Photonics-Enabled Technologies

Photonics in Nanotechnology Measurements: A Study of Atomic Force Microscopy

OP-TEC

Optics and Photonics Series

Photonics in Nanotechnology Measurements: A Study of Atomic Force Microscopy

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OPTICS AND PHOTONICS SERIES

**OP-TEC: The National Center of Optics
and Photonics Education**

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OP-TEC
National Center for Optics and Photonics Education

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PREFACE

This module addresses the role of optics and lasers in the field of optoelectronics. OP-TEC treats optoelectronics as a *photonics-enabled* technology. The current OP-TEC series on photonics-enabled technologies comprises modules in the areas of manufacturing, biomedicine, forensic science and homeland security, optoelectronics, and environmental monitoring, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of OP-TEC modules, visit http://www.op-tec.org.)

Manufacturing
- *Laser Welding and Surface Treatment*
- *Laser Material Removal: Drilling, Cutting, and Marking*
- *Lasers in Testing and Measurement: Alignment Profiling and Position Sensing*
- *Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing*

Environmental Monitoring
- *Basics of Spectroscopy*
- *Spectroscopy and Remote Sensing*
- *Spectroscopy and Pollution Monitoring*

Biomedicine
- *Lasers in Medicine and Surgery*
- *Therapeutic Applications of Lasers*
- *Diagnostic Applications of Lasers*

Forensic Science and Homeland Security
- *Lasers in Forensic Science and Homeland Security*
- *Infrared Systems for Homeland Security*
- *Imaging System Performance for Homeland Security Applications*

Optoelectronics
- *Photonics in Nanotechnology*
- *Photonics Principles in Photovoltaic Cell Technology*
- *Photonics in Nanotechnology Measurements: A Study of Atomic Force Microscopy*

The modules pertaining to each technology can be used collectively as a unit or separately as stand-alone items, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this module was prepared by John Pedrotti and edited by John Souders (CORD). Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

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Photonics in Nanotechnology Measurements: A Study of Atomic Force Microscopy

INTRODUCTION

Nanotechnology, as an industry, requires highly technical equipment and devices. Examples include scanning electron microscopes, transmission electron microscopes, and atomic force microscopes, all of which use photonics principles as the basis of their operation.

The focus of this module is the *atomic force microscope* (AFM). In its simplest configuration, an AFM directs the output of a diode laser onto a specialized probe (tip) that is scanned across the surface of a material. The probe is attached to a cantilever that allows the probe's position, relative to the surface of a material, to change. These changes can be recorded and provide a topographic map of the surface that helps identify the internal structure of the material.

Figure 1 *Photograph of Topometrix AFM*

To produce this map, the reflections of the laser diode at the probe are directed onto a photodiode where the photons of light are converted to an electrical signal and generate an image of the material's surface on a cathode-ray tube. This type of microscope can generate resolutions in fractions of a nanometer—more than 1000 times better than the optical diffraction limit—making it a very valuable device for working at the nanometer scale.

The AFM uses interferometry, optical gratings, and photodiodes. All of these components and devices use photonics principles in their operation. These photonics principles make the AFM a very useful nanotechnology tool with applications in biology, medicine, nanoparticle manipulation, AFM lithography, and materials analysis.

This module will discuss how photonics principles and devices enable the AFM to measure, analyze, and manipulate nanomaterials.

PREREQUISITES

The student should be familiar with the following before attempting to complete this module.

1. High school mathematics through intermediate algebra
2. CORD's Optics and Photonics Series Course 1, *Fundamentals of Light and Lasers*
3. CORD's Optics and Photonics Series Course 2, *Elements of Photonics*

   Module 2-1: *Operational Characteristics of Lasers*
   Module 2-2: *Specific Laser Types*
   Module 2-3: *Optical Detectors and Human Vision*
4. OP-TEC's Photonics-Enabled Technologies Series module *Photonics in Nanotechnology*

OBJECTIVES

Upon completion of this module, the student should be able to do the following:

- Explain the methods of operation of an AFM
- Explain how interferometry is used in atomic force microscopy
- Explain how a photodiode is used in atomic force microscopy
- Explain how an optical grating is used in atomic force microscopy
- Explain the modes of operation of an AFM
- List several applications in nanotechnology of an AFM
- Replace the probe and cantilever of an AFM
- Align the laser to the probe in an AFM
- Prepare a sample for inspection in an AFM
- Operate a Topometrix AFM and produce a surface image from a selected sample

SCENARIO

Meagan is a technician in a high-tech company that specializes in fabricating nano-scale structures such as nanotubes. She graduated with an AAS degree from a two-year degree program with a specialty in nanotechnology. Because lasers and optics are integral to the operation of many devices used in nanotechnology, Meagan elected to take courses in these topics as part of her degree program. At her company, Meagan works closely with engineers and scientists, often translating their ideas into pieces of hardware that allow manufacturing processes to be done more precisely and effectively. Her responsibilities include working with the tools and materials that test nanomanipulators and deposit nanoparticles into an epon matrix. She is responsible for ensuring that manufactured products meet quality control standards, and she performs inspections using diagnostic equipment such as atomic force microscopes, scanning electron microscopes, transmission electron microscopes, optical microscopes, and lasers. With her specialty in nanotechnology and elective courses in optics and lasers, Meagan has quickly become a highly respected employee and is enjoying the challenges of working as a technician in an exciting and rapidly expanding field.

SUBJECT MATTER

Photonics Devices in Atomic Force Microscopy

The atomic force microscope (AFM) uses a very basic photonics principle in its operation. As stated in the introduction to this module, the AFM incorporates a diode laser and photodiode to generate an image. The AFM also uses interferometry and optical gratings to increase the information gained about various materials, including those produced from nanotechnology methods. This section will discuss the photonics principles involved in *photodiodes, interferometry,* and *optical gratings.*

Operation of a photodiode

AFMs require light detectors to produce topographic surface maps of materials. One type of light detector that provides the level of resolution needed is a *photometer.* The sensing elements in a photometer are semiconductor devices called *photodiodes.* To understand the operation of these photodiodes, we will start with certain basics about semiconductor characteristics and structure and then expand this explanation to photodiode operations.

Atoms represent the basic building blocks of all materials and gases. At the center of every atom is a dense nucleus containing positively charged protons and neutral neutrons. Surrounding the nucleus is an electron cloud where individual electrons orbit the nucleus at well defined radii or shells. Depending on the element, there are a specific number of protons and an equal number of electrons. All known elements are cataloged in the *periodic table,* where the number of protons is the *atomic number* of the element.

A complete explanation of atomic theory is beyond the scope of this module. In simplified terms, as the complexity of an atom increases toward higher atomic numbers, so does the number of electrons orbiting the nucleus. Electrons orbit the nucleus like planets orbit the sun. The force that binds an electron to its nucleus is not gravitational, as between the sun and the planets, but electrostatic. This electrostatic force arises from the attraction of the opposite charges on a proton and electron. Quantum theory defines discrete electron orbit distances or shells. In addition, it limits the number of electrons that can exist in a single shell. The shells with the greatest radii are called the *outer shells.* The electrons existing in the outer shells of an atom also have the weakest electrostatic attraction to the nucleus since they are farthest from their proton counterparts.

The element silicon, atomic number 14, has a total of 14 electrons orbiting the nucleus. Quantum theory allows 2 electrons in the first shell, 8 electrons in the second shell, 18 electrons in the third shell, and so on. The general formula is $2n^2$ where n is the nth shell. Therefore, silicon has 2 electrons in the first shell, 8 electrons in the second shell, and the remaining 4 electrons in the third or outer shell. These 4 electrons are vital to our understanding of how photodiodes operate. These electrons, called *valence electrons*, are used to form bonds between atoms. This type of bonding is called a *covalent bond.* It occurs when pairs of electrons are shared between two atoms. Since silicon has 4 valence electrons, it can bond to 4 other silicon atoms. Through this sharing, silicon atoms create a condition in their third electron shell where all subshells are filled. This allows silicon atoms to form complex crystalline structures.

Pure silicon is an electrical insulator and does not facilitate the generation of an electrical current through it. As you will see later, the operation of a photodiode requires this capability. Electric current is the flow of electrons through a material. This requires extra electrons, whereas pure silicon in crystalline form uses all of its valence electrons to form the crystal structure or lattice. Therefore, before electricity will flow through it, pure silicon must be modified with impurities in a process called *doping.* This doping adds electrons to the material and can also add sites called *holes* that attract electrons. Both of these modifications increase the electrical conductivity of silicon.

As an example, atoms of phosphorus can be added to pure silicon to produce additional electrons. The theory is that a phosphor atom, a member of Group 5A in the periodic table, has 5 valence electrons in its outer shell. When the phosphorus is assembled into the silicon crystal lattice, 4 of these valence electrons form covalent bonds with adjacent silicon atoms. This leaves one electron that is free to leave the lattice. This doping of silicon with phosphorous forms a new type of material called a *semiconductor*, meaning that it is simultaneously an insulator and a conductor. Electrons not needed for bonding are free to travel to other atoms. Specifically, because the addition of phosphorus atoms provides additional electrons that are negatively charged, we call this an *n-type* semiconductor (where “n” indicates an average negative charge). These additional mobile electrons in the n-type material are called *donor electrons*. Other elements contained in Group 5A of the periodic table can also be used to dope silicon and create n-type semiconductor materials. Arsenic is one that is often used in photodiodes.

In the same manner, we can produce a *p-type* semiconductor (where “p” indicates an average positive charge). This semiconductor provides the holes for our photodiodes. To produce these holes, a material such as boron, a member of Group 3A in the periodic table, is added to pure silicon. Boron has 3 valence electrons; when incorporated into the silicon lattice structure, it results in a missing covalent bond that we call a *hole.* These holes are free to move throughout the lattice. This movement is equivalent to a flow of positive charge. Other elements in Group 3A have similar electronic outer structures and can be used to dope silicon to create p-type semiconductor materials. Gallium and indium are two such elements used in photodiodes.

A photodiode is formed when a layer of n-type semiconductor is placed on top of a layer of p-type semiconductor. The resulting layers create what is known as a *p-n junction*.

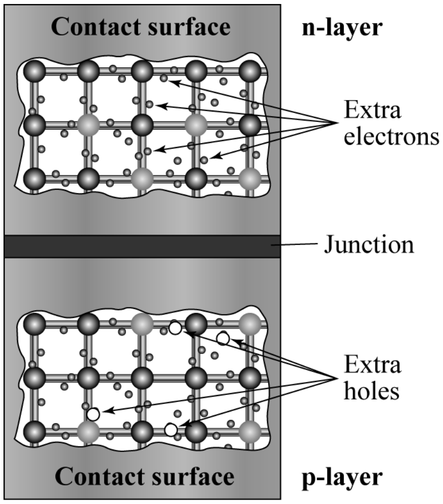


Figure 2 *Illustration of p-n junction*

A p-n junction creates an energy level difference between the two layers of semiconductors. The electrons in the n-type semiconductor diffuse into the p-type material, and the holes in the p-type material diffuse into the n-type material. In effect, when the mobile donor electrons diffuse across the junction from the n-side to the p-side, immobile positively charged ion cores are left on the n-side. Eventually enough electrons and holes cross the junction to generate an electrostatic force that opposes any further diffusion. The net result of this charge movement is the establishment of an electric field and associated potential difference across the p-n interface as shown in Figure 3.

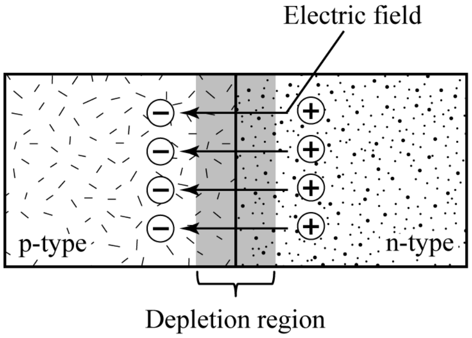


Figure 3 *Electric field and depletion region in the p-n junction of a semiconductor*

Another effect of this diffusion process is the creation of a *depletion region* at the p–n junction interface. Because of the electric field at this interface, any mobile charge carriers in this field will be "swept" out, leaving this area almost completely devoid or "depleted" of these carriers.

Now that you understand the basics of a semiconductor diode, let's shift our attention to how this diode can be used to detect light. Light is made up of tiny, mass-less bundles of energy called *photons.* The amount of energy in a single photon is determined from its wavelength or color. This is expressed mathematically as,

$$E = \frac{hc}{\lambda} \qquad (1)$$

where: h is Planck's constant 6.626×10^{-34} joules·seconds
c is the speed of light 3.0×10^{8} meters/second
λ is the wavelength of the light in meters

Joules is the standard unit of energy used by the International System of Units (abbreviated SI).

Example 1

Given: The wavelength of light 1×10^{-6} meters

Find: The energy in 10 billion photons in joules

Solution

Using $E = \frac{hc}{\lambda}$, calculate the energy of a single photon.

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34}\,\mathrm{J \cdot s})(3.0 \times 10^{8}\,\frac{\mathrm{m}}{\mathrm{s}})}{1 \times 10^{-6}\,\text{meters}}$$

$$E = 1.99 \times 10^{-19}\,\mathrm{J}$$

$$E = (1.99 \times 10^{-19}\,\mathrm{J})(10 \times 10^{9}) = 1.99 \times 10^{-9}\,\mathrm{J}$$

When photons are absorbed by atoms in the depletion region of a photodiode, the energy excites an electron. If the energy of the photon is equal to or greater than the energy gap between the valence band and conduction band of the depletion region material, the electron will jump into the conduction band and become a mobile charge carrier. The effect of this interaction is to produce an electron-hole pair. Since an electric field exists in the depletion region, the electron will be quickly swept toward the n-type material and the hole will move toward the p-type material. This movement of charge constitutes a current that can be detected. The magnitude of this flow is related to the intensity of the light incident on the photodiode.

So what happens to photons that strike the photodiode outside its depletion region? These photons still interact with the atoms in the n-type and p-type materials producing electron-hole pairs. Since these pairs are not produced in the depletion region, there is no appreciable electric field to accelerate them and produce a current. Instead, they diffuse through the material and only marginally contribute to the detectable current. It becomes clear from this discussion that the "sweet spot" on a photodiode is the depletion region. The wider this region is the greater will be the effectiveness of the photodiode in detecting light.

Two techniques are used for increasing the width of the depletion area. The first is to reverse-bias the photodiode. Figure 4 depicts this circuit configuration.

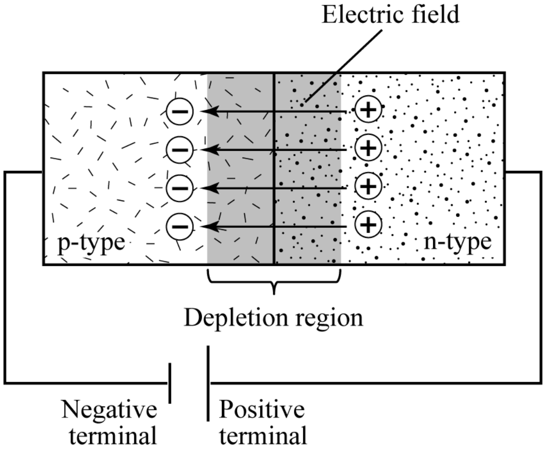


Figure 4 *Reversed-bias p-n photodiode*

With the positive terminal attached to the n-type material, electrons will be pulled away from the p-n junction. Similarly, the negative terminal will pull holes in the p-type material away from this junction. The net effect is to expand the depletion region and thus increase the effectiveness of the photodiode to detect light. Additionally, this wider depletion area leads to a lower capacitance and, thus, to a higher detection bandwidth.

The second technique uses reverse-biasing but adds an intrinsic layer (undoped material) between the n-type and p-type materials. Figure 5 demonstrates this new configuration.

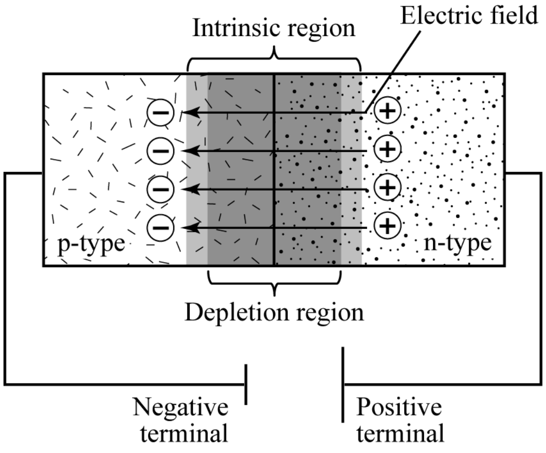


Figure 5 *Reversed-bias PIN photodiode*

This type of photodiode is called a *PIN.* In a PIN, the depletion region resides mainly in the *intrinsic region,* which is larger than the depletion region in a standard reversed-bias p-n diode.

The most common PIN diodes are based on silicon, which is responsive to light throughout the visible spectrum. For longer wavelengths, up to 1.7 microns, InGaAs PINs are used.

The light detector in an AFM consists of an array of photodiodes. As shown in Figure 6, the array consists of modules containing several photodiodes that form an electrical circuit. The purpose of using an array is to increase the surface area of the detector, thus increasing its effectiveness. Figure 6 depicts the structure of an array where a cell represents a single photodiode.

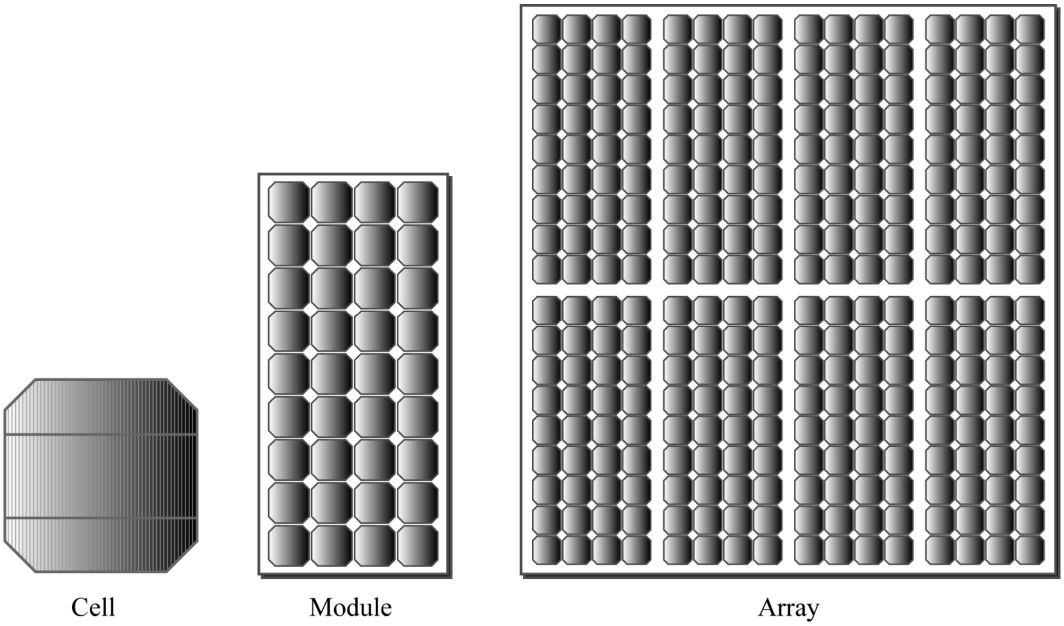


Figure 6 *Photodiode combinations*

The array is often divided into quadrants that allow the imagining system connected to it to discern the movement of the AFM probe. Figure 7 illustrates an array that is divided into four quadrants A, B, C, and D.

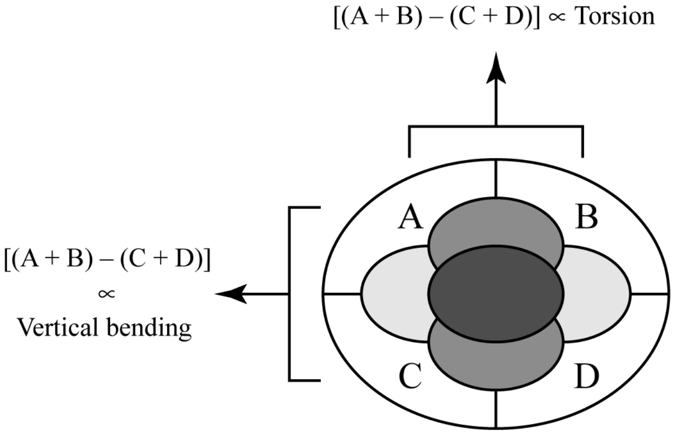


Figure 7 *Quadrant divisions of a photodiode array*

Vertical and lateral movements are calculated by taking differences in the signal levels measured in each quadrant. For instance, the difference between the signals coming from quadrants (A+B) minus that from (C+D) is proportional to the vertical deflection of the probe. In the horizontal direction, the difference between the signal coming from quadrants (A+C) minus that in (B+D) is proportional to the torsional deflection of the probe.

Let’s now tie the operation of a photodiode to an AFM. The current signal produced in an array of photodiodes can be used in an AFM as input for its imaging system, like a computer-based monitor. This system detects the magnitudes of these signals and the quadrant position on the photodiode array where the incident light strikes it. This information is then translated by the imagining system into images that depict the surface features of the material being studied. As an example, when the probe of an AFM goes from a low spot on a material’s surface to a high spot, the intensity of light incident on the AFM’s photodiode array will change, causing a proportional change in the input signal to the imagining system. Additionally, as the probe moves, the quadrant position on the photodiode array where the light strikes it will change. The imagining system will detect these changes and, using its internal software, determine the amount of rise that occurred. This rise will then be depicted graphically on the display screen of the imaging system. When the probe completes a full scan of the surface, the image on the display will represent a topographical map of the material being examined. Later we will show in more detail how these surface variations are detected by the AFM.

Operation of an optical interferometer

In your previous studies, you encountered the idea that light exhibits the same behavior as a wave. One of these behaviors is that when two waves interact with each other at the same location, their amplitudes combine, giving rise to an interference pattern. Optical interferometers use this behavior to make the nanometer scale measurements needed for atomic force microscopy.

An optical interferometer splits an initially coherent beam of light into two or more beams. These separate beams travel different optical paths and are then brought back together to form an interference pattern. These interference patterns can be used to determine the path length difference of the two beams. Because light has wavelengths in the nanometer range, interferometers can measure path length differences to this same dimension. This ability to measure very small differences is required in determining the atomic-level topography of material surfaces and is why interferometers are integral components of some types of AFMs.

There are several different types of interferometers, but for the purpose of explaining the operation of an AFM, we will concentrate on the Michelson interferometer shown in Figure 8. Our explanation will just present the principles of this interferometer that apply to its use in AFMs. A more detailed explanation can be found in most basic optics or physics textbooks.

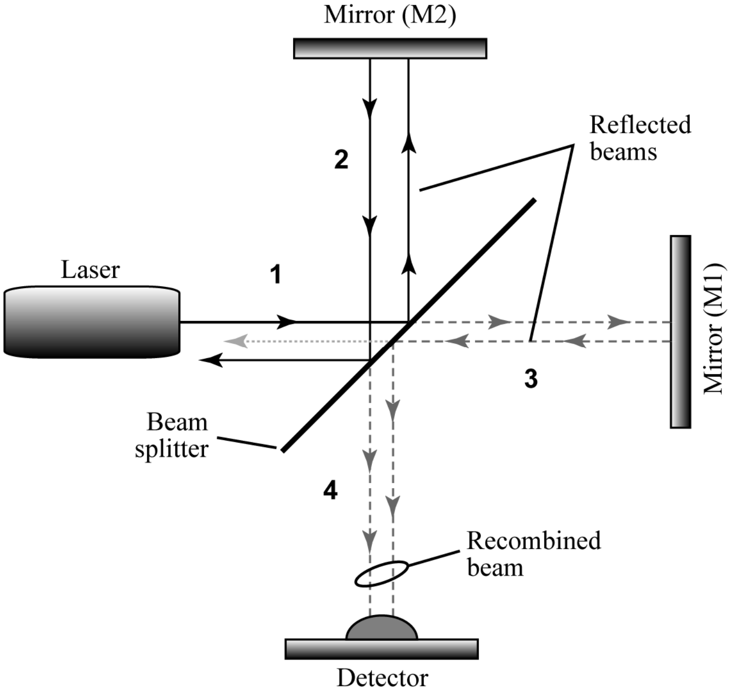


Figure 8 *Michelson interferometer*

Michelson interferometers use the interference effects of light waves to measure small distances. Figure 8 shows the essential optical elements involved. Light from a laser (wavelength λ) falls on a beam splitter coated as a partial reflector on its rear surface. The beam splitter divides the light into two beams. One is reflected toward mirror M2 while the other is transmitted toward mirror M1. Each beam is reflected by its mirror, returned to the beam splitter, recombined, and propagated toward the detector. Since the beam traveling toward the detector is the recombined beam, which includes the two overlapping beams, you can observe interference.

In a Michelson interferometer, one of the mirrors, M1, is mounted on a carriage. It can be moved back and forth with high precision. Suppose M1 is positioned so the two arms have equal lengths and both light beams travel equal path lengths. The light beams will arrive at the detector "in phase." Thus, these two beams constructively interfere at the detector and produce a bright spot with intensity I_{max}.

If, by contrast, mirror M1 has been moved toward or away from the beam splitter by an amount λ/4, the optical path will have changed by λ/2. (The beam transverses this new separation distance twice.) When the beams arrive back at the detector, they are λ/2 or 180° out of phase and destructively interfere, producing a dark spot with intensity I_{min}.

Obviously, the intensity of the light from the bright spot (I_{max}) is greater in magnitude than the intensity given off by the dark spot (I_{min}). Each of these intensities will generate currents at the photodiode array that are proportional to their magnitudes. The monitoring software connected to the photodiode will detect this change in current and associate it with a movement of mirror M1 equal to λ/4. If the light source for the interferometer is a HeNe laser, this change in position would be equal to 632.8 nm/4 or 158.2 nm. Though this is a small distance, AFMs must be able to measure distances or surface changes in the 1-to-10-nm range. For this to happen, mirror movements of less than $\lambda/4$ must be detectable.

To measure a distance less than $\lambda/4$ requires the detector array of the interferometer to be able to measure light intensities that are between $I_{\max}$ and $I_{\min.}$ Light intensities that are between these values occur when the recombined waves in path 4 are neither destructive nor constructive, but something in between. This situation is best described using the term *phase angle,* φ. As its name implies, this angle describes the phase relationship between the two waves. If $\varphi = 0$, the waves are in phase and result in constructive interference. If $\varphi = \pi$, the waves are out of phase and destructively interfere.

The phase angle is related to the distance d that M1 is moved by the following equation:

$$d = \frac{\varphi}{4\pi}\lambda \tag{1}$$

To check this equation, let $\varphi = 0$. Substituting this value into Equation 1 results in d being equal to 0. Thus, if there is no difference in path length ($d = 0$) between the beam splitter and two mirrors, M1 and M2, the phase angle, φ, of the two beams at the detector is 0. This is exactly the condition described previously for constructive interference. Likewise, if we let $\varphi = \pi$, Equation 1 will result in d being equal to $\lambda/4$, which is the condition for destructive interference. This quick check shows us that Equation 1 gives the proper relationship between d and φ and also gives us a way to calculate d if we know φ.

But how do we find φ? This question is answered by looking at the intensity of the light that is measured at the AFM photodiode array. The recombined waves from path 4 that enter the photodiode array can have various phase angles depending on their path length differences through the interferometer. The intensity of this recombined wave measured at the detector array is given by the following equation:

$$I = I_{\max} \cos^2 \frac{\varphi}{2} \tag{2}$$

Where $I_{\max}$ is the intensity measured at the detector array when the recombined waves in path 4 constructively interfere. This condition occurs when the phase angle is 0, 2π, 4π, and so on, and the $\cos^2(\varphi/2)$ term in Equation 2 equals its maximum value, 1. This is the intensity at the detector array when M1 has not been moved and paths 2 and 3 have equal path lengths. If φ is π, 3π, etc., the $\cos^2(\varphi/2)$ term in Equation 2 equals its minimum value, 0. This indicates the condition that destructive interference is occurring at the detector array and occurs when M1 is moved a distance $\lambda/4$. For angles of φ between 0 and π, the value of $\cos^2(\varphi/2)$ will vary between 0 and 1. This is the condition that was mentioned earlier as "neither destructive nor constructive, but something in between."

Example 2

Given: $I_0 = 1$ watt/m^2

Find: I for $\varphi = 0, \frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}, \pi$

Solution

From Equation 2: $I = I_{\max} \cos^2 \frac{\varphi}{2}$

$\varphi = 0$ $\qquad \cos^2(\frac{0}{2}) = \cos^2(0) = 1$

$\varphi = \frac{\pi}{4}$ $\qquad \cos^2(\frac{\pi/4}{2}) = \cos^2(\frac{\pi}{8}) = 0.85$

$\varphi = \frac{\pi}{2}$ $\qquad \cos^2(\frac{\pi/2}{2}) = \cos^2(\frac{\pi}{4}) = 0.5$

$\varphi = \frac{3\pi}{4}$ $\qquad \cos^2(\frac{3\pi/4}{2}) = \cos^2(\frac{3\pi}{2}) = 0.146$

$\varphi = \pi$ $\qquad \cos^2(\frac{\pi}{2}) = \cos^2(\frac{\pi}{2}) = 0$

Use results above to calculate I.

$\varphi = 0$ $\qquad I = I_0(1) = 1$ watt/m^2

$\varphi = \frac{\pi}{4}$ $\qquad I = I_0(0.85) = 0.85$ watt/m^2

$\varphi = \frac{\pi}{2}$ $\qquad I = I_0(0.5) = 0.5$ watt/m^2

$\varphi = \frac{3\pi}{4}$ $\qquad I = I_0(0.146) = 0.146$ watt/m^2

$\varphi = \pi$ $\qquad I = I_0(0) = \varphi$ watt/m^2

Notice the maximum and minimum values at $\varphi = 0$ and $\varphi = \pi$. All other values of φ result in intensities less than the maximum but greater than the minimum.

With basic algebra we can solve Equation 2 for φ.

$$\varphi = 2\cos^{-1}(\sqrt{\frac{I}{I_0}}) \qquad (3)$$

We now have the result we want, and here is how it is used. Let's assume M1 starts at a position where constructive interference occurs at the detector array. This means the intensity of the light incident on the detector array is $I_{\max}$. Next M1 is moved a distance equivalent to $\lambda/100$. (For a HeNe laser this would equal a displacement of 632.8 nm/100 = 6.328 nm.) As a result of this movement, the waves arriving at the detector array will interfere and generate an intensity I that is less than $I_{\max}$. Both these intensities, $I_{\max}$ and I, will produce currents at the detector array proportional to their magnitudes. Consequently, the following proportion is valid:

$$\frac{I}{I_{\max}} = \frac{i}{i_{\max}} \tag{4}$$

where i_{max} is the current generated in the detector array by intensity $I_{\max}$ and i is the current generated by intensity I.

Since the ratio of the currents and the ratio of the intensities are equal, the currents can be substituted for the intensities in Equation 3. The detector monitoring system of the photodiode measures both currents and with its software calculates φ using Equation 3. Once φ is calculated, the software uses Equation 1 to determine the distance, *d,* M1 moved. If M1 continues to change position, the detector monitoring system will measure the changes in current from one position to another and use these current changes to calculate the φ's and *d*'s related to this movement using Equations 1 and 3. When all movements are completed, the software will have a record of the positions M1 occupied and, using a graphing package, can display these movements on a computer monitor.

In summary, devices such as the Michelson interferometer can be used to determine the change in position of an object relative to some initial position. Depending on the precision of the device, the measured change can be as small as a fraction of a wavelength of the device's light source. This gives the nanometer resolution that is needed to develop topographical maps of surface variations resulting from molecular or atomic structures within materials. Later in this module, we will show how these interferometer principles are used in an AFM to develop topographical maps.

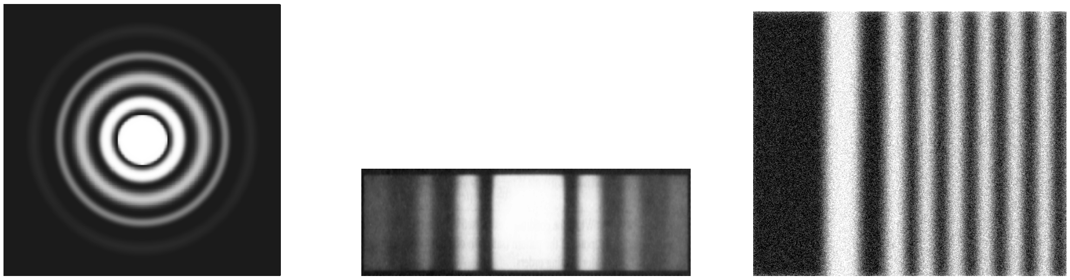
Operation of a grating

For certain measurements of surface features in nano-materials, a diffraction grating may be used in conjunction with an AFM. Before we look at characteristics of a diffraction grating, let us say a few words about light rays and light waves.

Light rays and shadows—We have all seen the sharp geometric shadows formed when rays of light pass around an obstacle such as a telephone pole or through an opening such as a window. Such shadows are formed by light when the dimensions of the obstacles and openings are much larger than the wavelength of light. In the study of light, we can always predict how shadows are formed by treating the light as made up of a group of light rays that pass by or through the obstacle.

Light waves and diffraction—On the other hand, when light passes through very small openings or around needle-shaped obstacles, the light spreads out, no longer forming sharp shadows. This spreading, called *diffraction*, occurs always when the dimensions of the obstacle or opening are of the order of the wavelength of light. So we are talking about a range of dimension such as 10 microns to 100 microns. Such spreading—or diffraction—is a characteristic of waves such as those that propagate light signals. It is helpful to think of the light waves as similar to water waves created by a cork bobbing up and down on the quiet surface of a pond. As the cork moves up and down, the waves move out in concentric circles around the cork.

Figure 9 shows the typical diffraction patterns formed by light passing through or around small obstacles. Figure 9a is a typical diffraction pattern for HeNe laser light passing through a tiny circular pinhole. Figure 9b is a typical diffraction pattern for monochromatic light passing through a narrow (vertical) slit. And Figure 9c is a typical diffraction pattern for monochromatic light passing the sharp edge of a razor blade.



a. b. c.

Figure 9 *Sketches of several common diffraction patterns*

As these figures demonstrate, diffraction effects become apparent when light passes around or through sharply defined boundaries. A diffraction grating makes use of this effect. Figure 10 shows monochromatic light incident on a long, narrow slit oriented perpendicular to the page. After passing through the slit (shown much larger here, for clarity), the light waves spread out, are focused by a lens, and form a pattern of fringes on a screen. The relative brightness of the fringes is shown by the varying intensity pattern on the screen, the central fringe being the brightest. To the right of the sketch is shown the alternate bright (B) and dark (D) fringes formed in the diffraction pattern. These fringes are formed as light waves from different regions of the slit opening travel different path lengths and thus, as in in the interferometer, interfere with each other. Where two waves interfere constructively, a bright spot appears on the screen. Dark spots represent destructive interference. The angle θ shown connects a point *P* on the screen to the center of the slit.

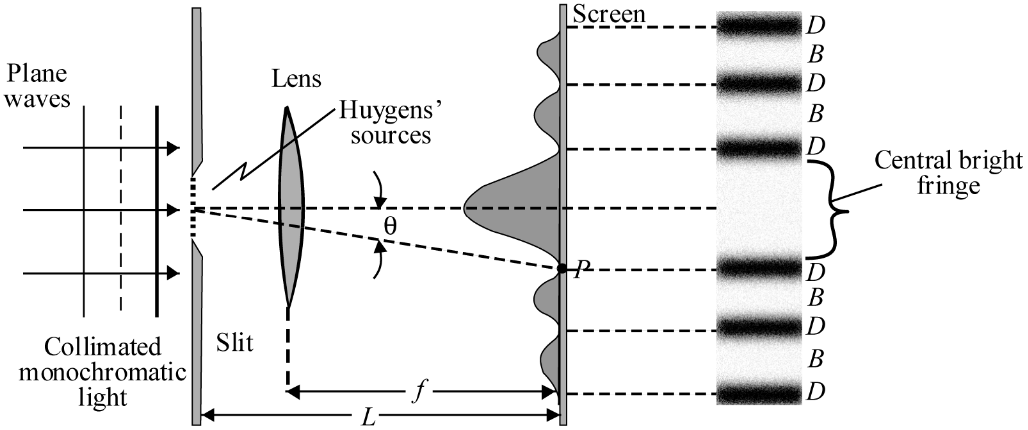


Figure 10 *Diffraction pattern from a single slit*

Since a diffraction grating contains thousands of slits, we need to expand our discussion from a single slit to many. First, let's take a small step and add one more slit. If now we pass monochromatic light through two very narrow slits as shown in Figure 11a, we find that the diffraction pattern changes. The internal bright fringe now contains narrow interference fringes caused by interfering waves from the two slits. In effect, we are now seeing both the diffraction effects and interference effects at work. A sketch of bright and dark regions on the screen show the bright and dark fringes caused by the diffraction of light from either of the two slits, and the interference of light from the two slits. Figure 11b, the intensity profile for the fringe pattern on the screen, shows the envelope due to the diffracted light (dashed lines), inside of which are the narrower fringes due to the interference from the two slits.

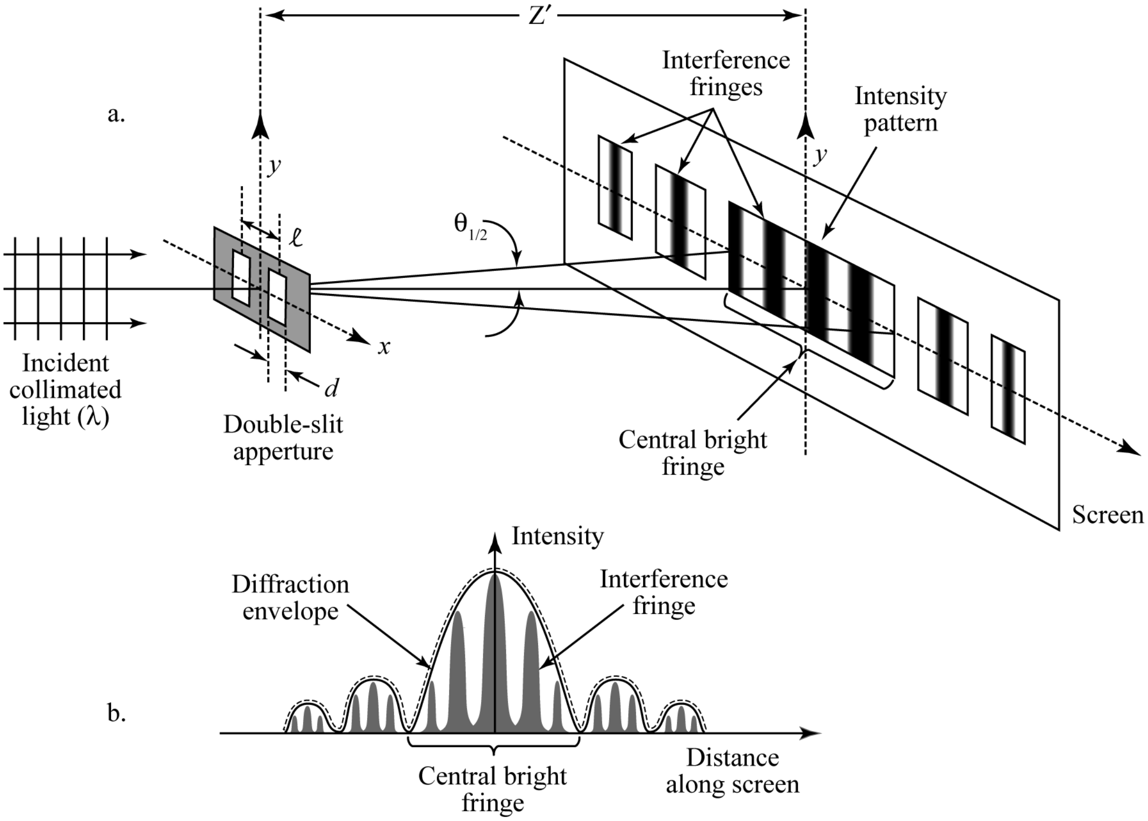


Figure 11 *Diffraction and Interference effects from a double slit*

If we continue to increase the number of slits, as indicated in Figure 12, the interference/diffraction effects cause the fringe pattern to sharpen and produce widely separated, narrow spots on the screen at different locations, called *orders*. This trend continues as slits are added. Note that on Figure 12 we have shown only 5 slits. In a true diffraction grating, there are thousands of narrow slits. The resulting intensity pattern contains a zeroth order ($m = 0$) on the symmetry axis and $m = \pm 1$, $m = \pm 2$, etc., orders above and below the central ($m = 0$) fringe.

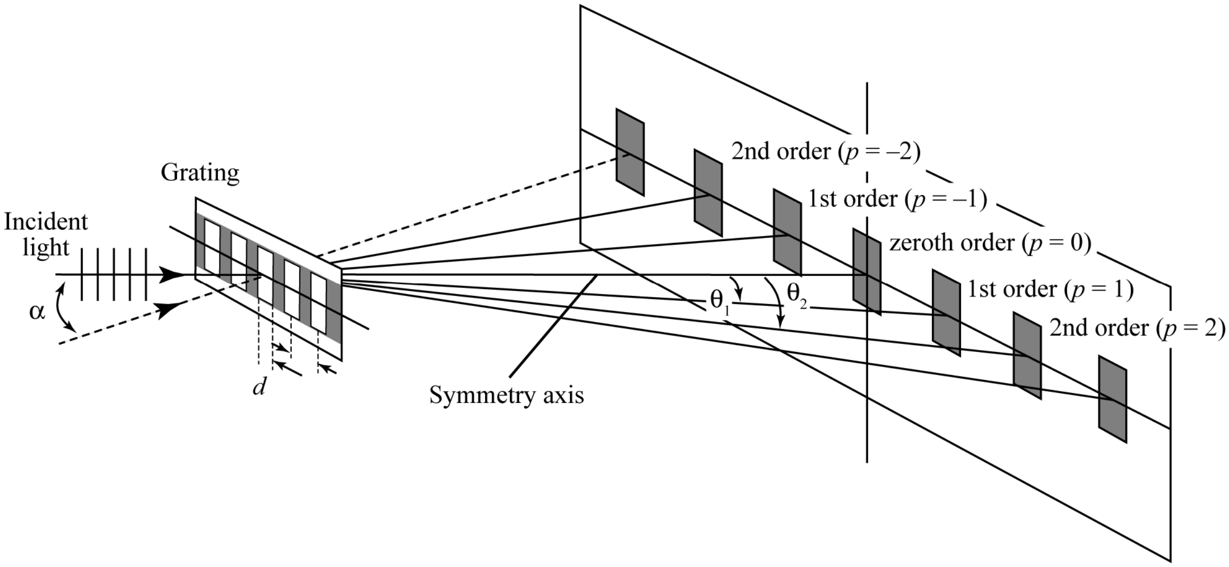


Figure 12 *Diffraction and interference effects from 5 slits*

Characteristics of a diffraction grating

A diffraction grating is described simply as a glass or polished metal surface on which are inscribed a large number of narrow slits or grooves—thousands per centimeter. The grating can be *a transmission grating*, in which incident light passes through the grooves and spreads out on the opposite side. Or it can be a *reflection grating,* in which the light reflects from the grooves and spreads out on the same side as the incident light. In some cases, a reflection grating is curved to form a concave grating surface and is therefore able to focus the diffracted light much the same as a concave mirror.

The essential geometry of a transmission diffraction grating, one that shows its operation, is sketched in Figure 13.

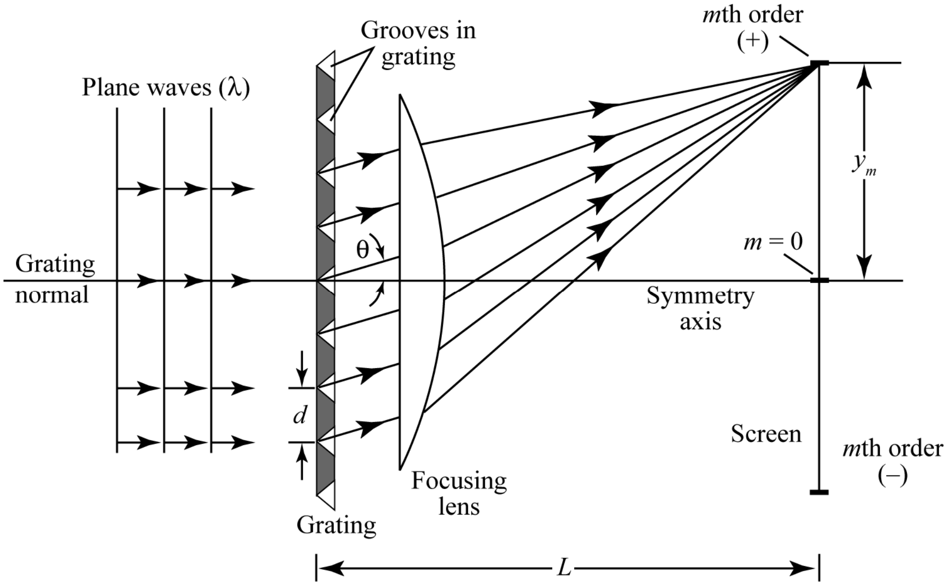


Figure 13 *Essential geometry of a transmission diffraction grating*

The grating equation that relates the geometry of the grating to the formation in the different orders is given by Equation 5.

$$m\lambda = d\sin\theta \qquad (5)$$

where: m is the order with values 0, = ±1, ±2, etc.
λ is the wavelength of the incident light
d is the spacing between adjacent grooves
θ is the angle between the symmetry axis and the line from the grating center to the mth order fringe

θ can also be determined using equation 6.

$$\tan\theta = Y_m/L \qquad (6)$$

where L is the distance between grating and screen and Y_m is the distance from the zeroth-order fringe to the mth-order fringe. The lens serves to focus the diffraction pattern (normally formed far from the grating) at a convenient distance from the grating equal to the focal length of the lens.

Example 3

Given: Light from a sodium lamp is collimated and sent through a transmission grating of 5000 lines/cm. The screen is located 1 meter from the grating and an unknown wavelength of light forms a fringe 30.8 cm up along the screen, in first order.

Find: (a) The angular deviation of θ for the fringe
(b) The wavelength of the light

Solution

(a) From geometry as seen in Figure 13 and Equation 6:

$\tan\theta = Y_m/L$

therefore: $\theta = \tan^{-1}\left(\dfrac{30.8\text{ cm}}{100\text{ cm}}\right) = 17.1°$

(b) Use Equation 5 to solve for λ.

$$\lambda = \frac{d\sin\theta}{m}, \text{ where } d = \frac{1}{5000} \text{ lines/cm} = 2\times10^{-4}\text{ cm or } 2\times10^{-6}\text{ m}$$

$$\lambda = \frac{(2\times10^{-6}\text{ m})(\sin 17.1°)}{1} = 5.88\times10^{-7}\text{ m}$$

$$= 588\times10^{-9}\text{ m or 588 nm (yellow)}$$

Example 4

Given: Light (650 nm) in second order ($m = 2$) for a grating of spacing $d = 2$ microns

Find: The angular spread between blue light (420 nm) and deep red

Solution

Use Equation 2: $m\lambda = d\sin\theta_m$

$$\sin(\theta_2)_{\text{red}} = \frac{m\lambda}{d} = \frac{(2)(650\times 10^{-9}\,\text{m})}{2\times 10^{-6}\,\text{m}} = 0.650$$

$$(\theta_2)_{\text{red}} = \sin^{-1}(0.650) = 40.5°$$

$$\sin(\theta_2)_{\text{blue}} = \frac{m\lambda}{d} = \frac{(2)(420\times 10^{-9}\,\text{m})}{2\times 10^{-6}\,\text{m}} = 0.420$$

$$(\theta_2)_{\text{blue}} = \sin^{-1}(0.420) = 24.8°$$

Thus the red light ($(\theta_2)_{\text{red}} = 40.5°$) and the blue light ($(\theta_2)_{\text{blue}} = 24.8°$) are spread out over an angular deviation of about 16° in the second order.

Like prisms, gratings are used to separate and spread light rays. This spread property has some important uses in AFMs.

Measurement Methods Used in Atomic Force Microscopy

The information presented in this module thus far has shown how photodiodes, interferometers, and gratings operate. The purpose of this section is to show how these photonics components function within an AFM.

Laser beam reflections and photodiodes

The first measurement method to be discussed involves the use of a photodiode and a laser. As was shown earlier, photodiodes convert light energy into an electrical signal. This signal can be measured by the AFM's detector monitoring system, which then reproduces the surface image of the material being examined on a computer monitor. Because of the coherent and monochromatic features of laser light, lasers become the prime choice as a light source for an AFM.

In general, laser light is directed onto the back surface of a cantilever such as that shown in Figure 14. The cantilever is able to move up and down much like a teeter-totter. Attached to the cantilever is a specialized probe or tip. This probe or tip is moved over the surface of the material being imaged, either in contact with the surface or just above the material's surface. This is shown in Figure 15. The back of the cantilever is highly reflective and the laser light reflects from the cantilever to the photodiode array. As the tip scans over the surface of the material being studied, it moves up and down with the contours of the surface. The change in vertical position of the tip changes the intensity and position of the light seen at the photodiode array. As explained in the section on photodiodes, the photodiode array is usually divided into quadrants (see Figure 7). The difference in signal strength produced in each quadrant provides information on the movement of the AFM probe and is used by the detector monitoring system to develop a topographical map of the material surface being studied. The feedback mechanism is used to prevent the tip from interacting too strongly with the surface. The PZT scanner, a piezoelectric tube, is used to maintain the sample distance from the cantilever. An alternative method to the PZT is to place the sample onto a tripod of piezoelectric crystals. The feedback mechanism and the PZT prevent damage to the sample and the tip.

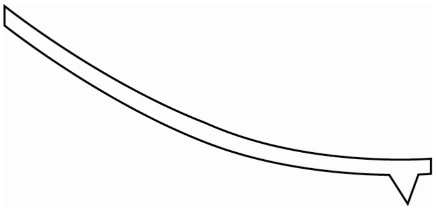


Figure 14 *Cantilever and tip*

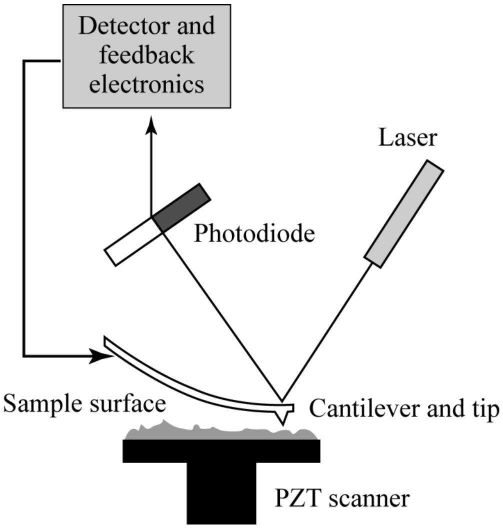


Figure 15 *Typical AFM using photodiode array*

The interferometer and the AFM

The interferometer can be used with an AFM to scan the surface of a material and recreate an image of that surface on a computer monitor. The set-up for this is a shown in Figure 16. The only change in the set-up of the Michelson interferometer is the replacement of the adjustable mirror with an adjustable platform. The material being studied is attached to the platform and the platform is moved so that beam 3 in the diagram scans the full surface. The phase relationship, φ, between beam 2 and beam 3 will change as beam 3 reflects off high and low spots on the material's surface. As seen in Equation 2, this change in φ will cause variations in the intensity of the light incident on the detector. These intensity changes will cause changes in the electrical signal generated by the detector that will be used by the detector monitoring system to recreate an image of the material's surface features. It should be noted here that the surface variations are very small in distance. This small change in distance creates a relatively small phase change, φ. Because of the relatively small change in φ, the phase shift will always stay between a maximum and a minimum condition. Thus, φ will take on values between 0 and π.

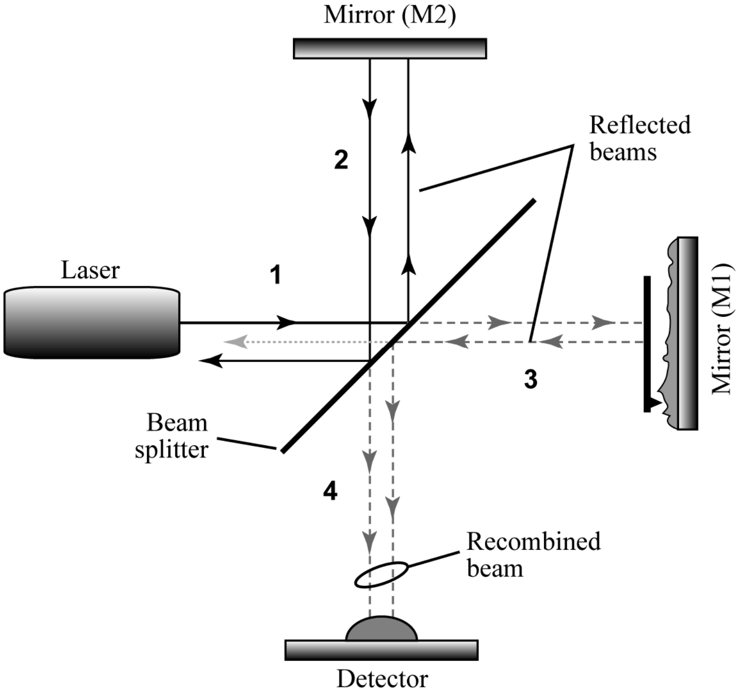


Figure 16 *Michelson interferometer used in an AFM*

It should be noted here that using an interferometer as the detecting mechanism in an AFM is a more accurate method but is not the method most commonly used to reproduce surface images. The use of a laser beam and photodiode is the more common method. This is because the interferometer is more complicated and tedious to align. The accuracy of the interferometer is not always needed. Thus, the photodiode and laser is often a more practical configuration.

Example 5

Given: An AFM using an interferometer configuration uses a diode laser with a wavelength of 633 nm.

Find: The change in path length if the phase shift φ is π/100.

Solution

Use Equation 1:

$$d = \frac{\varphi}{2\pi}\lambda$$

$$d = \frac{\pi/100}{2\pi}(633\text{ nm})$$

$$d = \frac{2}{100}(633\text{ nm}) = 12.66\text{ nm}$$

Thus the surface of the material either rises or recedes 12.66 nm based on this measured phase shift. The detector monitoring software would be able to interpret whether it was a rise or a depression.

Diffraction application in AFMs

There exists another AFM sensing arm that uses the principles of diffraction and interference to determine the topography of test samples. This arm is composed of interlocking fingers (sometimes referred to as interdigitated fingers) that are located along a cantilevered arm. Figure 17 shows a conceptual drawing and picture of this arm. On this arm, one set of fingers is firmly attached to it while the other is free to move. This movement is used to trace the surface features of a sample. For example, if the fingers trace a low spot or depression on the test sample, the moveable set of fingers will displace downwards relative to the fixed set of fingers. Conversely, while tracing a high spot or rise, the moveable fingers will displace upwards relative to the fixed set. If the area of the sample being traced is flat, there is no relative displacement of the fingers. In effect, with no relative displacement, both sets of fingers are coplanar.

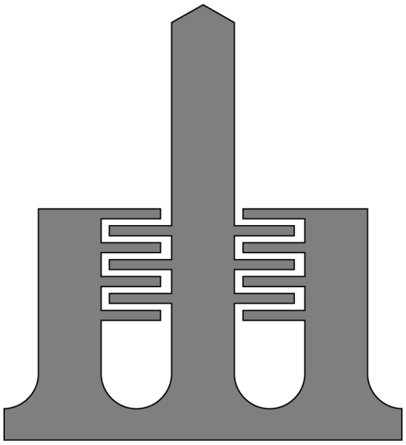


Figure 17 *Conceptual drawing of an interlocking-fingers sensing arm*

A laser and photodiode are used in conjunction with this finger arm to measure the fingers' relative displacement and determine the topography of a sample. To understand how these components work together to produce this surface map, let's first discuss the process for aligning them.

In the alignment process, light from a laser is directed onto the fingers, which are interlocked so that they are not displaced relative to one another. In other words, they are *coplanar.* From an optical perspective, these interlocking fingers act like a diffraction grating. However, unlike the transmission gratings described in a previous section, the fingers form a reflection grating. The reflected light from these coplanar fingers produces a diffraction pattern like those shown in Figures 12 and 13. When the zeroth-order fringe of this diffraction pattern is centered in the aperture of the photodiode and this aperture blocks all other fringes from illuminating the photodiode, the laser, arm, and photodiode of this AFM are aligned.

This alignment process provides us a key insight into how surface deviations are measured by the sensing arm. When the fingers are coplanar, as in the alignment process, the photodiode will have the full intensity, I_0, of the zeroth-order fringe incident on it and will generate a current i_0 proportional to this intensity. If, while scanning a sample, the photodiode generates a current i_0, then at the position on the sample where this occurs the fingers must be coplanar. Thus, whenever the photodiode generates a current of i_0, the position on the sample where this occurs is a flat spot.

The "flat" situation just described is illustrated in Figure 18. This figure simplifies the action of the interdigitated arm by depicting only two pairs of adjacent fingers—one fixed and one moveable. On an actual interdigitated arm there are several pairs of these fingers. However, all these pairs contribute in a like manner to the final intensity reading of the zeroth-order fringe. Thus, if you understand how these two pairs contribute to this intensity, you also understand how the full array contributes to it.

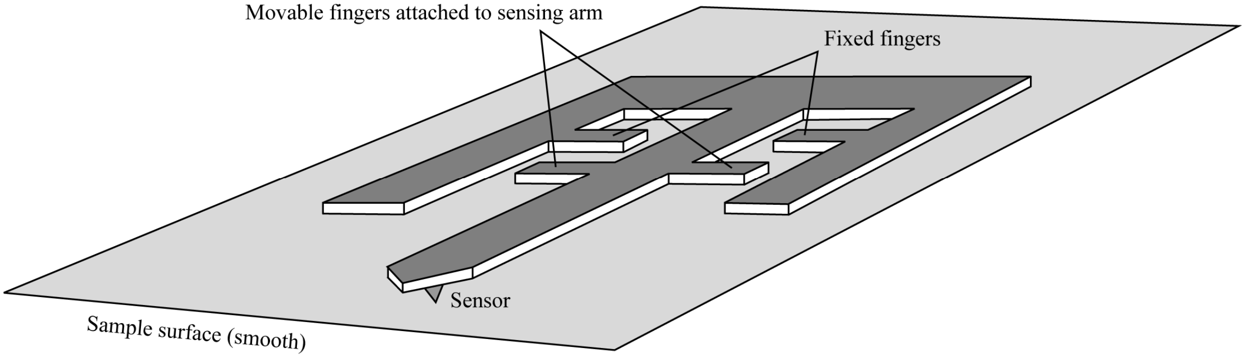


Figure 18 *A simplification of an interdigitated sensing arm tracing a flat spot on a sample surface. The fingers are coplanar.*

To see how this sensing arm traces surface features, look at Figure 19. In this figure the sensing arm is located at a surface depression. The moveable fingers have moved from a coplanar position with the fixed fingers to a position below them. In contrast, if the sensing arm was tracing a surface rise, the movable fingers would be above the fixed fingers. Each of these configurations affects the length of the path that light travels from the laser in the AFM to the photodiode aperture. This difference in path length allows us to measure the depth or rise of a surface feature.

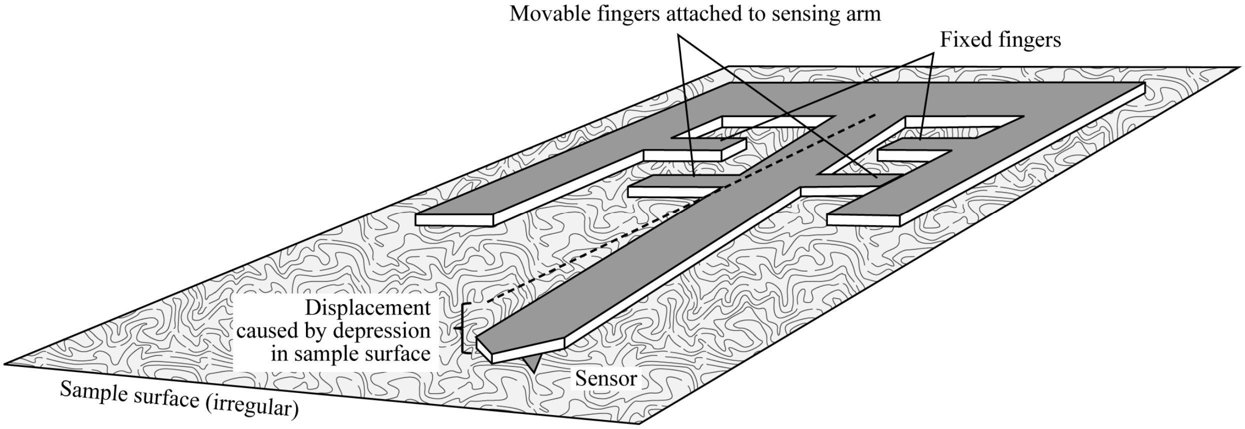


Figure 19 *A simplification of an interdigitated sensing arm tracing a depression along a sample surface. The movable fingers are no longer coplanar with the fixed fingers but are positioned below them.*

To understand how this path length difference is correlated to the amount of depth or rise on a surface, look at Figure 20. This figure shows front views of the sensing arm for both the "flat" case shown in Figure 18 and the "depression" case shown in Figure 19. In Figure 20a (in which the perspective shows the device tilted slightly toward the viewer), light from the laser is shown as two rays. These rays reflect off the fingers and are directed to the center of the aperture of the photodiode. In Figure 20a, these rays originate from the same laser and travel identical distances from the laser to the fingers and, after reflection, the same distance to the photodiode. They have the same path lengths. When they arrive at the photodiode they will constructively interfere. Rays reflecting off the other pairs of adjacent fingers on the arm will also constructively interfere at the photodiode with net effect of generating intensity I_0.

But what happens when the fingers trace a low or a high spot on the sample? In these cases, the adjacent finger pairs will not be coplanar. This is shown in Figure 20b, where the moveable fingers are displaced downward due to a depression on a sample surface. In this figure, the ray incident on the movable finger will travel a different path length to the photodiode than the ray incident on the fixed finger.

Because of this relative displacement between the adjacent fingers, the path length of the light reflecting from the movable finger is more than the path length of the light reflecting from the fixed finger. As shown in Figure 20b, this difference is $2d$. If $d = \lambda/4$, the path length difference is 2 ($\lambda/4$) or $\lambda/2$. This means the two rays from the adjacent fingers will arrive at the photodiode $\lambda/2$ or π out of phase. As you will recall, this is the condition for destructive interference. Since all other pairs of adjacent fingers will generate the same result, zero intensity is measured at the photodiode with a corresponding current, i_0, that is also very near zero. The current will not be exactly zero because of random noise generated in the photodiode.

We have now examined the two opposite conditions of full constructive and destructive interference. What happens if a rise or depression on a sample is less than $\lambda/4$? In other words, the two rays arrive at the photodiode neither destructively nor constructively interfering, but something in between. While discussing the Michelson interferometer, we asked the same question and then went on to present Equations 1 through 4 as answers. These equations also are applicable for the interdigitated sensing arm. As in the interferometer, the photodiode detection and monitoring system will continuously monitor the change in current generated at the photodiode as the sensing arm traces the sample under investigation. Using its software, the detection and monitoring system will use Equations 1 and 3 to calculate the relative displacement of the fingers at different sample positions. When these displacements are displayed on a monitor, they will represent the topography of the sample. Depending on the laser used and the precision of the detection and monitoring system, displacements less than a nanometer can be resolved using this arm.

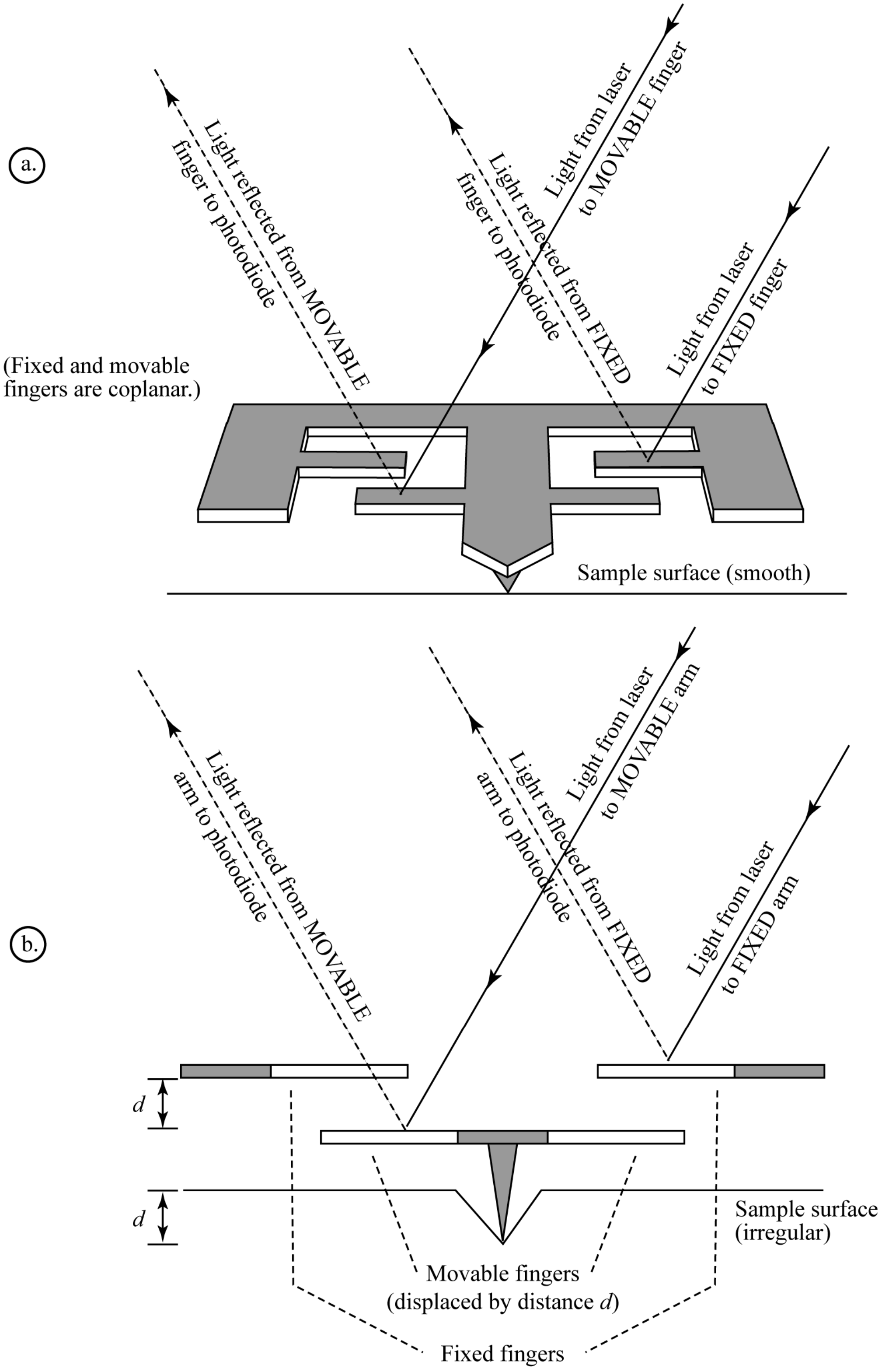


Figure 20 *(a) Front view (tilted slightly forward) of interdigitiated sensing arm at a flat spot on a sample surface. Path lengths of the light from the laser reflecting from both the fixed and moveable fingers back to the photodiode aperture are identical. (b) Front view of interdigitated sensing arm as a depression in a sample surface is traced. Light from the laser reflecting from the movable fingers back to the photodiode has a path length 2d greater than that of light reflecting from the fixed fingers.*

Example 6

Given: The detection and monitoring system of a photodiode in an AFM using an interdigitated sensing arm detects a change in current while scanning two adjacent positions along a sample's surface. The starting position of the sensing arm is at a flat portion of the surface and the second position is on a rise. The ratio of the two currents, $\frac{i}{i_0}$, is 0.02, where i is the current generated at the photodiode for the flat position and i_0 is the current at the top of the rise. The AFM uses a HeNe laser with a wavelength of 632.8 nm.

Find: The amount of rise in the surface between these two positions

Solution

The software in the detection monitoring system would first use the proportion in Equation 1 to discern the following:

$$\frac{I}{I_0} = \frac{i}{i_0} = 0.02$$

Next, the software would use Equation 3 to calculate the phase angle, φ.

$$\varphi = 2\cos^{-1}\left(\sqrt{\frac{I}{I_0}}\right) = 2\cos^{-1}\sqrt{0.02} = 2.85 \text{ radians}$$

Knowing φ, the software uses Equation 1 to find the amount of rise, *d,* between these adjacent positions.

$$d = \frac{\varphi}{4\pi}\lambda = \frac{2.85}{4\pi}(632.8 \text{ nm}) = 143.52 \text{ nm}$$

This position on the sample and its rise will be stored within the detection and monitoring system and used with other similar values to produce a complete image of the sample's topography.

Modes of Operation of an AFM

It was mentioned earlier in this module that the AFM tip is moved over the surface of a material either in contact with the surface or just above the surface. This is called the *mode of operation* of an AFM. There are three modes of operation. They are *contact, noncontact,* and *tapping mode*. Each mode has advantages and disadvantages. This section will discuss the basic operation of each mode and its specific advantages.

Contact mode of operation

In the *contact mode* the tip makes contact with the sample surface. A repulsive force is established between the AFM's probe tip and the sample's surface. This is done by pushing the cantilever against the sample surface using a piezoelectric positioning element. A *piezoelectric* device is a crystal material that is sensitive to a change in voltage. When the voltage across the crystal changes, the crystal expands or contracts. In the contact mode, the deflection of the cantilever is measured and compared to a set value in a DC feedback amplifier. If the values differ, a voltage is applied to the piezoelectric device, changing the vertical position of the sample to restore the set value of deflection. The voltage applied by the feedback amplifier to the piezoelectric device is a measure of the change in height of the sample.

The problems of most concern with this method are *tracking forces* applied to the sample by the AFM. Tracking forces are forces that interfere with the free movement of the tip and cantilever mechanism. They are generally caused by attractive forces such as meniscus and Van der Waal's that occur in ambient conditions. In ambient conditions, surfaces are covered with water vapor and nitrogen. The water vapor and nitrogen interfere with the probe's *free* movement, thus hindering accurate measurement of the repulsive forces. To correct this problem, the AFM can be operated in a vacuum or the sample and tip can be submerged in a liquid. These solutions bring technological problems as well. A vacuum environment, especially at ultra-high vacuum pressures, is costly to achieve and maintain. In a liquid emersion system, leaks and sample damage must be considered.

Another problem that can occur, especially when using semiconductors and insulators as samples in a liquid environment, is the trapping of electrostatic charges. These charges can contribute to substantial attractive forces between the sample and the probe. This results in data distortion and possible sample and tip damage. Another obvious problem is that semiconductor wafers cannot be practically submerged into liquid materials.

Noncontact mode of operation

The *noncontact* mode of operation is an attempt to avoid the problems of the *contact mode.* In this mode the tip hovers from 50 to 150 angstroms above the sample surface. This method uses the attractive Van der Waal's forces between the tip and the surface to form the topographical images. Because the attractive forces between the tip and surface are substantially weaker than in the contact mode, AC detection methods must be used to detect the small forces. The AC system measures the change in amplitude, phase, or frequency of the oscillating cantilever in response to the force gradients generated by the irregularities along the material's surface. For best resolution of these surface details, measurements of the force gradients from Van der Waal's forces must be made within 1 nm of the surface. Unfortunately, the fluid contaminant layer (water vapor) is substantially thicker than this, resulting in the tip becoming mired in this layer. Therefore, a true measurement of the material's surface cannot be measured with this method. This method is rarely used.

Tapping mode of operation

The *tapping mode* of operation offers many advantages over the *contact mode*. In the tapping mode the tip is oscillated at very near the resonant frequency of the cantilever. A piezoelectric crystal is used to oscillate the tip with amplitude greater than 20 nm. The tip oscillation is maintained by a constant feedback loop. The oscillating tip is moved toward the sample until it just touches the sample surface. When the tip encounters a high spot along the material's surface, it has less room to oscillate and the amplitude of oscillation is decreased. Conversely, when the tip encounters a depression in the surface, it has more room to oscillate and the amplitude of oscillation is increased. The changes in oscillation are measured and a representation of the surface topography can be obtained.

This system virtually eliminates the "tracking forces" problems of the contact mode because the tip has enough oscillation amplitude to overcome the tracking force and the adhesion problems present in the other modes. Another advantage of this method is that the oscillating method makes the vertical feedback system very stable, producing very consistent and repeatable results. Tapping mode operation can be used in ambient conditions as well as in liquid emersion. However, liquid emersion techniques require a change in the frequency of oscillation of the tip.

Advantages and disadvantages of operating modes

A comparison between the contact and tapping modes of imaging shows the advantages of each mode. The contact mode is the only mode that can obtain atomic resolution images, and scan times are usually slightly faster than in the tapping mode. The tapping mode provides higher resolution for most other applications with less damage to samples imaged in air.

Applications of Atomic Force Microscopy

Nanotechnology is the practice of manipulating materials and processes at the atomic level. Because of this, its applications are spread across many fields of study from biological research to manipulating materials at the atomic level. This section will provide a few examples of these applications.

Biology

Biological applications of the AFM are many and varied. Examples are DNA and RNA analysis, dynamic behavior of living and fixed cells, the study of intermolecular forces, and the research and development of biomaterials. Specifically AFMs have played a key role in advancing the design and fabrication of contact lenses and making available to medical researchers images of developing and dying neurons.

Nano-manipulation

Nano-manipulation is simply manipulating materials at the nano-level (defined as smaller than 100 nm dimensions). Specific applications are dip-pen lithography, electrical corrals, linking nanoparticles, positioning nanoparticles, embedding nanostructiures, and cutting and bending with an AFM. Nano-manipulation occurs primarily to the chemical sciences.

Material analysis

A major area of application ranging across many disciplines is the use of the AFM in material sciences. Examples are thin film coating analysis and materials identification. The AFM is used in the polymer industry as a characterization tool. It is often used in conjunction with scanning electron microscopes (SEM) and provides valuable information related to films, injection and blow moldings, and multiphase polymer systems.

Advantages and Disadvantages of Atomic Force Microscopy

To conclude this module, a discussion of the advantages and disadvantages is needed. There are only three major disadvantages to atomic force microscopy. The first is that the image area that can be produced is much smaller than that of other imaging techniques. The sample area that can be viewed is limited by the small and delicate movements required to produce the accurate image of the surface being studied. The second is that image quality is limited by the size and radius of the tip. The smaller the diameter of the AFM tips, the better the resolution of the scanned image. The science of nanotechnology is already creating better resolution by offering smaller-diameter tips made from carbon nanotubes. A second effect of these tubes is that they substantially increase the strength of the tips. The third disadvantage of the AFM is that it has slower scanning times than other imaging devices.

The major advantages of the AFM are numerous. The first is that it is capable of delivering a true three-dimensional image of a surface. Second, the samples require no special preparation or treatments. Third, no vacuum environment is required for most applications. And fourth, images have greater resolution than those produced by SEMs.

The AFM is a unique device that is photonics enabled. Used alone or in conjunction with other imaging techniques, it is changing the face of nanotechnology and advancing numerous fields of study. It has become and will continue to be an important device in many scientific disciplines.

EXERCISES

1. List three photonics devices used in atomic force microscopy and briefly describe how each is used.
2. Explain the operation of a photodiode.
3. Explain the operation of an interferometer.
4. Draw the shift in wavelengths if *m* is equal to 1, 1.5, and 2. Be sure to draw both waves and show the shift.
5. Determine whether a condition of destructive interference or constructive interference is seen by the detector if the changes in path lengths of the interferometer are as follows: Assume that the laser wavelength is 633 nm.
   a. $\Delta d = 1107.75$ nm
   b. $\Delta d = 1582.5$ nm
   c. $\Delta d = 158.25$ nm
6. Determine the path length difference for a 532-nm interferometer system if the wavelength shift is $m = 2$, $m = 2.5$, and $m = 1$. Which shifts will result in constructive interference at the detector?

7. Calculate the change in path length of an interferometer if the laser wavelength is 675 nm and the wavelength shift *m* is 2.005. Explain what the detector would see and why this is not a maximum or minimum condition.
9. An AFM using an interferometer configuration uses a diode laser with a wavelength of 633 nm. Calculate the change in elevation between two points on a sample surface if the interferometer measures a phase shift φ of $\pi/10$.
10. Light from a sodium lamp is collimated and sent through a transmission grating of 6000 lines/cm. The screen is located 1.05 meters from the grating, and an unknown wavelength in the light forms a fringe at 35 cm along the screen in first order. Calculate the angular deviation for the fringe. Calculate the wavelength of light.
11. The detection and monitoring system of a photodiode in an AFM using an interdigitated sensing arm detects a change in current while scanning two adjacent positions along a sample's surface. The starting position of the sensing arm is at a flat portion of the surface and the second position is on a rise. The ratio of the two currents, $\frac{i}{i_0}$, is 0.02, where i is the current generated at the photodiode for the flat position and i_0 is the current at the top of the rise. The AFM uses a HeNe laser with a wavelength of 632.8 nm. What is the amount of rise in the surface between these two positions?
12. List and explain the three contact modes of an AFM.
13. List the advantages of the contact mode and the tapping mode.
14. Briefly describe the advantages of AFM over other forms of microscopy.

LABORATORY

With the multitude of different AFM models, it is difficult to provide a single laboratory exercise that all users of this module can implement. With the AFM equipment available to them, we encourage users to design hands-on activities for reinforcing the concepts presented in the module. In particular, we suggest that users review the technical manual of their AFM and select for this activity maintenance, alignment, or calibration procedures that highlight the concepts and components presented in the module. Such procedures will identify the locations in the AFM of these components and their systematic interactions with each other. Knowing these interactions and practicing operational procedures related to the AFM will enable users to have a deeper understanding of AFM capabilities and be better equipped to maintain them.

The following is an example of the type of laboratory we would encourage.

This exercise gives the student practice in aligning the diode laser of a Topometrix AFM. The student should follow all safety precautions when working with the laser and should be familiar with the AFM manual. Other AFM models can be substituted here, but it should be noted that the alignment instructions will vary according to the model of AFM.

Materials

Topometrix AFM (system TMX 2000, head TMX 2010, computer TMX 486/66)
Technical manual for Topometrix AFM
Jeweler's loupe

Procedures

Following are the general procedures for alignment of an optical system of SFM in the AFM mode.

Note: Each time a cantilever or sample is exchanged, an optical alignment must be done.

1. Observe and follow all safety precautions.
2. Turn on software to system.
3. Place software in safe mode of operation.

Note: Safe mode is an alignment tool with low operating powers of the laser so that the possibility of injury to the operator is minimized during visual alignment.

4. Adjust the laser so that the operator can visibly confirm that the beam is striking the tip of the cantilever.

Note: The use of a jeweler's loupe may be needed for this step.

5. Replace any safety precautions that may have been removed for visual alignment (for example, cover or interlocks).
6. Remove software from safe mode of operation.
7. Place software in alignment mode of operation.

Note: At this time, the software should have an indicator of detector signal displayed.

8. Using the laser adjustment knobs, adjust the laser while observing the detector signal. Continue to adjust until the maximum detector signal is obtained.
9. Once the signal generated by the laser is maximized, use the mirror adjustment knobs while observing the detector signal. Continue to adjust until the maximum detector signal is obtained.

Note: The operator must repeat steps 8 and 9 until the maximum power is achieved.

Note: If the specified output (from the manual) for the system is not reached, continue with step 10. If the specifications are met, you may begin imaging the sample.

10. Use the detector adjustment knobs to obtain the maximum detector signal. Then return to steps 8 and 9.

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