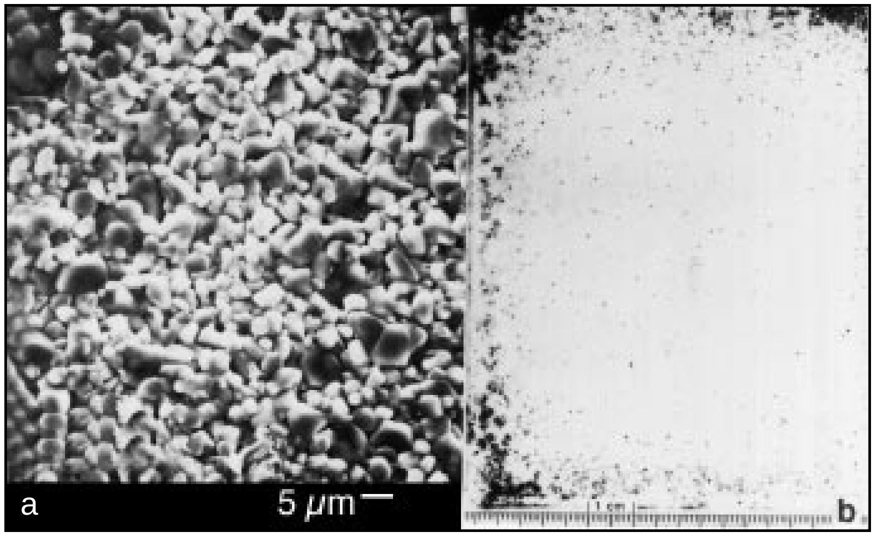
Donald M. Mattox, Technical Director • Society of Vacuum Coaters
440 Live Oak Loop • Albuquerque, NM 87122
Phone: 505/856-7188 • FAX: 505/856-6716

PVD Processes: Characterization of Surface Morphology

The morphology of the substrate surface, on the micron and submicron scale, is important in the nucleation and growth of atomistically deposited thin films. The surface morphology of the deposited film is important to electrical, optical, magnetic and frictional properties of the film. There are a number of techniques that can be used to characterize surface morphology and surface roughness, as well as look at individual features on a surface.



Slip-cast 96-percent alumina substrate material: (a) SEM picture showing surface morphology and particle size; and (b) Kr^{85} autoradiograph showing variation of absorption that can occur over the surface.

Surface Profilometers

Surface profilometers are used to measure the morphology of a surface, as well as measure step heights and the aspect (depth-to-width) ratio of surface features. There are two categories of surface profilometers: Contacting types, which use a stylus that moves over the surface in contact with the surface; and non-contacting types that use mechanical probes. Some of the profilometer equipment can be used in several modes. One instrument, for example, might be used in a contacting or non-contacting atomic force microscope (AFM) mode; a scanning tunneling microscope (STM) mode; magnetic force (magnetic force measuring) microscopy; or as a lateral force (friction measuring) instrument. In more advanced profilometers that use a mechanical stylus or probe, the movement (position) of the probe is monitored using a reflected laser beam in an optical-lever configuration, by a piezoelectric transducer, or by displacement interferometry.

Stylus Profilometers

Stylus profilometers use a lightly loaded stylus (as low as 0.05 mg) to move over the surface. The vertical motion of the stylus is measured. The best stylus profilometers can give a horizontal resolution of about 100 Å and a vertical resolution as fine as 0.5 Å, though 10–20 Å is more common. In the scanning mode, the profilometer can give a 3D image of the surface from several hundreds of microns square to several millimeters square. The ability of the stylus profilometer to measure the depth of a surface depends on the shape of the stylus tip and tip shank. Stylus profilometers have the advantage of offering long-scan profiling, the ability to accommodate large-sized surfaces, and pattern recognition. The pattern recognition capability allows the automatic scanning mode to look for certain characteristics, then move automatically to those sites, allowing a "hands-off" operational mode.

Scanning Tunneling Microscope

The scanning tunneling microscope is based on the principle that electrons can tunnel through the potential barrier, from a fine tip to an electrically conductive surface, if the probe tip is close enough (several angstroms) to the surface. The system is typically operated in a constant-tunneling-current mode, as a piezoelectric scanning stage moves the sample under the tip. The vertical movement of the probe is monitored to within 0.1 Å. Under favorable conditions, surface morphology can be determined with atomic resolution. The observations are often sensitive to surface contamination. At present, the STM can only be used on electrically conductive surfaces, but techniques are being developed using rf potentials that will allow its use on insulating surfaces.

Atomic Force Microscope

The atomic force microscope, sometimes called the scanning force microscope, is based on the forces experienced by a probe tip as it approaches a surface to within a few angstroms. The typical probe tip has a 500 Å radius, and is mounted on a cantilever that has a spring constant less than that of atom-atom bonding. This cantilever spring is deflected by the attractive van der Waals (and other) forces, and repulsed as it comes into contact with the surface ("loading"). The deflection of the spring is measured to within 0.1 Å. By holding the deflection constant and monitoring its position, the surface morphology can be plotted. Because there is no current flow, the AFM can be used on electrically conductive and nonconductive surfaces, and in air, vacuum or fluid environment. The AFM can be operated in three modes: Contact, non-contact, and "tapping." The contact mode takes advantage of van der Waals attractive forces as surfaces approach each other, and provides the highest resolution. In the non-contacting mode, a vibrating probe scans the surface at a constant distance, and the amplitude of the vibration is changed by the surface morphology. In the tapping mode, the vibrating probe touches the surface at the end of each vibration, exerting less pressure on the surface than in the contacting mode.

Scanning White Light Interference Microscope

The scanning white light interference microscope generates a pattern of constructive (light) and destructive (dark) interference fringes, resulting from the optical path difference from a reference surface and the sample surface. In an advanced scanning system, a precision translation stage and a CCD camera generate a three-dimensional interferogram of the surface, which is stored in a computer memory. The 3D interferogram is then transformed into a 3D image by frequency domain analysis. One commercial scanning interferometer can scan a surface at 1.0 µm/s to 4.0 µm/s, with a lateral resolution of 0.5 µm to 4.87 µm, and a field-of-view of 6.4 mm to 53 µm, depending on the magnification. It can measure the height of surface features up to 100 microns with a 1 Å resolution and 1.5-percent accuracy, independent of magnification. Typical imaging time for a 40 µm scan is less than 30 sec.

Scanning Near-field Optical Microscope

Surfaces can be viewed optically to 1500 times, but the resolution of standard optical microscopes is diffraction-limited to a lateral resolution of about 5000 Å, with a poor depth-of-field at the high magnifications. The strict optical analog of electron tunneling in the STM is the tunneling of photons in the scanning near-field optical microscope (SNOM), which uses an optical probe very near the surface. As the probe is moved farther away from the surface, the lateral resolution decreases. The vertical resolution, however, is preserved, and it is in this regime that the photon tunneling microscope (PTM) operates. The sample surface must be a dielectric for the PTM to function. The vertical resolution of the PTM is about the same as the scanning electron microscope (SEM); however, the lateral resolution is less. The PTM has the advantage that it can be used at atmospheric pressure.

Scatterometry

Scatterometry measures the angle-resolved scattering of a small spot (about 30 µm) of laser-light from a surface. The distribution of the scattered energy is determined by the surface morphology. The scattering is sensitive to dimensions much less than the wavelength of the illuminating light, so it can be used to characterize submicron-sized surface features as small as 1/20 of the wavelength of the incident light. From the spatial distribution, the root mean square (rms) roughness of the surface can be calculated.

Scanning Electron Microscope

A surface can be viewed in an optical-like form using the scanning electron microscope. Instead of light, the SEM uses secondary electrons emitted from the surface to form the image. The secondary electrons are formed by a finely-focused beam of several keV electrons being scanned over the surface. The angle of electron emission depends on the surface morphology, so the spatially-analyzed secondary electrons allow an image of the surface to be collected and visually presented. The magnification of the SEM varies from several tens-of-diameters to 250,000 times, with high lateral and vertical resolution. The SEM can also be used to look at a fracture or polished cross section normal to the surface of interest. This is often the only way to look at small diameter and deep surface features, such as cylindrical "vias" that may be 0.5 microns across and 2 microns deep (*i.e.*, a depth-to-width ration of 4:1).

Gas and fluid absorption on a surface is proportional to the surface morphology. Adsorption of a radioactive gas, such as Kr^{85}, which is a low-energy beta emitter, allows the autoradiography of the surface. This type of analysis allows the relative characterization of the whole surface. By using a Geiger chamber, the radioactivity of the whole surface can be measured and compared to a standard. The figure shows an SEM picture and a Kr^{85} autoradiograph of a slip-cast 96-percent alumina ceramic, which is commonly used as a substrate for microelectronic fabrication. The areas of high Kr^{85} adsorption are dark. The autoradiograph is of the whole 3.75 by 4.5 in. surface, while the SEM view covers a region about 0.0006 by 0.0006 in. Variations of morphology (absorption) over the surface are obvious from the autoradiograph. Instead of radioactive gases or fluids, fluorescent dyes can be used to directly view the substrate surface for local variations in morphology. o

Free Details: Circle 126 on postpaid reader service card.