content of the images. Fig. 4 shows the two dimensional point spread function for 1.0 eV electrons in a 2 T field.

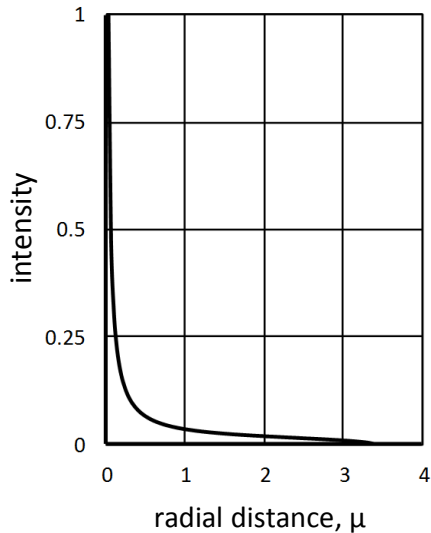


Fig. 4 VPPEM point spread function

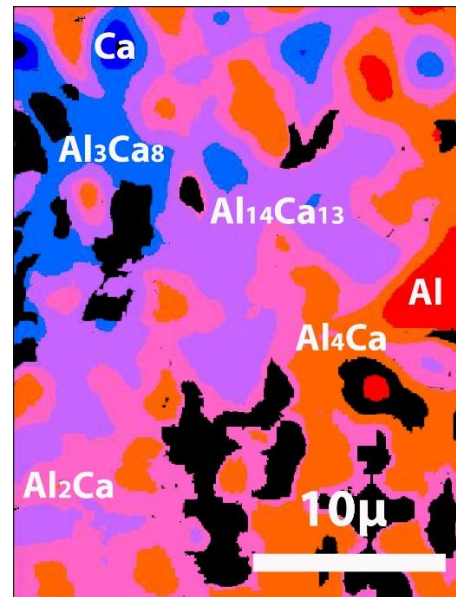


Fig. 5 VPPEM phase image of Al-Ca alloy

The VPPEM point spread function (PSF) is very sharply peaked in the center with a wide tail. Because 50% of the signal is in the wide tail at over 1.5 μ from the center, this determines the edge resolution, but the PSF has significant high frequency components which can be enhanced by deconvolution.

To get the most out of deconvolution the spectral image stack must be aligned to remove sample drift during the multiple exposures (at beamline U4A in the region of 30 minutes). The spectral image stack is then broken up into regions that have unique spectra. These images are used to define endpoint images. The end point images are then deconvolved using the VPPEM PSF by application of the Lucy-Richardson deconvolution algorithm^[8, 9]. Using scatter diagrams the images are partitioned into regions, and from the spectra of the regions are assigned.

The false color image of Figure 5 is of the reaction zone between Calcium and Aluminum. The sample is a high distortion strengthened wire for overhead power transmission^[10, 11]. When annealed the Ca and Al react forming a brittle zone of intermetallics, and impurity phases (unassigned black areas). The spatial resolution has been improved by the deconvolution to better than 300nm.

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