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## Spectroscopic Imaging of Heterogeneous Nanomaterials – X-Ray Photoemission Microscopy at the NSLS

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*We report the present status of a newly installed low-energy electron microscopy and photoelectron microscopy end station at NSLS beamline U5UA. In the first test experiments on sub-monolayer Au coverages deposited on Ru(0001), we demonstrate core-level and valence band photoelectron imaging with a lateral resolution of about 65 nm at a field of view of 10 μm. In contrast to other installations for photoelectron microscopy, the new NSLS end station uses illumination under normal incidence, maximizing the photon flux and enhancing the sensitivity for future in-plane characterization of magnetic materials.*

Low-energy electron microscopy (LEEM) has contributed considerably to the understanding of dynamic surface processes such as adsorption, thin film growth, or chemical reactions under ultra-high vacuum conditions. The contrast observed in LEEM arises from local changes in atomic surface structure, resulting in pronounced modulations of the local reflectivity for electrons impinging on the sample with kinetic energies of typically a few electron volts. In general, these variations may reflect atomic steps, co-existing surface phases, or chemical inhomogeneities. While the biggest advantages of LEEM are its *in-situ*, video-rate imaging capability of sample areas of about 2-50 μm in diameter with a lateral resolution better than 10 nm and high surface sensitivity, this technique only probes surface structure and does not generally provide element or chemical specificity. If combined with an energy filter and a tunable photon source of sufficient

flux and brilliance, however, the low-energy electron microscope may also be used for *spectroscopic imaging*, i.e., for laterally resolved element-sensitive surface mapping known as x-ray photoemission electron microscopy (XPEEM) (see **Figure 1**). Here, we illustrate the capabilities of our new setup at NSLS beamline U5UA, consisting of

a recently installed Elmitec LEEM III instrument with an imaging energy analyzer, by discussing first experimental results on the model system Au/Ru(0001).

Au/Ru(0001) was chosen as a model system for initial LEEM/XPEEM imaging because it constitutes a heteroepitaxial system in which the film nearly perfectly wets the substrate, and in which there is negligible intermixing between film and substrate materials. Hence, sharply delineated two-dimensional (2D) Au islands on Ru can be grown at submonolayer coverage, providing an ideal test structure for element-specific surface imaging. In **Figure 2**, bright-field LEEM micrographs are displayed that show the evolution of the surface morphology upon Au deposition onto a Ru(0001) single crystal. Starting from the clean surface on which only atomic steps and step bunches are visible as dark bands (**Figure 2a**), the heterogeneous nucleation of Au islands (dark patches) is



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observed, which starts at the lower side of the substrate step edges (**Figure 2b**). Upon further deposition, dendritic 2D island growth by Au adatom capture, i.e. adsorption of Au atoms and subsequent diffusion to the edges of the growing islands, and the nucleation of additional islands at substrate steps are competing processes. Finally, the growth is stopped at about a half-monolayer Au coverage (**Figure 2c**) to obtain a patterned surface for the photoemission electron microscopy (PEEM) experiments.

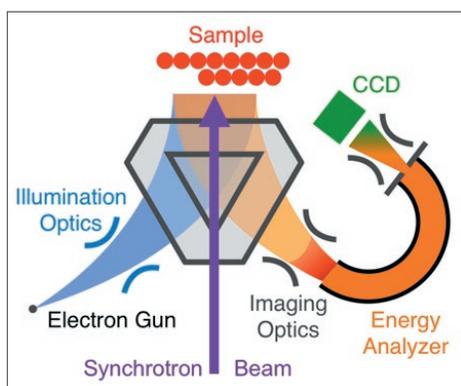
In the following, we will provide examples for three different modes of photoemission microscopy based on the kinetic energy of the detected electrons: In PEEM, the slow inelastically scattered electrons, which exhibit kinetic energies close to 0 eV, are employed, generally providing chemical image contrast

due to local work function variations at high overall intensity. Such an image is shown in **Figure 3a**, in which the Au-covered regions appear dark due to an increase of the work function as compared to the clean Ru surface.

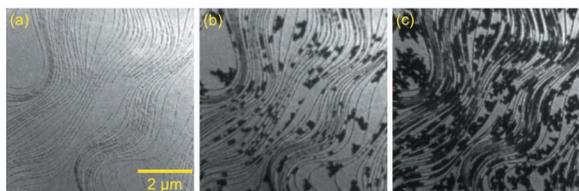
In contrast, XPEEM makes use of photoelectrons that can be attributed to specific atomic core-levels, thereby providing direct access to the spatial distribution of the corresponding elements or chemical states. This elemental or chemical specificity is demonstrated in **Figure 3b**, which shows an image that has been acquired using Au  $4f_{7/2}$  core-level photoelectrons. This can be interpreted as an intensity map of the elemental Au distribution, thus confirming the previous identification of monolayer gold islands.

Finally, a different type of contrast may be achieved in valence band photoelectron emission microscopy (VPEEM) when the electron energy analyzer is tuned onto distinct features about 4.5 eV below the Fermi level in the valence band structure of the sample (**Figure 3c**). Since all bright regions in this image also show up bright in Figure 3(b), this electronic state can be localized at the Au atoms. Hence, if the lateral element distribution is already known, e.g. as a result of preceding XPEEM investigations, then it is possible to identify contributions to the electronic structure from VPEEM micrographs.

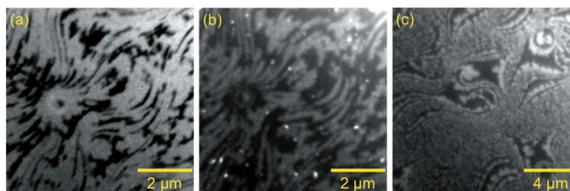
Future research will comprise in-situ studies of oxidation and catalysis on transition metals, growth of organic thin-film semiconductors, and characterization of magnetic materials.



**Figure 1.** Schematic of the LEEM/PEEM setup at beamline U5UA.



**Figure 2.** LEEM image sequence ( $E = 6.5$  eV) acquired during Au evaporation onto Ru(0001). (a) Clean Ru(0001) surface. Only step edges are visible. (b) and (c) Nucleation and 2D fractal growth of Au islands (dark) at the substrate step edges.



**Figure 3.** (a) PEEM image obtained with secondary electrons. (b) XPEEM image obtained with Au  $4f_{7/2}$  core-level photoelectrons. The bright spots are artifacts from the CCD camera. (c) XPEEM image obtained with valence band photoelectrons.