WHY BREWSTER ANGLE MICROSCOPY - BAM

Optical techniques are used in a large variety of research fields of pure and applied science for investigating surface properties. The biggest advantage of optical techniques in surface characterization is that they are non-invasive (non-contact), which is important in circumstances were the surface structures are either very soft or must not be contaminated or scratched. Brewster Angle Microscopy is one optical technique that has been widely used for the past 10 years, especially in thin film research. The Brewster angle microscopy (BAM) technique was developed slightly more than 10 years ago mainly for characterizing one molecular thick monolayers at the air/water interface (e.g. a monolayer with typical thickness of ca 2 nm). Later it was also adapted for studies concerning interfaces such as glass, mica and SiO_2.

A large range of other surface characterization methods such as X-ray Photoelectron Spectroscopy (XPS or ESCA), Secondary Ion Mass Spectrometry (SIMS), Small Angle X-ray Scattering (SAXS), synchrotron X-ray diffraction, Ellipsometry, Imaging Ellipsometry, fluorescence microscopy, Transmission and Scanning Electron Microscopy (TEM and SEM), Scanning Tunneling Microscopy (STM), Scanning Probe Microscopy (SPM), Raman and IR spectrometry also exists. Some of these techniques are non-imaging techniques and gives information about the chemical composition of the surfaces, and often the main interest lies in the information of the morphology or phase behavior of thin films. In such cases one has to rely on the scanning microscopes (TEM, SEM, STM and SPM), SAXS, synchrotron X-ray diffraction, Imaging Ellipsometry, fluorescence microscopy techniques, Raman and IR sprectrometry and BAM. However, the main drawbacks of most of these techniques are that they are very expensive and they are only suitable for characterizing films on solid substrates. Only fluorescence microscopy techniques and BAM can be considered to be cheap surface characterization techniques with the advantage that they can be used for characterizing both solid and liquid interfaces. Furthermore, in comparison to fluorescence microscopy techniques the main advantage of the BAM technique, apart from being non-invasive, is that it allows the direct observation of ultra-thin films on air/water interfaces or on dielectric substrates without using any fluorescent probes in the studied materials.

WHAT IS A BREWSTER ANGLE MICROSCOPE – BAM

Sunlight and almost every other form of natural and artificial illumination produces light waves whose electric field vectors vibrate in all planes that are perpendicular with respect to the direction of propagation. When light is reflected from a flat surface of a dielectric (or insulating) medium it becomes partially polarized, which means that the electric vectors of the reflected light vibrates in a plane that is parallel to the surface of the material (see figure 1).

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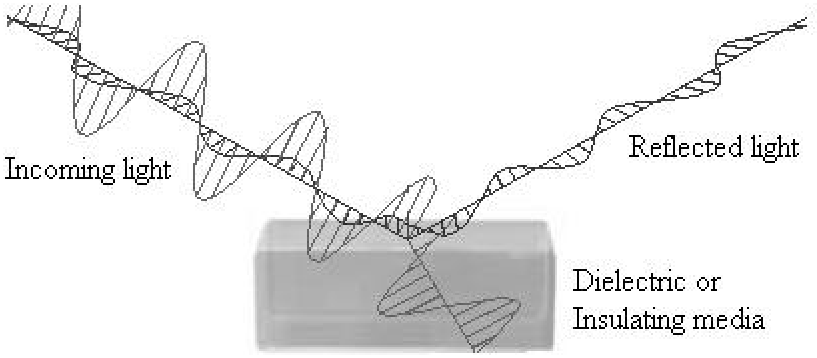


Figure 1. Schematic illustration how polarization of light is changed upon reflection from a dielectric or insulating media.

Common examples of naturally occurring sources of polarized light are light reflected from undisturbed water, glass, plastic and paper sheets, and highways. Bright reflections originating from these kinds of horizontal surfaces are partially polarized with the electric field vectors vibrating in a direction that is parallel to the ground. In these instances, light waves that have the electric field vectors parallel to the surface are reflected to a greater degree than those with different orientations. This light can be blocked by so called polarizing filters oriented in a vertical direction, which can be illustrated with a pair of polarized sunglasses (see figure 2).

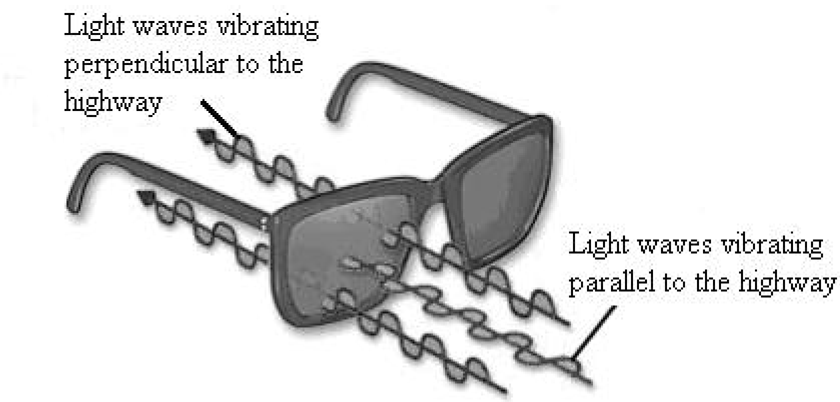


Figure 2. Illustration of the action of polarized sunglasses.

The lenses of the sunglasses have polarizing filters that are oriented vertically with respect to the frames. In figure 2, the light waves perpendicular to the highway have their electric field vectors oriented in the same direction as the polarizing lenses and, thus, are passed through. In contrast, the light waves parallel to the highway are perpendicularly oriented in respect to the filter orientation and is blocked by the lenses. Polarizing sunglasses are very useful when driving in the sun or at the beach where sunlight is reflected from the surface of the road or water, leading to glare that can be almost blinding. Polarizing filters are also quite useful in photography, where they can be attached to the front of a camera lens to reduce glare and increase overall image contrast in photographs or digital images. Polarizers utilized on cameras are generally designed with a mounting ring that allows them to be rotated in use to achieve the desired effect under various lighting conditions.

The human eye lacks the ability to distinguish between randomly oriented and polarized light, and plane-polarized light can only be detected through an intensity or color effect such as the example above with the sunglasses. When the electric field vectors of light are restricted to a single plane by filtration of the beam with specialized materials, then the light is referred to as **plane** or **linearly polarized** with respect to the direction of propagation, and all waves vibrating in a single plane are termed **plane parallel** or **plane-polarized** (see figure 3).

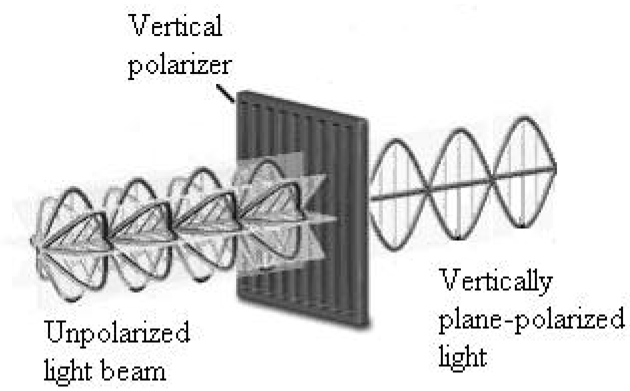


Figure 3. Schematic illustration how vertically plane-polarized (linearly polarized) light is obtained from an unpolarized light beam by using a filter (vertical polarizer).

The first clues to the existence of polarized light was found around 1669 when Erasmus Bartholin discovered that crystals of the mineral Iceland spar, e.g. calcite, produce a double image when objects are viewed through the crystals in transmitted light (see figure 4). Bartholin also observed that when calcite crystals are rotated about their axis, one of the images moves in a circle around the other, providing strong evidence that the crystals are somehow splitting the light into two different beams.

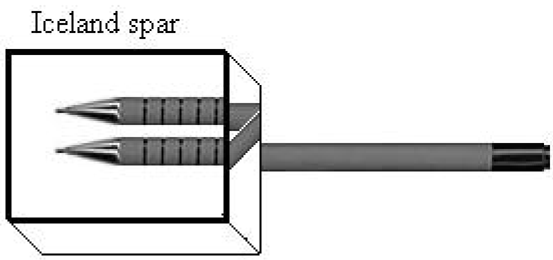


Figure 4. Illustration of the double image produced of a ball-point pen when viewing through a piece of transparent colorless Iceland spar (e.g. a form of calcite)

In the beginning of 19^{th} century Sir David Brewster, a Scottish physicist, discovered the polarization phenomenon of light reflected at specific angles. In his studies on polarized light, Brewster discovered that when light strikes a reflective surface at a certain angle, the light reflected from that surface is polarized into a single plane i.e. plane-polarized. This angle is commonly referred to as **Brewster's angle**, and can be easily calculated utilizing the following equation for a beam of light traveling through air:

$$n = \sin(\theta_i)/\sin(\theta_r) = \sin(\theta_i)/\sin(\theta_{90-i}) = \tan(\theta_i)$$

where **n** is the refractive index of the medium from which the light is reflected, θ_i is the angle of incidence, and θ_r is the angle of refraction.

The principle behind Brewster's angle is illustrated in figure 5, which shows a single ray of light reflecting from a flat surface of a transparent medium having a higher refractive index than air. The incident ray is drawn with only two electric vector vibration planes, but is intended to represent light having vibrations in all planes perpendicular to the direction of propagation. When the beam arrives on the surface at a critical angle (Brewster's angle; represented by the variable θ in Figure 5), the polarization degree of the reflected beam is 100 percent, with the orientation of the electric vectors lying perpendicular to the plane of incidence and parallel to the reflected surface. The incidence plane is defined by the incident, refracted, and reflected waves. The refracted ray is oriented at a 90-degree angle from the reflected ray and is only partially polarized.

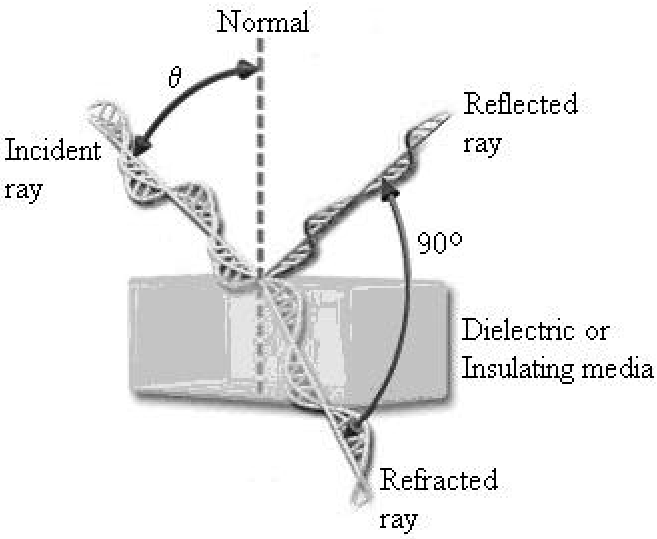


Figure 5. Illustration of the Brewster´s angle.

Light reflected from a highway surface at the Brewster angle often produces annoying and distracting glare, which can be demonstrated quite easily by viewing the distant part of a highway or the surface of a swimming pool on a hot, sunny day. Modern lasers commonly take advantage of Brewster's angle to produce linearly polarized light from reflections at the mirrored surfaces positioned near the ends of the laser cavity.

The principle behind the Brewster Angle Microscope (BAM) makes use of the zero reflectance of an air/water interface or dielectric substrate for vertically linearly polarized light at the Brewster Angle of incident. As the equations above shows the Brewster angle is determined by the refractive indexes of the substrates involved for example for air/water (refractive index of 1.333), air/glass (refractive index of 1.515), and air/diamond (refractive index of 2.417) interfaces the critical (Brewster) angles are 53, 57, and 67.5, respectively. When a condensed phase of a (mono)layer with different refractive index is spread or deposited on the interface of interest a measurable change in reflectivity will occur. The reflected light can then be used to form a high contrast image of the lateral morphology of the spread or deposited layer. For example, a monolayer spread on an air/water interface is extremely thin, approximately 0.5 % of the wavelength of visible light. The relative effect it has on the electric field reflected from a water surface is therefore very small and the monolayer is under normal conditions quite invisible. However, if the water surface is illuminated with pure vertically linearly polarized light at the Brewster angle before spreading the monolayer at the air/water interface, there is no reflection from the water surface. The background is then completely dark and after spreading of the monolayer and compressing it the tiny effect of the monolayer can be visualized. This is schematically shown in figure 6.

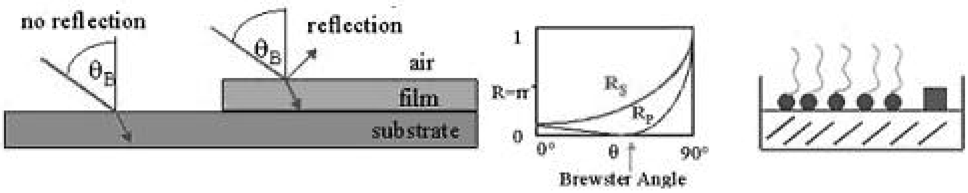


Figure 6. Schematic illustration of the change in reflectivity due to a thin film on a substrate or air/water interface.

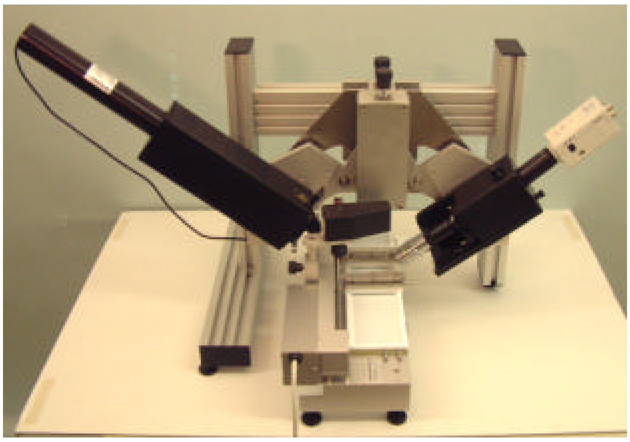
APPLICATIONS OF BREWSTER ANGLE MICROSCOPY

Thin organic films are the source of high expectations as being useful components in many practical and commercial applications such as sensors, detectors, displays and electronic circuit components. Various functionalities of supported thin films, spread monolayers, bilayer membranes, Langmuir-Blodgett (LB) or self-assembled films have been achieved by mixing organic or amphiphilic molecules with different active components. Thus, ordered multicomponent molecular assemblies with controlled concentrations of the functional units have become the subject of intensive research aiming at construction of ultrathin optical and electronic devices, understanding of the structural arrangement and intermolecular interactions in model biological systems, characterization of recognition processes at a molecular level etc. Functioning of the biomembranes, as well as the conducting and spectroscopic properties of thin films, depends on the spatial distribution of their constituents. Therefore, the characterization of the miscibility or phase separation of the thin film components appears to be an essential step in the design and preparation of functionalized structures. BAM is a technique, which easily helps to increase this kind of knowledge and a partial list of the application areas of the BAM is shown below.

- Phase behavior of monolayers i.e. domains and order phenomena
- Influence of subphase compositions on monolayer structures
- Phase separation in monolayers and thin films
- Real time monitoring of photochemical reactions
- Real time monitoring of polymerization reactions
- Detection of polymers and materials which cannot be detected with fluorescent probes
- Adsorption kinetics
- Gibbs adsorption layers
- Formation of multilayers
- Monitoring surface treatments
- Determining the quality and homogeneity of thin (organic) films and LB films
- LB-films on solid structures

KSV OPTREL BAM300

Typically, the resulting reflection is only about a millionth of the incident intensity. This puts high demands on the optical components used in the BAM setup i.e. laser, polarizers, lens and CCD camera. Therefore, only high quality components suitable for this purpose is used in the KSV Optrel BAM300 setup. Pictures of the KSV Optrel BAM300 installed on a KSV Minitrough is shown below.



The KSV Optrel BAM 300 is designed to the purpose i.e. for imaging thin films on water and/or rigid substrates such as glass slides and silicon wafers (see the list of applications above). In order to make it affordable to the research people and to avoid unnecessary costs, the following design criteria have been used when the BAM 300 was developed:

- No unnecessary motorized adjustments where manual adjustment (usually one-time adjustment) is sufficient.
- Better designed optics enables usage of less expensive laser without sacrificing the quality of the image:
- More sensitive camera needs less light intensity
- Bigger numeric aperture (due to the better optics) needs less light intensity
- Better quality objectives, e.g. with high quality antireflection coatings, minimize the need of light

  NOTE! The higher power lasers (20mW or even 50mW green lasers are still available by request as an option). We are aware that increasing the light intensity/surface area increases the contrast of the images.

- The high quality laser provides higher intensity/surface ratio with less overall laser power and in this way avoids the potential danger of heating up the thin film or the substrate.
- Only the highest quality Glan-Thompson polarizers are used. High quality polarizers with polarizing ratio of 10^{-8} ensure maximum image quality.
- The user-friendly software with its advanced image processing tools allow additional information to be generated from the images.
- The user-friendly hardware and software tools make the set-up and alignment of the instrument easy and quick.

SPECIFICATIONS OF THE KSV OPTREL BAM300

Software	User friendly user interface under Windows 2000/XP, with built in controls for the KSV LB troughs.

Mechanics

Goniometer	Easy to adjust, adjustable range 45° - 75°, accuracy 0.01°. Motorized adjustment as option.
Analyzer/Polarizer	Miniature precision rotation stages, easy to adjust.
Vertical lift	High accuracy vertical adjustment of the BAM, easy adjustment. Motorized adjustment as option.
Mounting bridge	Flexible, customizable mounting bridge with leveling screws. Easy to install together with KSV LB troughs.

Imaging

Camera	Computer controlled, high grade, CCD camera with 768 x 72 pixels, variable electronic shutter timings and gain controls, CCIR as standard (EIA as option)

Image processing

- Continuous real time monitoring of moving objects
- Scanning feature (option) to build overall focused images
- Various dedicated image processing functions
  - Re-sizing
  - Profile
  - Filtering
  - Background compensation
  - And more …
- Image storage on hard disk, storing into files and database

Optics

Light Source

Standard HeNe laser, 10 mW @ 633 nm
Other lasers as option (20 mW or 50 mW green laser)

Objectives and Field of View

Magnific.	Working Dist.	Num. Apert.	Field of view (w × h, appr.)
20×	20 mm	0.42	200 × 150 microns
10×	33.5 mm	0.28	400 × 300 microns
5×	34 mm	0.14	800 × 600 microns

Others: please consult factory

Field of View

See above.

Spatial Resolution

2 microns.

Scanner

Due to the viewing angle the image is focused in the center of the field of view only. The sophisticated scanning software option scans the range of focus settings to store completely focused images.

Angle of incidence

45° - 75°

Polarizing Optics

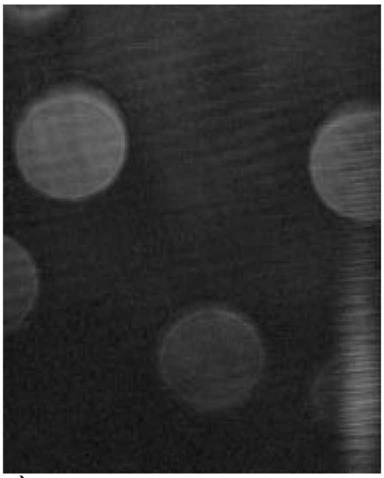
High quality Glan-Thompson polarizers

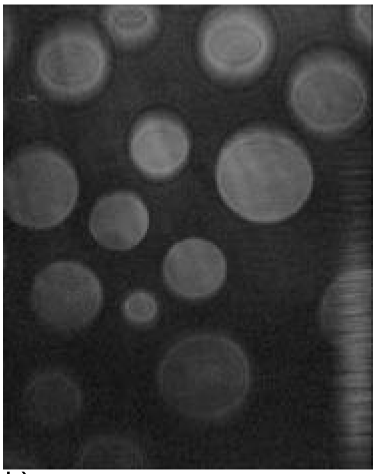
Options

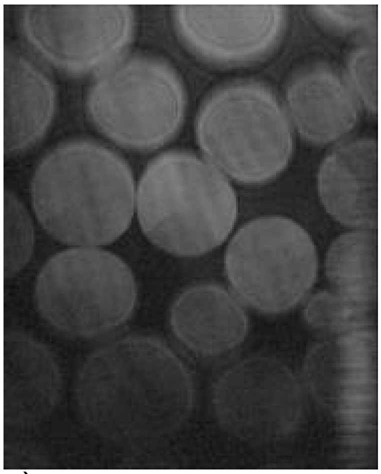
- Higher laser powers (e.g. Green laser 20mW or 50mW) available as option
- Image Scanning feature (see above)
- Motor controlled Goniometer adjustment
- Motor controlled height adjustment
- High performance PC Computer (please inquire for current specifications)
- LB Troughs, several sizes and versions
- Choice of three exchangeable objectives (see above)
- Vibration isolation table

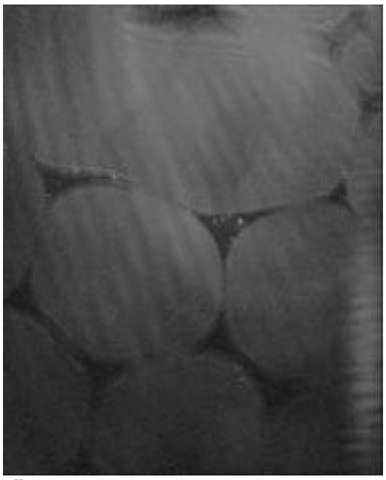
EXAMPLE MEASUREMENTS MADE WITH THE KSV OPTREL BAM300

Myristic acid monolayer on pure water at a temperature of 22 °C

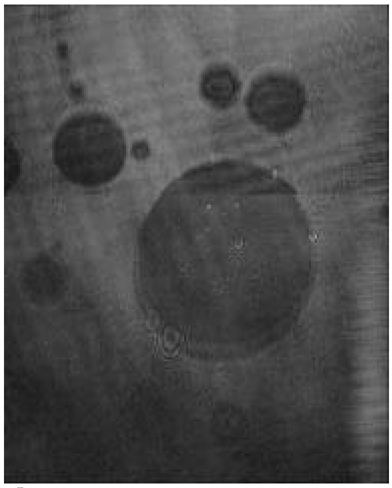

a)


b)


c)


d)

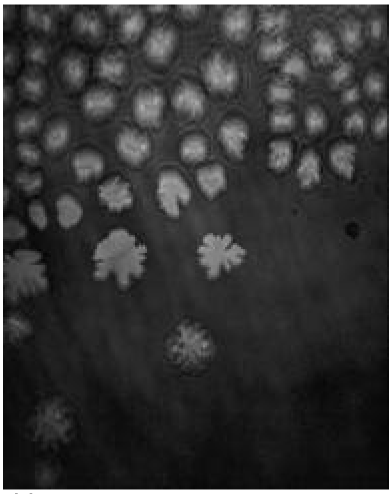

e)

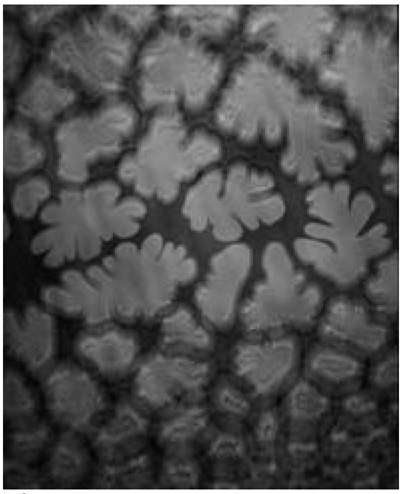

f)

The images above shows the morphological changes along the compression-decompression isotherm of Myristic acid, a fatty acid with 14 hydrocarbons in the chain. The sequence a)-e) of BAM micrographs shows the growth and compression of the formed bright circular domains in the transition region into a continuous condensed phase at high surface pressures. The last micrograph f) shows the formation of the fluid phase of low density upon decompression.

Dimyristoylphosphatidylethanolamine monolayer on pure water at a temperature 22 ^{o}C


a)


b)


c)


d)


e)


f)

The images above shows the morphological changes along the compression isotherm of a dimyristoylphosphatidylethanolamine monolayer, a phospholipid with 2 hydrocarbon chains with 14 hydrocarbons in each chain. a) BAM micrograph showing pure water as a reference. The sequence b)-e) of BAM micrographs shows the formation, growth and compression of the formed bright domains with characteristic shape in the phase transition region. The last micrograph f) shows the end of the phase transition and the formation of the solid phase; disappearance of the dark area.

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