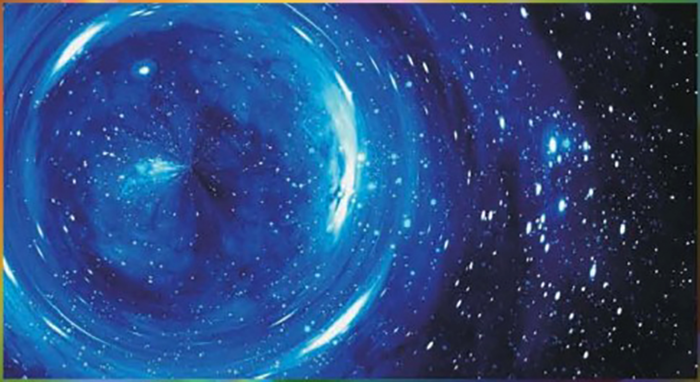
Photonics-Enabled Technologies

Photonics in Nanotechnology



OP-TEC

Optics and Photonics Series

Photonics in Nanotechnology

Photonics-Enabled Technologies

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, environmental monitoring, and optoelectronics, 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

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, *Photonics in Nanotechnology,* was prepared by Dr. John Ready. Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Photonics in Nanotechnology

INTRODUCTION

Nanotechnology is a rapidly developing new field that offers many substantial advances in areas such as communication, display, laser technology, solar cells, alternative energy, and medicine. As its name implies, nanotechnology deals with technology development at the atomic or molecular range with dimensions approximately 1 to 100 nanometers. (A nanometer is one billionth of a meter.) Nanotechnology is extremely multidisciplinary and includes microscopy, spectroscopy, organic chemistry, thin film deposition, lithography, and semiconductor processing.

Photonics is a key to many important nanotechnological devices and structures and is used extensively in their fabrication. Photonic techniques are extremely important in measuring the properties of nanostructures and characterizing their properties. Photonics and nanotechnology interact in contributing to a large number of important applications such as optical couplers, solar cells, light emitting diodes (LED), diode lasers, photodetectors, and biochemical markers. Thus, photonics is an important supporting area that will enable the promise of nanotechnology to be fulfilled.

This module will describe how photonics enables the fabrication, measurement, and utilization of components and devices in the nanoregime of size.

PREREQUISITES

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

1. High school mathematics through intermediate algebra and basics of trigonometry
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*

OBJECTIVES

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

- Define *nanophotonics.*
- Define *quantum dots.*
- Define *nanowires.*
- Define *quantum wells.*
- Calculate the de Broglie wavelength of an electron in a nanostructure.
- State how photonics technology is used to fabricate nanostructures.
- Describe examples of how photonics is used to measure and characterize nanostructures.
- Describe how photonic technology and nanotechnology combine to provide useful applications for nanophotonics.
- Define *pulsed laser ablation* and describe how it is used to make nanostructures.
- Name some of the lasers that have been used in fabricating or characterizing nanostructures.
- Gain experience in the fabrication of nanostructures and in the characterization of their properties using photonic techniques.

SCENARIO

Sylvia is a photonics technician working in a nanotechnology development laboratory at a large university. She graduated from a two-year Laser Electro-Optics Technician training program at a community college. She now has the responsibility of maintaining, servicing, and operating a commercial tunable femtosecond-duration pulsed Ti:sapphire laser. Working under the direction of an associate professor at the university, she uses the laser to grow ZnSe nanowires on crystalline substrates using a process called pulsed laser deposition. Because the dimensions and properties of the nanowires depend on the laser properties of pulse energy, wavelength, and pulse duration, she varies these laser parameters in a systematic investigation to determine how the nanowires and their properties depend on deposition conditions. Sylvia works in close collaboration with other specialists in the nanotechnology laboratory and enjoys the challenges and rewards of her work.

STUDY NOTE

Because quantum effects are closely tied to nanotechnology, this module includes a brief, nonmathematical review of quantum effects for students who are not familiar with the subject. The overview simply states the most important principles without providing detailed proof. The overview also provides a conceptual explanation of how quantum effects form the foundation of nanotechnology.

As an additional study aid, several technical terms that relate to lasers or material processes are defined in the *glossary* at the end of the module. Terms that appear in the glossary are italicized in the text.

DISCUSSION

Nanotechnology is an exciting new field that has the potential to produce many useful devices and applications. Nanotechnology is still in the early stages of development. Some commercially developed products have reached the marketplace, but most of the work is still in experimental laboratories. Nanodevices are still relatively expensive and require extensive effort to produce.

Many technologies support the development of nanotechnology. These include microscopy, **chemical vapor deposition**,* wet chemistry, and materials science, among others. Photonics also supports and promotes the development of nanotechnology. In particular, photonics allows nanodevices to be fabricated more rapidly and at less expense. Photonic techniques are also valuable for characterizing the properties of nanomaterials. Because of these facts, we say that photonics *enables* nanotechnology.

Lasers play important roles in supporting nanotechnology. For example, lasers are used both to fabricate nanostructures and to measure their properties. Since nanotechnology has broad applications, several types of lasers are used.

Fabrication of nanostructures by pulsed laser **ablation** requires short pulse duration and high peak power. The short pulse duration is necessary to ensure that the laser light heats only a thin layer of the target material's surface. With short pulses, there is little time for thermal conduction of energy into the bulk of the target, and a large portion of the laser energy is used to supply the latent heat of vaporization. Ti:sapphire lasers with femtosecond pulse duration are widely used to produce these ablation effects. Such lasers also offer the advantage of tunability, which allows the laser output wavelength to be adjusted to the target material wavelengths at which light energy is most readily absorbed.

Frequency-tripled and frequency-quadrupled pulsed Nd:YAG lasers, operating at wavelengths of 355 and 266 nanometers respectively, have also been used for laser ablation. Their ultraviolet wavelengths are effectively absorbed by many target materials. These lasers have a pulse duration in the nanosecond regime, which is short enough to ensure that no damage is done to the target material's substrate.

For measuring, or *characterizing,* the properties of nanostructures, one does not usually need very high power or short pulse duration. Characterization often involves measurement of the **photoluminescence** of a nanostructure. To detect this effect, one usually needs a laser with a relatively short wavelength because the photoluminescence will be at a longer wavelength than the exciting radiation. Continuous argon ion lasers, with wavelengths of 488 or 514.5 nm, are

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*Terms in boldface appear in the glossary.

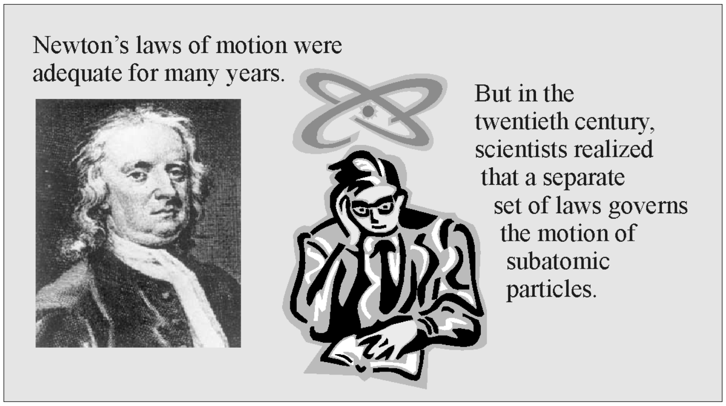
often used for this purpose. Or when still shorter wavelengths are needed, continuous **frequency-tripled** and **frequency-quadrupled Nd:YAG lasers**, operating at 355 and 266 nanometers, are employed.

This module emphasizes the use of photonics in fabricating nanomaterials and devices and the methods by which photonics is used to characterize those materials. We will also emphasize devices and **nanophotonics**, an interaction in which nanotechnology and photonics work together in the production of devices such as detectors and emitters of radiant energy. However, before we begin, let's briefly review the strange world of quantum mechanics.

An Overview of Quantum

In the late 19th century, the laws of motion formulated by Isaac Newton (1643–1728) were adequate to explain the motion of macroscopic objects (e.g., baseballs) that move at low speeds compared to the speed of light (186,000 miles per second). For many years, these laws were all scientists and engineers needed to predict the motion of objects, given their initial velocities and directions.

But in the early 20th century, as the atomic nature of matter became known, scientists came to realize that the classical laws of motion were not adequate to explain and predict the motions of subatomic particles. In the first few decades of the 20th century, scientists developed a new branch of mechanics was developed—quantum mechanics—that could be used to predict the motion and interaction of subatomic particles.

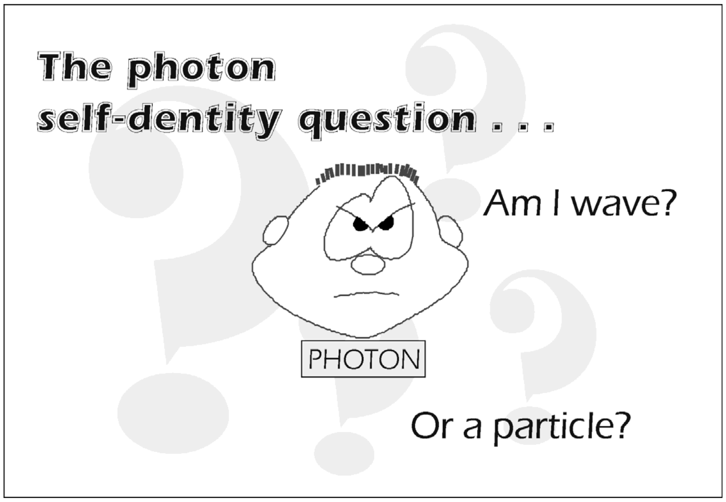


It is helpful to consider the relationship between classical mechanics and quantum mechanics. Both are effective in dealing with their proper subjects—classical mechanics in dealing with macroscopic objects (e.g., baseballs) and quantum mechanics in dealing with submicroscopic objects (subatomic particles). But the laws of physics should not change as the sizes of the objects being described change. This apparent dilemma is dealt with in what is called the *correspondence principle.*

Basically, the correspondence principle states that as systems become large, the laws of classical mechanics will emerge as an approximation of the laws of quantum mechanics. The basic idea of the correspondence principle is that all objects obey the laws of quantum mechanics. Classical mechanics is the behavior of the quantum mechanics of a large system, that is, a large collection of particles. (A precise definition of how "large" a system must be for classical mechanics to apply is beyond the scope of this module.) The laws of classical mechanics follow from the laws of quantum mechanics at the limit of large systems. Thus, classical mechanics can be considered as a limiting case of quantum mechanics. Both types of mechanics can coexist and be applied to their proper types of problems.

One of the first effects of quantum physics, discovered very early in the 1900s by Albert Einstein, is that the energy of light can act as if it consists of packets of energy. These packets are called *photons.* Before Einstein's discovery, it was assumed that light is a wave phenomenon. This assumption is logical: In many situations—diffraction experiments, for example—light *does* exhibit a wavelike character as it interferes with itself and creates regions of brightness and darkness. But in other situations, such as the photoelectric effect, in which electrons are expelled from surfaces struck by light, light acts like a particle. Each photon has a discrete energy equal to the quantity hf, where h is Planck's constant (6.63×10^{-27} erg-seconds) and f is the frequency of the light in cycles per second or hertz.

Thus, given (a) the photoelectric effect and (b) the conclusions of many pre-Einstein experiments on light, physicists have concluded that light has a dual nature: In some situations it has characteristics similar to those of particles while in others it displays wavelike properties. This aspect of light, referred to as the *dual nature of light,* is a difficult concept to grasp and is not fully understood by physicists even now. Still, the particle nature of light and its quantization into discrete photons is well established.

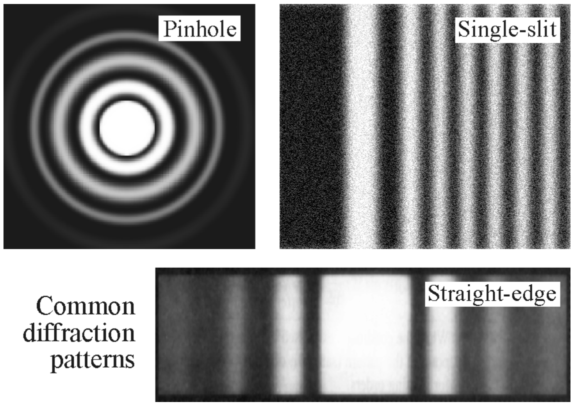


If something that was originally thought to be a wave can act like a particle, does that mean a particle can act like a wave? The answer is yes. In the 1920s, it was demonstrated that electron beams, which are believed to consist of particles, can produce interference patterns, a phenomenon that is characteristic of waves. Since that time many other experiments have verified that other particles, including atoms and molecules, can exhibit wavelike behavior. Scientists now recognize that light waves and atomic particles can both exhibit wavelike *and* particle-like behavior. This is referred to as the *wave-particle duality of light and matter.*

The wavelength of a particle is defined by the *de Broglie wavelength*, which is mathematically given as $\lambda = h/mv$, where h is Planck's constant, m is the particle's mass, and v is its velocity. The fact that particles such as electrons are characterized by a wavelength is a consequence of wave-particle duality. This is important in nanotechnology because, when the size of the nanostructure becomes less than the de Broglie wavelength, the particle is no longer free to move as it would in a larger structure. In other words, at this dimension, the *wave properties* of the particle become predominant in determining its motion.

Let's pause for a moment and consider what we mean by the wave properties of a particle. We do not mean that the particle moves in space like a wave. Instead, we mean that its wave property simply acts as a mechanism for determining the locations the particle is most likely to occupy. Notice we did not use the singular form of *location,* but the plural. The wave nature associated with a particle is not definitive, but probabilistic. It gives us a range of locations a particle can occupy and the probabilities of its being in those locations. That's right; for very small particles we can no longer calculate exact locations. We can only determine their most likely locations.

One interesting aspect of a particle’s wave nature is that it can prohibit the particle from being in certain locations. To understand this, let’s take a simple experiment whose results you have already studied. If light is sent through a small aperture, it will generate a diffraction pattern. This pattern is a series of light and dark regions. This pattern occurs, according to the wave nature of light, because light waves emanating from the aperture interfere constructively with each other, causing bright regions and dark regions.



Common diffraction patterns

Another way to look at this diffraction pattern is to consider the wave nature of a particle. We have already stated that light can be thought of as a large group of moving photons. As these photons move through the aperture of our experiment, their wave nature allows us to determine what locations they can occupy beyond the aperture. The bright spot (central maximum) that appears in the center of the diffraction pattern is the most probable location for the photons to go. The second maximum in the pattern, which has less brightness (fewer photons), is the next-most-probable location. Other maximums result from locations with even smaller probabilities. The dark regions occur because no photons are reaching them. This means the wave nature associated with these photons will not allow them to go to those locations, thus causing the dark spots. The probability of going to those locations is zero.

Experiments have shown that electrons passing through an aperture also generate a diffraction pattern. Thus, these diffraction experiments demonstrate that both light and electrons—though light is obviously a wave and an electrons are obviously particles—can have *both* wave-like and particle-like properties.

Since the wave properties of particles provide only the *probability* that they will be in particular locations at given times, this means that we cannot locate particles exactly. This lack of exactness leads to another important principle of quantum mechanics called the *uncertainty principle.* Formulated by a German physicist named Werner Heisenberg in the 1920s, the uncertainty principle states that one cannot determine both the position and the momentum of a particle exactly at the same time. There is a lower limit on the precision to which one can measure both these quantities simultaneously. Thus, according to the uncertainty principle, there will always be some lack of precision in the measurement of the location of a particle or in the measurement of its motion, or in both. If we know the exact location of a particle, we cannot account for its motion precisely—and vice versa.

The uncertainty principle does not affect our everyday lives, because the value of Planck’s constant is very small. A good baseball player can simultaneously determine both the location and movement of a pitched baseball well enough to hit it. But in the submicroscopic world of atomic particles, the uncertainty principle limits the accuracy of simultaneous measurements of motion and location.

Another quantum mechanical phenomenon that can be important in nanotechnology is called *tunneling*. Tunneling allows particles to move to and from different regions within nanostructures, even when there is an energy barrier that seems high enough to prevent them from doing so. As stated above, particles have a wave-like nature that helps us to determine their probable locations. When this wave nature interacts with the energy barrier, the most probable location for a given particle is *within* the region that contains the energy barrier. However, there is also a smaller probability that the particle will penetrate the barrier and end up in a region outside the energy barrier, even if the particle didn't have enough energy to get over the barrier. This is the probability that the particle can "tunnel" through the barrier.

In practice, tunneling applies only to very small particles, such as electrons. In the large-system limit to quantum mechanics, a large object such as an automobile approaching a barrier such as a mountain will not be expected to tunnel through the mountain. However, since a car is composed of a large number of particles and all particles have a wave nature, quantum mechanics would predict an infinitely small probability that the car could "tunnel" through the mountain and appear on the other side. As the size of an object approaches that of an electron, the probability of this tunneling effect becomes greater.

We now turn to some of the applications of quantum mechanics in nanotechnology. We begin with what is called the *band model of solids*. This determines why some solids are electrical conductors, some are insulators, and some are semiconductors.

According to the laws of quantum mechanics, a particle, such as an electron, cannot take on energy, just as it cannot be in any specific location. Particles are constrained to have specific values of energy, depending on their environment. These values of energy are called *energy levels*. The energy levels of electrons within atoms (or molecules) are determined, in a probabilistic sense, by their wave nature. When the atoms are well separated from one another, as in a gas, the electrons in different atoms interact very little and their energy levels are fairly narrow and discrete. But as the atoms move closer together, the electrons interact more and more, causing the energy levels to broaden and form bands.

Figure 1 demonstrates this situation by showing how an electronic energy level broadens and splits into bands as the distance between atoms changes. The figure plots an energy level versus the average distance between atoms (the *abscissa*). Near the right of the figure, the average distance between atoms is large, as in a gas. The energy level is fairly narrow. As the average distance between atoms decreases (moving left in the figure), the energy level broadens and splits into two bands of allowed energy states, as in a solid.

This figure shows two allowed energy bands for electrons in a solid. Each band contains many closely spaced energy levels. The lower energy band is generally completely filled. It is called the *valence band.* The upper band is typically empty, having no electrons. It is called the *conduction band*.

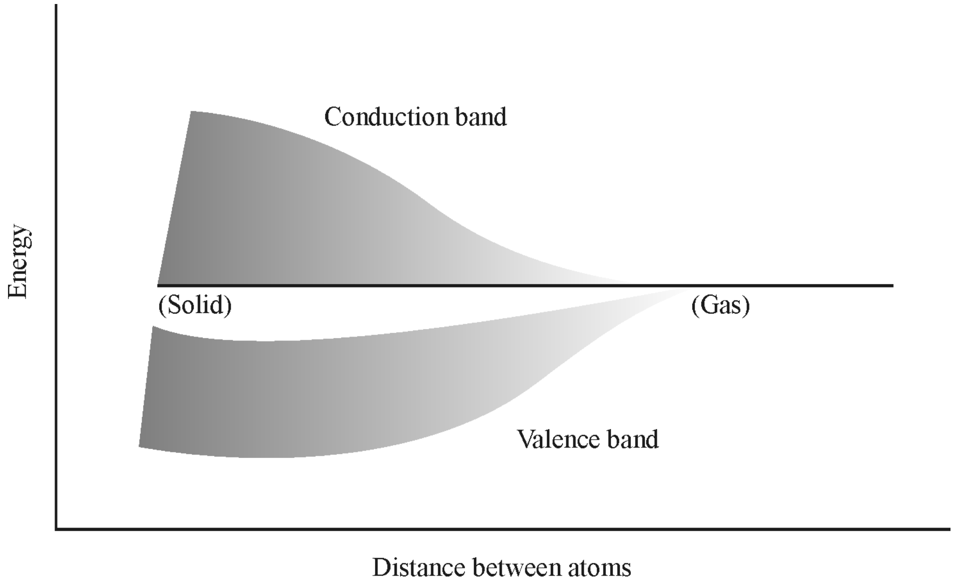


Figure 1 *Schematic representation of how an electronic energy levels change as the distances between atoms change*

Figure 2 shows three cases of how the valence band and conduction band can be related in a solid.

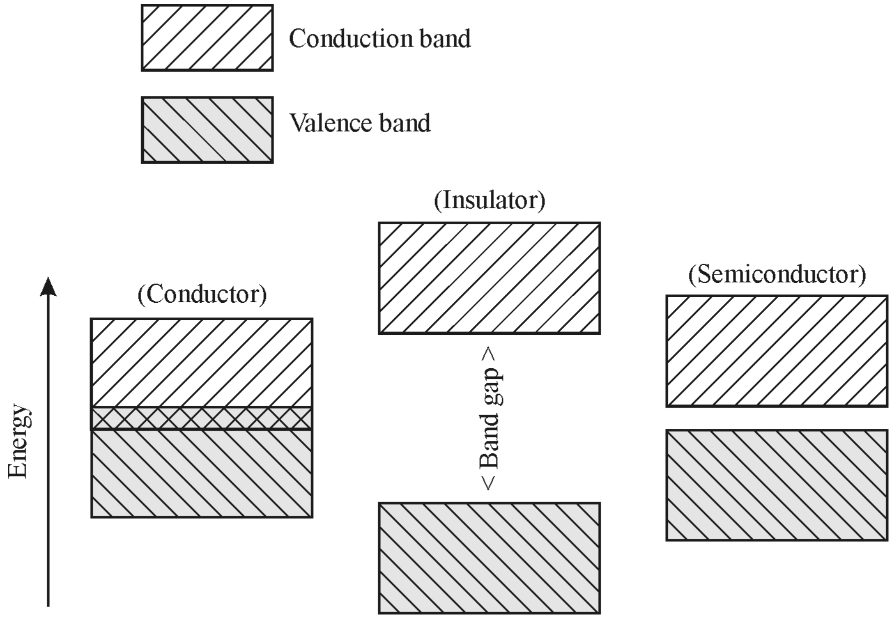


Figure 2 *Possible band structures in a solid*

In the left portion of the figure, the valence and conduction bands overlap in energy. If an electric field is applied, the electrons in the valence band can gain energy and move into empty states in the conduction band and be accelerated. When this happens, as in the case with most metals, the material is functioning as an electrical conductor. In the center portion of the figure, there is a gap between the valence and conduction bands. This is called the *forbidden band gap.* No electrons can have energy in the band gap. If an electric field is applied, the electrons in the filled valence band typically cannot gain enough energy to move to the conduction band. Materials that cause electrons to behave in this way are functioning as electrical insulators. An example is rubber. The right portion of the figure shows a situation in which the band gap is relatively narrow. In this case, when an electric field is applied, a few electrons may enter the conduction band. Once in the conduction band, the electrons may gain energy from the field and create a degree of electrical conductivity—substantially less than that of a metal. Materials that cause electrons to behave in this way are functioning as semiconductors. Examples are silicon and gallium arsenide.

Bottom line—The situations represented in Figures 1 and 2 illustrate a key concept in nanotechnology: As individual atoms are brought together to form a solid or nanostructure, their quantum wave properties as they relate to energy levels begin to interact. The net outcome is that the resulting aggregate of atoms can have an energy level structure that is different from that of the individual atoms that compose it. For instance, when iron atoms are brought together to form a solid, an energy band structure forms that gives the resulting solid high electrical conductivity. That structure does not exist for the individual atoms; it is a property of the solid *formed by* the atoms. Likewise, bringing together individual atoms to form semiconductors and insulators generates specific properties for those solids that are not characteristics of the individual atoms involved.

Nanotechnology entails bringing together individual atoms to create useful aggregates. These aggregates are typically atoms of the same element arranged in some nanostructure. The energy level structures of the aggregates or nanostructures are different from the energy level structures of the individual atoms that compose them. In nanotechnology, the main objective is to produce nanostructures whose energy level structures meet the requirements of specific applications.

Figure 3 provides an example. The diagram labeled A shows some of the allowed energy levels for some individual atom. The diagram labeled D on the far right shows the energy bands for a solid structure containing large numbers of these atoms. The two diagrams in the center (B and C) represent some of the energy levels of nanostructures, like a quantum dot, that are composed of a specific number of these atoms confined to some specified dimension and geometry.

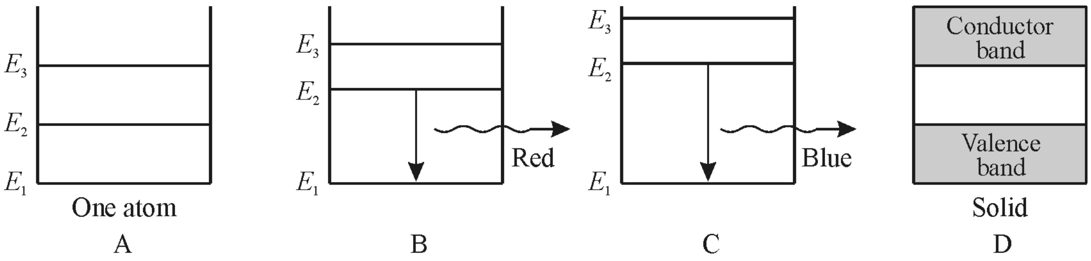


Figure 3 *Energy level diagrams for different arrangements of similar atoms*

These four diagrams represent a continuum from one atom to collections of atoms ranging from a few (B and C) to a huge number (D). Notice that the nanostructure energy levels depicted in diagrams B and C differ from those of the individual atom and the solid. In nanotechnology the nanostructures depicted in B and C could be manufactured for a specific application.

For instance, the energy levels in the nanostructure depicted in diagram B have E_2 and E_1 levels. This structure could be manufactured so the difference between those two levels is exactly the energy carried by a photon of red light. If a light source shines on this nanostructure, it will absorb photons in this light and gain energy by moving from a lower to a higher energy level. One such transition could be from level E_1 to level E_3. Since the structure will want to return to the lower energy state E_1, it can do so using a number of different transition paths. One path includes the transition from level E_2 to E_1, which results in the emission a photon that will appear as red light. Likewise the nanostructure whose energy levels are depicted in diagram C could be manufactured so that the difference between its levels E_2 and E_1 is exactly the energy carried by the photons in blue light. Thus, depending on the specified need (red or blue light), a nanostructure could be manufactured to produce one of these specific colors.

The remainder of this module will present a number of specific types of nanostructures and their applications. As you learn about them, remember that the quantum concepts presented in this section cause the effects they produce.

Use of Photonics for Fabrication of Nanostructures

Devices that are important in nanotechnology can be fabricated using laser interactions with materials. These devices include *quantum dots, nanowires,* and *quantum wells.* Let's discuss each of these.

Quantum dots

A quantum dot is a nanostructure that confines in all three directions the motion of charge carriers, such as electrons. A quantum dot contains a small number (less than 100) of charge carriers and can be generated by chemical processes, **electron beam lithography***,* and **atomic beams** in a vacuum environment.

The confinement restrictions of the atoms in these dots cause quantum effects that generate energy levels for the dots that are different from those found in bulk material made of the same atoms. Quantum dots thus have different electronic and optical properties than those of the base material from which they are formed and can be customized to meet specific applications.

One optical feature of small quantum dots is color. The larger the dot, the redder is its fluorescence when stimulated by absorbed light. The smaller the dot, the bluer is its fluorescence. Figure 4 shows this relation between the laser excitation and the fluorescent emission.

These optical features of quantum dots have potential applications in quantum computation and light sources, including diode lasers, photodetectors, and displays.

Solid-state quantum computation is a new technology that uses quantum mechanical phenomena to perform operations on data. This application involves attaching leads to a structure containing quantum dots and applying a voltage. This allows control of the flow of electrons through the dots, thus varying the amount of charge stored in them. This variation in charge storage can be encoded and represented as information. It is envisioned that a number of entangled quantum dots, called *qubits,* could make quantum calculations possible. This is a future application that is being studied at a number of laboratories.

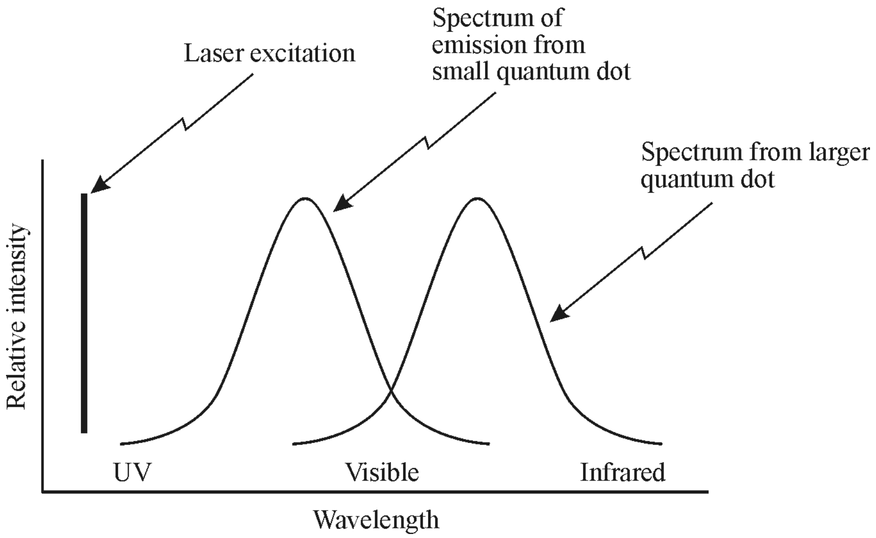


Figure 4. *Relation between exciting radiation and emission for two sizes of quantum dots*

In other applications quantum dot lasers and displays have already been demonstrated experimentally. Another potential application is in solar cells. Applications in lasers, displays, and solar cells will be discussed more fully in a later section of the module.

Some quantum dots are small regions of one material buried in another material with a larger band gap. For example, in the case of a GaAs/AlAs quantum dot, GaAs of dimensions 10×10×10 nm is surrounded by the higher band gap material AlAs. See Figure 5. These configurations provide the opportunity to develop nanosize semiconductor devices that can be configured into circuits that support computer and signal processing applications.

Figure 5 *GaAs/AlAs quantum dots*

Quantum effects also allow quantum dots to be used as lasers. Quantum dot lasers can emit light at wavelengths determined by the energy levels of the dots, whereas conventional semiconductor lasers emit at wavelengths determined by the band gap. Quantum dot laser wavelength can be adjusted by changing the size of the dot. Because of the high density of states, it is easy to produce the population inversion needed for laser operation. The small active volume of these dots also leads to low power requirements and low threshold current.

Lasers have been used to modify the characteristics of quantum dot light emitting diodes (LED). Scientists in Singapore (see *Photonics Spectra,* April 2007, p.108) used **laser annealing** to broaden the spectral width of LEDs. The InAs quantum dot LEDs were originally formed by metalorganic chemical vapor deposition. The LEDs were then annealed with a continuous Nd:YAG laser operating at a wavelength of 1064 nanometers. As a result of the annealing, the bandwidth of the emission from the LEDs was increased from 295 to 360 nanometers. This broadening is desirable for broadband light sources that can be used in applications such as **wavelength division multiplexing** and optical fiber based data transmission.

Lasers have also been used to switch previously grown quantum dots between different states. Scientists at the University of Southampton (see *Photonics Spectra,* November 2005, p.114) prepared gallium nanoparticles by exposing the tip of a silicon fiber to a gallium atomic beam in a vacuum chamber at a temperature of 80ºK. When the resulting quantum dots were irradiated with a continuous diode laser at a wavelength of 1550 nm, they exhibited structural changes as the temperature was varied between 80ºK and 300ºK. The changes were monitored with a second diode laser operating at 1310 nm. The intensity of the reflected light from the second laser changed as the quantum dots underwent their structural changes. Thus, photonics was used to activate quantum dots that could serve as switching or memory devices. The changes in the structure of the quantum dots were reversible and could be induced by nanowatts of the 1550-nm light. The state of the structure could be used to represent information that could be read out by the 1310-nm light.

Nanowires

While quantum dots have the motion of electrical charge carriers confined in all three directions, nanowires have the charge carriers confined in two directions, while they are free to move in the third direction. Nanowires, also called *quantum wires,* have widths of tens of nanometers or less but can be substantially longer in the third dimension. Nanowires may exhibit length-to-width ratios of 1000 or more. Nanowires can show a variety of shapes, sometimes nearly straight lines and sometimes zigzag structures. Figure 6 shows one manifestation of a set of irregular nanowires, the light areas, on a dark substrate

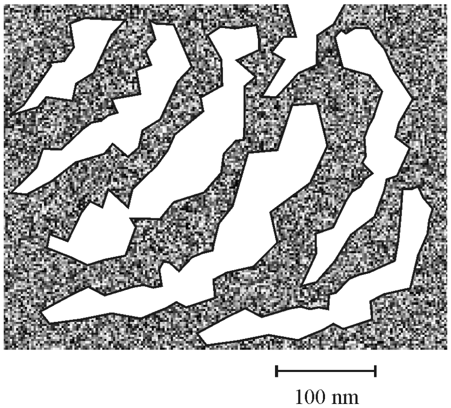


Figure 6 *Drawing of a set of nanowires on a dark substrate*

Because charge carriers in nanowires are confined across their widths, quantum effects come into play that cause them to have energy levels different from the energy levels found in bulk materials of the same composition. For instance, the electrical conductivity of a nanowire is much less than that of the corresponding bulk material.

As mentioned earlier and presented in more detail here, particles such as electrons are characterized by a wavelength, called the *de Broglie wavelength,* which may in a sense be considered the “size” of the particle. (See the discussion of wave-particle duality in the section titled “An Overview of Quantum.”) The de Broglie wavelength λ is defined as:

$$\lambda = h/mv \qquad \text{(Eq 1)}$$

where: h is Planck’s constant (equal to 6.63×10^{-27} erg-sec),
m is the particle mass (equal to 9.11×10^{-28} gm for an electron), and
v is the particle velocity.

We see that the de Broglie wavelength decreases as the particle velocity increases.

Let us consider an example. For an electron with a velocity of 10^6 cm/sec, the de Broglie wavelength is:

$\lambda = 6.63 \times 10^{-27}$ erg-sec / (9.11×10^{-28} gm × 10^6 cm/sec)
$\lambda = 7.28 \times 10^{-6}$ cm = 72.8 nanometers

An electron with this de Broglie wavelength will be confined in a nanostructure with a dimension of a few tens of nanometers. When we generate nanostructures that confine the electron motion in two dimensions (say, x and y), we get a nanowire (also called a quantum wire).

There are many different types of nanowires, including metallic (example: gold), semiconducting (example: silicon), and insulating (example: silicon dioxide). One promising application of nanowires is in electrical circuits designed to connect very small components. For example, scientists have doped nanowires to create p-type and n-type semiconductor wires and then crossed two differently doped nanowires to create a p-n junction. By connecting different p-n junctions, the scientists were able to produce logic circuits, such as AND or NOR gates, that have applications in computers.

Nanowires have been fabricated largely by chemical processes or by **vacuum deposition** processes using electrically heated sources. Such fabrication processes are often relatively slow and expensive. Vacuum deposition processes using lasers are under study and may relieve these restrictions. These laser-assisted processes can provide a simple and effective way to deliver material for growing the desired structure. Figure 7 shows a typical arrangement for growing a structure using this process.

For example, workers from laboratories in Japan and China (see *Photonics Spectra,* November 2006, p. 107) have grown ZnSe nanowires using pulsed laser ablation. In pulsed laser ablation, material is vaporized from a target and then deposited on a surface as the vaporized material condenses. Frequently, the operation is carried out in a heated chamber and in a controlled atmosphere. Usually a laser with a very short pulse duration is employed, to maximize the amount of energy deposited on the surface. The arrangement for doing ablation operations is similar to that shown in Figure 7.

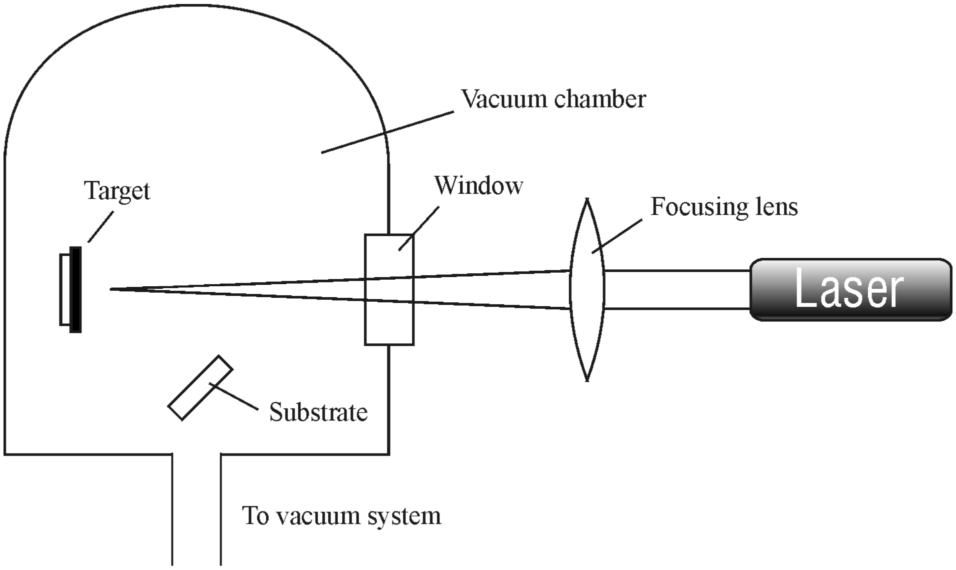


Figure 7 *Typical arrangement for laser deposition*

In the Japanese and Chinese experiments, the workers used a Ti:sapphire laser operating at a wavelength of 800 nm and emitting 130 femtosecond duration pulses. The irradiation produced craters on the target surface. Nanowires were grown within the craters, but not in the surrounding areas. The lengths and diameters of the nanowires were dependent on the conditions of the laser radiation. Typical values were diameters in the range of 30 to 80 nanometers and lengths of 1.3 micrometers. The speed at which nanowires could be produced using lasers was substantially higher than that associated with other techniques.

The ability to control the dimensions and hence the electrical and optical properties of nanowires allows fabricators to customize these wires to meet specified requirements. Researchers at Lawrence Berkeley National Laboratory in California (see *Photonics Spectra,* November 2005, p. 112) used a Ti:sapphire laser operating at a wavelength of 800 nanometers to irradiate a target of compressed zinc oxide. The evaporated ZnO was deposited on a substrate of gold-coated sapphire forming nanowires. The nanowires had fairly uniform diameters on the order of 100 nanometers. Because of their composition and structure, these nanowires had the capability to function as ultraviolet lasers. When they were irradiated by 266 nanometer radiation from a Nd:YAG laser, they produced laser output at 380 nanometers.

Nanowires can also be configured as grids that can be used as polarizers for the deep ultraviolet portion of the electromagnetic spectrum. This region of the spectrum is particularly important in semiconductor lithography. Polarizers for this region of the spectrum have not been completely satisfactory. To produce these grids, scientists at NanoOpto in New Jersey (see *Laser Focus World,* April 2007, p. 31) used a frequency-quadrupled Nd:YAG laser emitting at 266 nanometers in a two-beam interferometric arrangement to irradiate a silicon wafer coated with an aluminum film. After processing, the structure exhibited lines of aluminum with width of 40 nanometers and with center-to-center spacing of 118 nanometers. See Figure 8. The grid of nanowires exhibited 65% transmittance and an extinction ratio (the ratio of the intensity of the selected direction of polarization to the intensity of the perpendicular direction) of 200 at a wavelength of 266 nanometers.

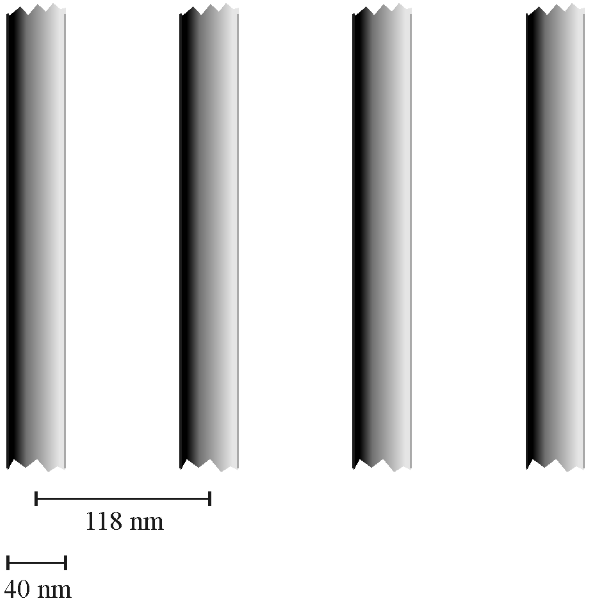


Figure 8 *Arrangement of nanowire grids for a polarizer application*

The examples described above illustrate how nanowires can be fabricated using photonic techniques and also show that a variety of applications are possible.

Nanotubes

Nanotubes are considered a subclass of nanowires. Their dimensions are similar to those of nanowires, with diameters of a few or a few tens of nanometers but substantially greater lengths. As the name implies, they have tubular cross sections. Figure 9 shows the structure of a nanotube. An especially interesting type of nanotube is made from carbon, but other materials have been used, including titanium dioxide, boron nitride, and silicon. Our discussion will emphasize carbon nanotubes.

Carbon nanotubes can take different forms: single-walled and multi-walled. A single-walled carbon nanotube is a seamless cylinder with a diameter around one to 10 nanometers. Cylindrical carbon nanotubes have unusual properties that make them useful for applications in photonics. They also have great strength and high electrical conductivity. They can be used in composite materials to strengthen other nanostructures. Carbon nanotubes have already been used as fibers in polymers to increase their mechanical strength.

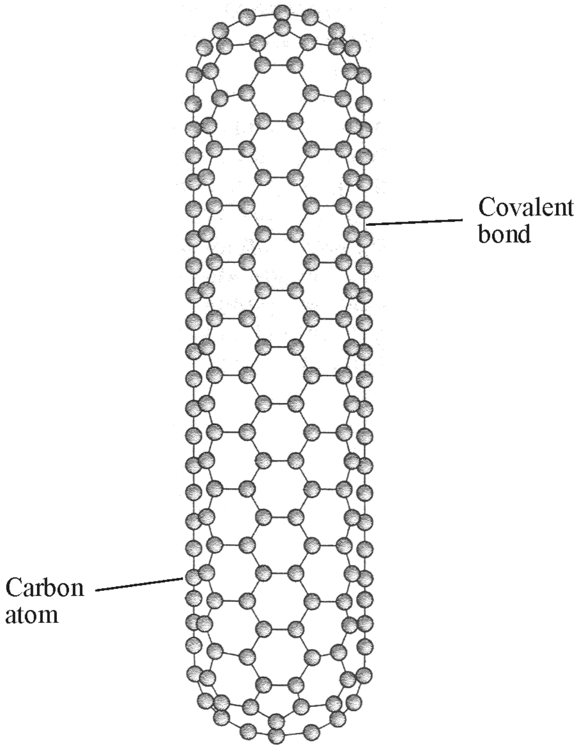


Figure 9 Nanotube structure

Multi-walled carbon nanotubes have multiple layers of graphitic carbon rolled in a tubular shape. In one structure, the layers of graphite are arranged in concentric cylinders, with one smaller single-walled nanotube inside a larger one. In a second arrangement one sheet of graphitic carbon is rolled around itself. Multi-walled carbon nanotubes can have properties different from the single-walled variety. The structure of a nanotube strongly affects its electrical properties. Carbon nanotubes may be either metallic or semiconducting.

Carbon nanotubes have been fabricated by a number of techniques, including laser ablation, chemical vapor deposition, and **arc discharge**. For our purposes, we emphasize laser ablation.

In laser ablation, a pulsed laser vaporizes a graphite target and the vaporized material is deposited on a surface. The process takes place in a heated chamber with an inert gas atmosphere; the resulting carbon nanotubes grow on the cooler surfaces of the chamber.

The first growth of carbon nanotubes by laser ablation used graphite targets and yielded multi-walled nanotubes. Later work used a target that contained graphite and particles of a metal catalyst, such as a mixture of cobalt and nickel. This yielded single-walled carbon nanotubes. The diameter of the nanotubes could be controlled by varying the reaction chamber temperature. Being able to control the diameter is important in fabricating nanotubes that meet specific photonics applications.

It is possible to make quantum wires out of metallic carbon nanotubes. Wires from carbon nanotubes have high electrical conductivity and are light in weight and high in tensile strength, but, at least so far, they are also expensive to produce. It may be possible to create macroscopic quantum wires from carbon nanotubes. Such a structure could be a rope consisting of strands of carbon nanotubes. No single strand would have to stretch the entire length of the rope, because electrons could move from strand to strand by means of “tunneling.” Such ropes would be useful in commercial applications in which relatively long, strong bonding members are required.

Nanobelts

Nanobelts are yet another variant of nanowires. They are thin but relatively long, as are nanowires, but can be somewhat wider than nanowires. Figure 10 compares nanobelts and nanowires. They may compete with nanowires for some applications. Nanobelts may have certain advantages over nanowires, such as fewer defects.

In one example of nanobelts fabricated by photonic processes, workers in Taiwan (see *Photonics Spectra,* November 2005, p. 115,) used a pulsed Nd:YAG laser operating at a wavelength of 1064 nm to ablate a target of CdSe powder. The vaporized material condensed on a silicon substrate and formed belt-like structures 40 to 70 nm thick and with lengths in the range of tens to hundreds of micrometers. These nanobelts had widths that tapered from 3 micrometers down to 100 nanometers and exhibited photoluminescence when excited with 514.5 nm radiation from an argon laser.

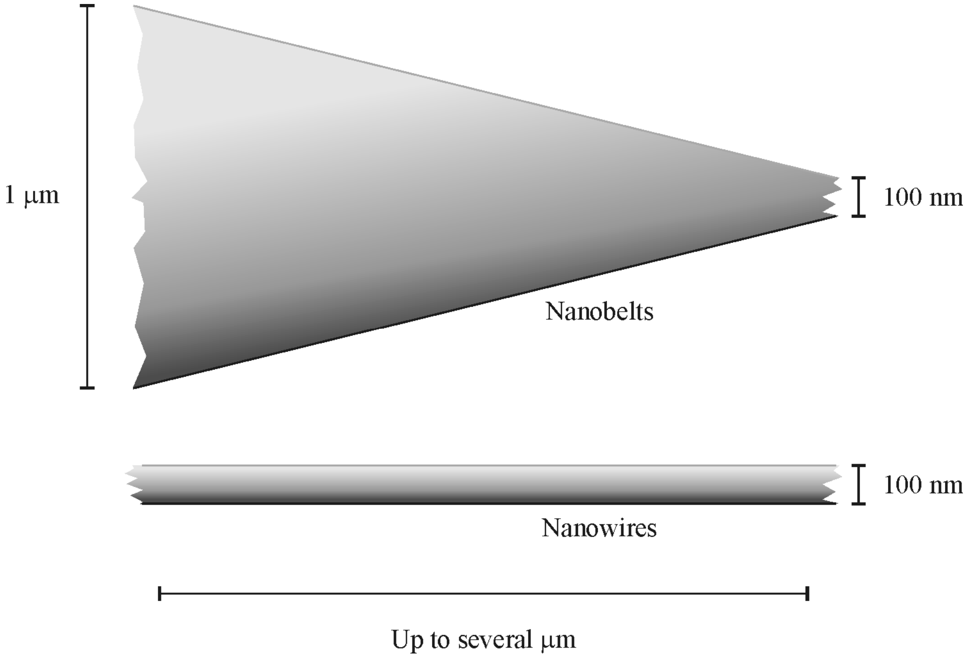


Figure 10 Comparison of nanobelts and nanowires

Figure 11 shows a typical arrangement for measuring photoluminescence. The photoluminescence of the CdSe nanobelts was substantially higher than that from bulk CdSe powder, presumably because of the crystallinity of the nanobelts. By manufacturing nanobelts with appropriate energy level structures, we can customize them to meet needed applications. For instance, CdSe nanobelts are being considered for applications in displays.

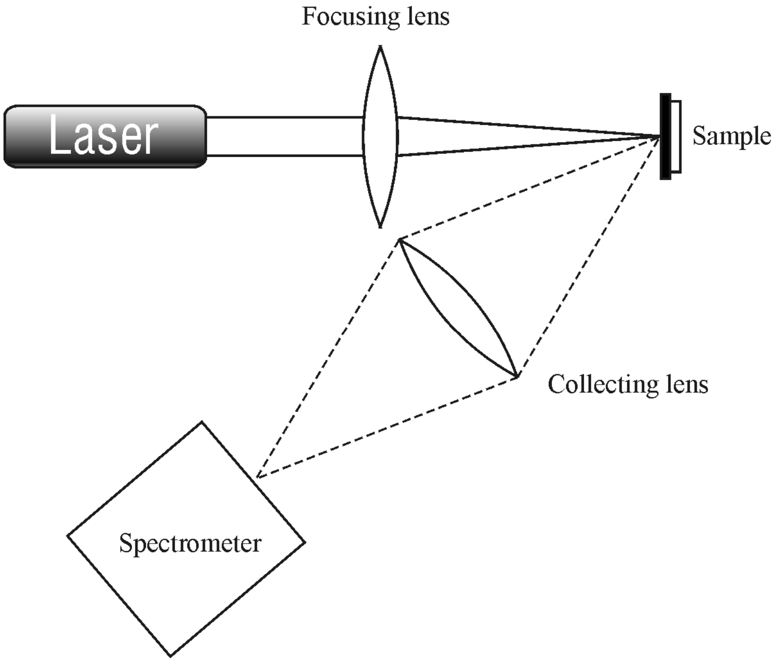


Figure 11. *Typical arrangement for measurement of photoluminescence*

Quantum wells

We have defined quantum dots and several categories of nanowires. In these nanostructures, charge carriers are confined in three and two dimensions respectively. We now consider quantum wells that confine charge carriers to one dimension (z), forcing them to occupy a planar region. As a result of this confinement, quantum effects occur. In the other two directions (x and y), these charge carriers behave as they would in a bulk material. Figure 12 shows the orientation of these directions.

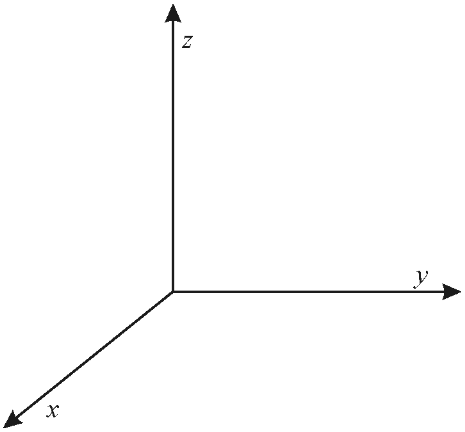


Figure 12 *Orientation of directions*

This confinement occurs when the quantum well thickness becomes less than the de Broglie wavelength of the particles. Quantum mechanical effects change the energy band structure and produce energy levels called *energy subbands.* In nanomanufacturing, we fabricate quantum wells that have energy subbands that meet the needs of specified applications.

Quantum wells are formed in semiconductors by growing a thin layer of material with a lower band gap between two layers of material(s) with higher band gap (example: a layer of gallium arsenide between two layers of AlAs) (Figure 13). This type of structure is called a **double heterostructure** because there are two boundaries with different materials on each side. Such structures are fabricated by techniques such as **molecular beam epitaxy** and chemical vapor deposition. The layer thickness can be controlled down to monolayers of atoms.

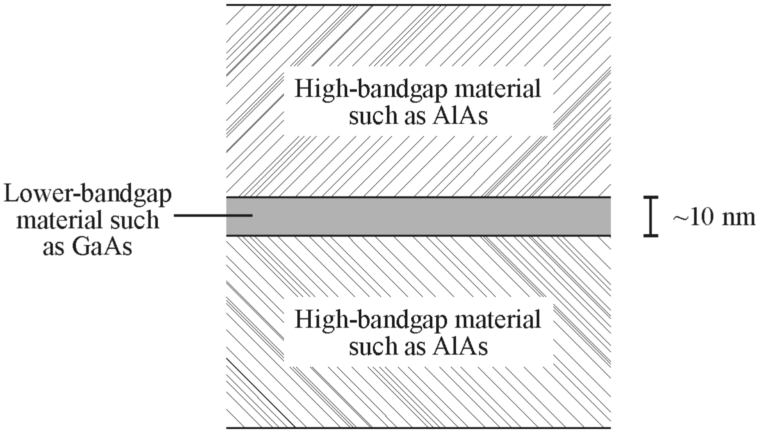


Figure 13 *Quantum well structure*

Quantum wells are used in diode lasers and infrared photodetectors. They are also used in high electron mobility transistors (HEMT), which are employed in low-noise electronics.

Electrons in quantum wells have a larger number of available states than do electrons in bulk materials. If the thickness of the center layer in a double heterostructure (like the thickness of the GaAs layer between two AlAs layers) is reduced below a certain thickness, quantum effects become apparent. One effect of this reduction is that the energy levels available to the electrons change and a higher number of states become available. This happens when the center layer thickness becomes less than the de Broglie wavelength of the electron. This is important because these wells can be fabricated into lasers whose output wavelengths will vary based on the layer's thickness. This variability gives us the ability to tune laser light to meet specified requirements. Additionally, increasing the number of quantum well energy states allows more electrons and holes to be near the edges of the conduction and valence bands. The increase in population of these bands helps achieve a population inversion that is necessary for a laser to operate.

Because they are nanostructures with potential laser properties, quantum wells are an excellent example of nanophotonics, which will be described later. The advantages of using quantum wells, quantum wires, and quantum dots will become evident when we look at various optoelectronic devices.

Photonics for Characterization

Photonic devices and techniques are widely used for measuring the properties of nanostructures and characterizing their performance. It may be fair to say that characterization may be the most important aspect of photonics-enabling nanotechnology. Techniques used include fluorescence, photoluminescence, optical spectroscopy, **two-photon excitation** of nanostructures, and Raman spectroscopy. This section will describe representative applications of photonics for measuring and characterizing nanostructures.

In what could perhaps be considered a typical use of photonics techniques to characterize the properties of nanostructures, scientists from Duke University and the U. S. Army (see *Photonics Spectra,* August 2006, p. 108,) studied the photoluminescence of sulfur-doped nanostructures. They used sulfur-doped nanowires with diameters around 20 nanometers and nanobelts with dimensions around 100 × 300 nanometers. These nanostructures were irradiated by a He-Cd laser and a xenon arc lamp. As compared to the photoluminescence from undoped ZnO, the photoluminescence from the doped nanostructures increased substantially. The spectrum of the photoluminescence extended from 400 nm to slightly more than 600 nm, with a peak at a wavelength slightly greater than 500 nm, which is near the peak response of the dark-adapted human eye. This is important because it can provide for light sources that will allow people to see well in the dark. This application clearly shows that photonics techniques can be used to discern between similar nanostructures that have small compositional differences—doped or undoped. Such sensitivity could prove valuable in regulating the quality of nanofabrication processes.

Another example involved the use of photoluminescence to determine the emission properties of quantum dots embedded in microtubes. Scientists at the Max Planck Institute in Stuttgart, Germany (see *Photonics Spectra,* June 2006, p. 125), used molecular beam epitaxy to grow InAs quantum dots between GaAs and InGaAs layers in a multilayer structure. The structure contained a sacrificial layer that could be etched away. The remaining GaAs/InGaAs layers rolled on themselves because of strain arising from the lattice mismatch of the two components. The rolling resulted in a microtube with diameter of 10 micrometers. Quantum dots were embedded in the walls of the microtubes. Figure 14 shows the structure.

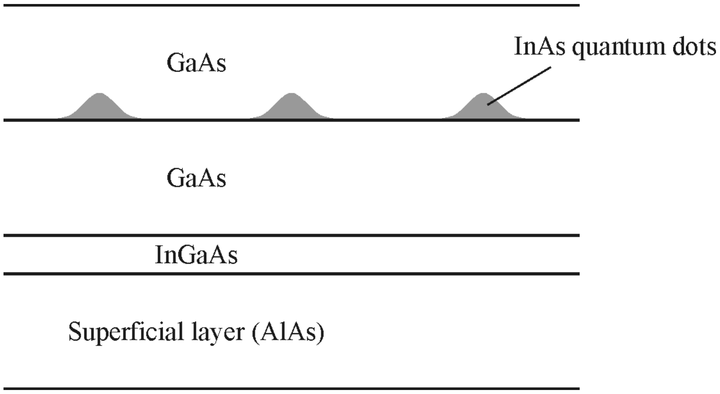


Figure 14 *Quantum dots embedded in the walls of nanotubes*

These structures were cooled to 7ºK and irradiated with laser light from a Nd:YVO_4 laser at a wavelength of 532 nm. The photoluminescence from the quantum dots was collected with a spectrophotometer. It was found that the intensity of the photoluminescence increased by a factor of 3.5 as compared to the photoluminescence of the quantum dots in the original planar structure. There was also a shift of the wavelength of the photoluminescence to the red. These differences were attributed to differences in the strain experienced by the quantum dots in the microtube as compared to the planar structure. The tubes also acted as **waveguides** for the photoluminescence, a property that is useful in building nanoscale-directed light sources. This example illustrates that photonics techniques could be used to characterize micro- and nanostructures by measuring the strain resulting from differences in their structural configurations.

Two-photon photoluminescence has also proved to be an effective process for characterizing nanostructures. Researchers at Argonne National Laboratory and in France (see *Photonics Spectra,* March 2006, p. 122) fabricated nanorods with lengths in the range 50 to 300 nanometers and widths around 30 nanometers using electron beam lithography. (Nanorods are similar to nanotubes but are solid instead of hollow.) These nanorods were irradiated with 120 femtosecond duration pulses from a Ti:sapphire laser at a wavelength of 785 nm. Luminescence stimulated by *two-photon absorption* was analyzed with a spectrograph. The results indicated that the wavelength of the peak of the luminescence shifted to the blue as the length of the rods decreased. The emission almost disappeared when the polarization of the excitation was in the direction of the narrow dimension of the rods. The results of these measurements helped the scientists to better understand the origin of the emission and determine the nanorod size and shape.

Photonics techniques were also used to measure the photoconductivity of quantum dots. The scientists at the State University of New York in Buffalo (see *Photonics Spectra,* November 2005, p. 113) fabricated PbSe quantum dots by a chemical synthesis process that incorporated an organic compound into the dots. The incorporation of this organic material allowed the dots to absorb light with wavelengths in the 1.1 to 1.9 micrometer region. When the dots were irradiated by a continuous diode laser operating at wavelengths of 1.34 and 1.55 micrometers, they exhibited infrared-stimulated photoconductivity substantially greater than that of earlier types of quantum dots. These results offered the possibility of extending the response of solar cells farther into the infrared spectrum.

Measurements such as those described above demonstrate the power of photonic methods in determining the characteristics of nanostructures, including their sizes and optical and electronic properties.

Photonics and Nanotechnology Joint Ventures

We have so far considered how photonics enables and supports nanotechnology. We turn now to the joint interaction of photonics and nanotechnology, in which nanotechnology improves the devices and techniques of photonics and in which photonics supports nanotechnology by utilizing nanostructures. We call this interaction nanophotonics.

One extremely promising example of nanophotonics is the use of quantum dots to improve the efficiency of solar cells. When a bulk semiconductor absorbs a photon, one hole-electron pair is produced. Only a single pair of charge carriers is produced, regardless of whether the photon energy is relatively high or low. (The photon energy must be equal to or greater than the energy of the band gap to produce any charge carriers.) If a photon has energy exactly equal to the energy of the band gap, it produces one pair of charge carriers. If it has more energy, it still produces only one pair. Photons with energy above the band gap do not generate any additional charge carriers. With respect to the goal of increasing solar cell efficiency, this excess photon energy is “wasted.”

But with quantum dots, high-energy photons can produce multiple charge carriers. This allows better use of the photon energy and higher efficiency. For example, quantum dots of lead selenide can produce up to seven hole-electron pairs with the absorption of a single photon as compared to a single hole-electron pair in conventional solar cells. This factor considerably increases the maximum theoretical solar cell efficiency.

Quantum dots also offer spectral tunability. This occurs because the absorption properties of semiconductor quantum dots are dependent on their size. For example, as the size of CdSe quantum dots is decreased, the peak response can be tuned from the red to the blue portion of the visible spectrum. Thus, if these dots are used in solar cells, the response of the solar cells can be altered to better match the solar environment.

In one example, scientists at the University of Notre Dame developed solar cells made from CdSe quantum dots (see *Laser Focus World,* April 2006, p. 44). They used CdSe quantum dots with diameters around 3 nanometers. The dots were linked to 50-nm TiO_2 particles by a linking molecule that contained the organic material carboxylate. The linking structure allowed transfer of electrons generated in the quantum dots. As the thickness of the structure increased, the absorbance of the quantum dots increased and the structure appeared darker. This work demonstrated the ability of CdSe quantum dot arrays to absorb photons and generate photocurrent in a nanostructured cell. This type of research could produce solar cells with higher efficiencies than current technology allows.

Quantum dots have also been used as lasers. For example, workers at the National Institute of Standards and Technology (NIST) and Stanford and Northwestern Universities fabricated tiny lasers in which quantum dots played a dominant role. The scientists deposited layers of indium arsenide on gallium arsenide. In the deposition process, the indium arsenide formed islands with diameters around 25 nanometers. The scientists then etched disks with diameters around 1.8 micrometers on pillars of gallium arsenide. The resulting structures were pillars of gallium arsenide with about 130 indium arsenide quantum dots on a pillar. This structure was excited by light and exhibited laser operation at a wavelength around 900 nanometers. Since the emission frequencies of the different quantum dots were slightly different because of their size, not all the dots contributed to the laser emission simultaneously. In fact, often only a single quantum dot would contribute at any one time.

In another demonstration of lasers based on nanostructures, NL Nanosemiconductor of Germany fabricated lasers based on quantum dots. The investigators grew ten layers of InGaAs quantum dots on a GaAs substrate. The quantum dots had relatively low gain; each layer had gain about ten times less than its quantum well counterpart. The use of multiple layers allowed the device to be customized by changing the properties of each layer. The resulting laser had an output of 750 milliwatts and operated at a wavelength of 1300 nm. It had a broadband output, with a spectral width of 75 nm. Such a broad spectral width, although different from the narrow spectral width of most lasers, could be useful for applications involving wavelength division multiplexing.

Another approach to developing lasers based on nanotechnology involves the use of nanocavities. These lasers have planar structures, like quantum wells. The nanocavities, nanometer-sized holes in the structure, create an optical **resonator** that act as a reflective mirror. The nanocavities may be formed by techniques such as **electron-beam milling** or **focused-ion-beam milling**. Such nanocavity lasers provide small, on-chip light sources. The lasers are very small and efficient. Thus, they can be integrated into photonic integrated circuits.

As an example of lasers using nanocavities, workers at Stanford University (see *Laser Focus World,* January 2006, p. 17) developed nanocavity lasers from indium gallium arsenide phosphide quantum wells. The devices were formed in silicon-on-insulator substrates. The nanocavities that formed the optical resonators had diameters in the range 180 to 230 nanometers and were spaced on 500-nanometer centers. The sizes of the cavities controlled the resonant frequency of the laser. A 9 × 9 array of the devices produced output power comparable to that of conventional **vertical cavity surface emitting lasers** (VCSEL). The devices could be used in applications such as optical telecommunication and optical image processing,

Nanowires also have potential laser applications. Scientists at Harvard University (see *Photonics Spectra,* March 2003, p. 24) developed electrically driven lasers based on nanowires. They grew single-crystal CdS nanowires with dimensions and chemical composition that were well controlled. The nanowires had diameters in the range 80 to 200 nanometers. The scientists then integrated the nanowires with p-type silicon electrodes to form a laser structure. Because of the relative simplicity of their fabrication, such structures could reduce the costs of lasers for applications such as medical diagnostics and information storage.

Another joint venture between nanotechnology and photonics involves nanorods. As mentioned earlier, researchers at Argonne National Laboratory and in France (see *Photonics Spectra,* March 2006, p. 122) fabricated nanorods with lengths in the range 50 to 300 nanometers and widths around 30 nanometers using electron beam lithography. Because the photoluminescence changed with the environment, the nanorods could be used as sensors for detecting the presence of various types of molecules. The implications of this finding are significant for detecting trace elements of a substance and will have applications in homeland security.

Nanotechnology can also produce photodetectors. In one example, workers at the National University of Singapore (see *Photonics Spectra,* June 2006, p. 124) fabricated ZnO nanowires that served as photodetectors. On silicon substrates coated with silicon nitride they deposited gold to form micrometer-sized electrodes and bond pads. They then deposited zinc on the electrodes and heated the structures to 700ºC in the presence of oxygen. The zinc first melted and then oxidized to form a web of ZnO nanowires with diameters between 20 and 40 nanometers that connected the electrodes. See Figure 15. They then used a light-emitting diode at a wavelength of 379 nanometers to illuminate the nanowires. They observed photoresponse with a **time constant** less than 0.4 milliseconds, substantially faster than that of other photodetector designs based on ZnO nanowires.

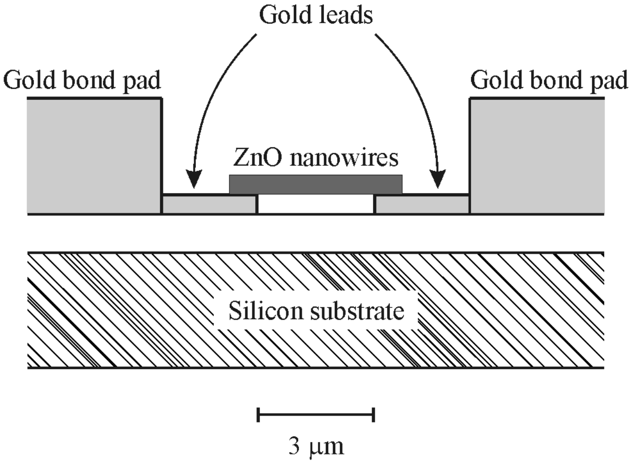


Figure 15 *Drawing of ZnO nanowire photodetector structure*

These results were significant because the processing technology used to produce the nanowires less complicated and time-consuming than that of earlier techniques used to produce ZnO nanostructures with photoresponse. Thus, these techniques offer promise for mass production of nanowire-based photodetectors.

Quantum dots are also being developed for displays. Quantum dots produce monochromatic light. By contrast, a conventional liquid crystal display (LCD) requires a fluorescent lamp that is color filtered to produce red, green, and blue pixels. See Figure 16. The liquid crystal is between two transparent electrodes and between two crossed polarizers. With no voltage applied, the polarizers cut off all the light. With voltage applied, the liquid crystal rotates the polarization so that light is transmitted through the structure. But each pixel has a filter that transmits only one color in the lamp's spectrum. Thus, in an LCD display most of the light is absorbed by the filters. Quantum dot displays will be more efficient and require less electrical power because no light is lost to filters and more light reaches the viewer.

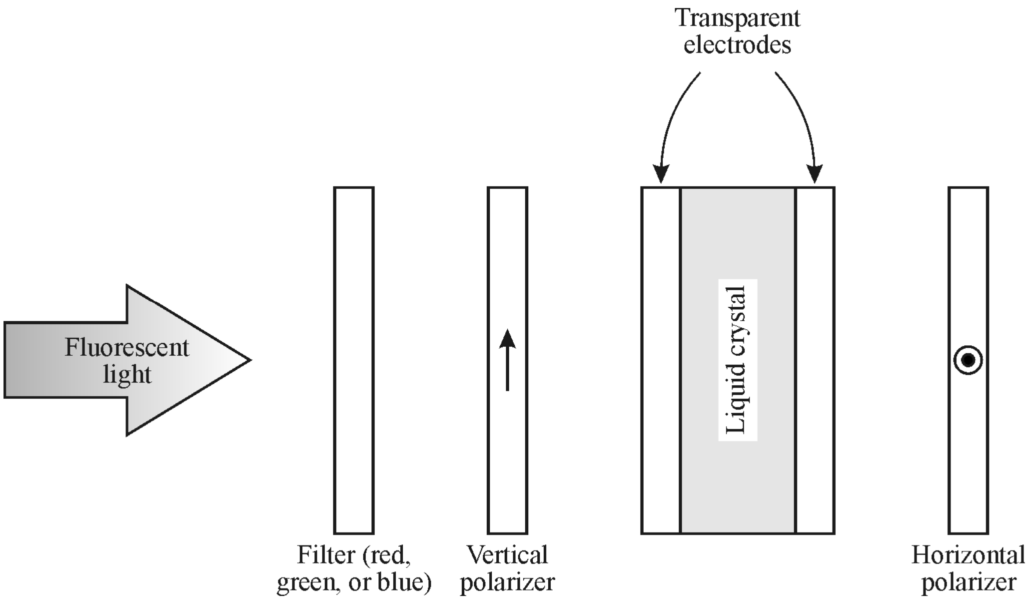


Figure 16 *Structure of one pixel of a conventional liquid crystal display*

As the size of the quantum dots varies, the color they emit changes. Also, quantum dots emit very pure colors compared to other displays such as LEDs. In LEDs and other conventional displays, the primary colors (red, green, and blue) have admixtures of other colors. With quantum dots, an emitter for a primary color emits only that color.

One example of a prototype display based on quantum dots is a monochromatic 32-by-64-pixel device that shows the potential of nanotechnology in producing improved displays. The device is the size of a cell-phone screen and about one-sixteenth of an inch thick. It has a layer of quantum dots between two semiconductor regions. The dots have diameter around 5 nanometers. The light originates from the quantum dots. See Figure 17.

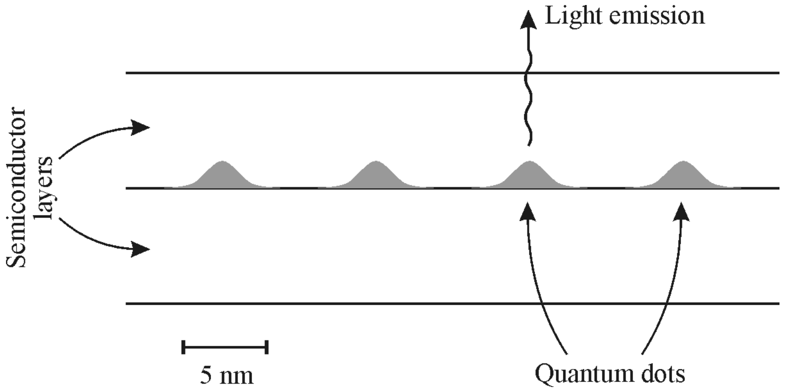


Figure 17 *Quantum dot display*

These quantum dot displays will use much less power than conventional displays and will be easier to see in sunlight. They will also offer higher contrast, since the dark regions emit no light and, thus, are fully black, whereas the dark areas on conventional displays are only gray. Thus, nanotechnology offers great promise for improved display technology.

These examples show how laser light sources and other photonics tools interact with nanotechnology to produce potentially useful optical sources, detectors, and other devices.

GLOSSARY

The following terms are given in boldface when they first appear in the text.

Ablation: Removal of material from a surface by laser pulses with short pulse duration and high peak power. The short pulse duration ensures that the laser light heats only a thin layer at the surface of the target material. There is little time for thermal conduction of energy into the bulk of the target and a large portion of the laser energy is used to supply the latent heat of vaporization for the material.

Arc discharge: A luminous electrical discharge between two electrodes.

Atomic beam: A collimated beam of neutral atoms.

Chemical vapor deposition: Deposition of films on a surface by a chemical reaction of at least two vapor species at the surface, with the result that the species are broken up and react to form a film of the desired material. The surface is generally heated so that the reaction occurs only at the surface. An example is the reaction of trimethyl gallium – $Ga(CH3)_3$ – and arsine – AsH_3 – to deposit films of GaAs.

Electron beam lithography: Lithography is a process used in semiconductor fabrication in which parts of a surface are selectively removed. In optical lithography light passes through a mask to deliver a specified pattern to a photosensitive material on top of the surface. The photosensitive material is then treated chemically to engrave the pattern of the light onto the underlying surface. Electron beam lithography replaces the light with an electron beam which is scanned under computer control.

Electron-beam milling: Removal of material from a surface by a beam of high-energy electrons.

Double heterojunction laser: A laser formed by a thin layer of active semiconductor material bordered on each side by a different material or materials. A heterojunction is a junction between two different semiconductor materials. Because in the device defined here there are two junctions between different materials, it is called a double heterojunction. The outer layers are of material with a wider band gap than the inner active layer. An example is AlAs/AlGaAs/AlAs.

Double heterostructure: A structure formed by a thin layer of semiconductor material bordered on each side by a different material or materials. See double heterojunction laser.

Focused-ion-beam milling: The use of a beam of ions to remove material from a surface. The high-energy ions are emitted from a source and ionized by a large electric field and are focused by electrostatic lenses to a spot on the surface to be machined. They remove material by sputtering atoms from the surface.

Frequency-doubled Nd:YAG laser: A laser whose active material is neodymium-doped yttrium aluminum garnet and whose basic frequency, which corresponds to a wavelength of

1064 nm, has been doubled through interaction with a nonlinear optical material, with a resulting wavelength of 532 nm.

Frequency-quadrupled Nd:YAG laser: A laser whose active material is neodymium-doped yttrium aluminum garnet and whose basic frequency, which corresponds to a wavelength of 1064 nm, has been quadrupled through interaction with a nonlinear optical material, with a resulting wavelength of 266 nm.

Frequency-tripled Nd:YAG laser: A laser whose active material is neodymium-doped yttrium aluminum garnet and whose basic frequency, which corresponds to a wavelength of 1064 nm, has been tripled through interaction with a nonlinear optical material, with a resulting wavelength of 355 nm.

Laser annealing: Semiconductor materials, like silicon, may be doped with other elements by bombardment with high-energy ions of other elements, like arsenic. This process provides a doped layer near the surface of the semiconductor, but the single-crystalline nature of the surface layer has been lost. The surface layer may be heated by a laser beam and the surface regrown to restore its crystallinity. This process is called laser annealing.

Molecular beam epitaxy: Epitaxy is the growth of crystals on a crystalline substrate. The crystalline orientation of the substrate determines the orientation of the crystal being grown. In molecular beam epitaxy, the crystal growth occurs by delivery of atoms or molecules from some material source, often by heating the source, so that atoms or molecules of the source material arrive at the substrate at a relatively low rate, usually one atom or molecule at a time. The result is a crystal with a high degree of perfection.

Nanophotonics: The multidisciplinary technology of light-matter interactions that occur within a subwavelength scale where the physical, chemical and structural nature of nanostructured materials defines and controls these interactions

Photoluminescence: The emission of light by a material which absorbs and is excited by light from another source. The emitted light has longer wavelength than the exciting light. The spectrum of the emitted light provides information about the properties of the irradiated material

Resonator: In laser physics, it is a structure, usually a reflecting structure, which contains the active laser material, and which causes the laser light to bounce back and forth so that it passes many times through the active material.

Time constant: A time that characterizes the speed with which a specified system can respond to change. Often it is quantized by the length of time in which some specified parameter has completed (1-1/e) or about 63% of the total amount that it will change when the system experiences an instantaneous change in conditions.

Two-photon excitation: Excitation of an absorbing material by simultaneous absorption of two quanta of light energy. The material is raised to a higher-lying energy state than if it had absorbed one quantum of light energy.

Two-photon photoluminescence: Photoluminescence caused by simultaneous absorption by a material of two quanta of light energy. The photoluminescence will generally be at a shorter wavelength than that caused by absorption of one quantum of light energy.

Vacuum deposition process: Deposition of a thin film of a desired material on a substrate contained in a vacuum environment. The process can take many forms, usually involving heating and evaporation of a source of the desired material at a position where the evaporated material can easily flow to the substrate. The vacuum environment allows easy flow from the source to the substrate without chemical reaction.

Vertical cavity surface emitting laser (VCSEL): A semiconductor laser diode from which the laser beam emerges from the top surface, in contrast to the more usual edge-emitting semiconductor lasers which emit their light from end surfaces. VCSELs offer the advantage of providing a larger area for beam emission.

Waveguide: A waveguide is a structure which confines and guides electromagnetic waves and allows their transmission with relatively low loss. In optics they are usually materials with high index of refraction, surrounded by a material with lower index of refraction. This structure guides optical waves by total internal reflection. A common optical waveguide is the optical fiber.

Wavelength division multiplexing: A technology which combines a number of optical signals on a single light beam by using different wavelengths to carry different signals. This permits an increase in the capacity of the light beam to transmit information.

LABORATORY

Purpose

The purpose of this laboratory is to provide the student with experience in the fabrication of nanostructures and in the characterization of their properties using photonic techniques. In many examples of the use of photonics in fabricating and measuring the properties of nanostructures, the equipment is very expensive, and for any given selection of equipment suggested for laboratory procedures, may not be readily available.

It is likely that this course will be presented in institutions that have research and development efforts in nanotechnology and that some set of sophisticated and relatively expensive equipment will be available. Thus, the equipment list and procedures presented in the following paragraphs should be regarded as suggestions which may be modified in accordance with the equipment that is available.

Equipment

As the statement directly above indicates, this equipment list is a suggested list which may be modified, depending on what equipment is actually available.

Pulsed femtosecond-duration Ti:sapphire laser
Vacuum chamber with optical window
Compressed ZnO powder
Gold-coated sapphire or silicon substrates
Source of argon gas
Heated target holder
Heated substrate holders
Lenses and lens holders

Electron microscope
Pulsed 266-nm Nd:YAG laser
Spectrophotometer

Procedures

As the statement following the purpose of the lab indicated, this set of procedures is a suggested list which may be modified, depending on what equipment is actually available.

1. Within the vacuum chamber, set up the equipment so that a substrate is near the target and facing the target. The target should be positioned so that the laser beam can reach it through the chamber window. The beam should be focused onto the target at a point where material vaporized from the target will easily deposit on the substrate. The target should be heated to around 900 C.
2. Evacuate the vacuum chamber and refill with argon gas to a pressure near one atmosphere.
3. Direct the Ti:sapphire laser at the target and vaporize material so as to deposit it on the substrate. Have the laser tuned to a wavelength near 800 nm. Allow a controlled number of pulses to strike the target. Be sure to use all appropriate laser safety procedures.
4. Repeat steps 1–3 with varying total numbers of pulses, so as to vary the total energy delivered to the target.
5. Repeat steps 1–4 with the focusing changed to vary the power per unit area striking the target. Repeat for several different focusing conditions.
6. Tune the laser to several different wavelengths, and repeat steps 1–5 for each wavelength.
7. Examine the substrates with deposited ZnO using an electron microscope. Observe whether nanowires are present. For samples with nanowires, measure the lengths and diameters of the nanowires.
8. Using samples with nanowires, irradiate them with the Nd:YAG laser light so that light emitted from the nanowires is collected by the spectrophotometer. Obtain the spectra of the photoluminescence emitted by the nanowires.

Data collection

The data collected should include the wavelength of each laser exposure, the power per unit area delivered to the target during each laser exposure and the energy per unit area delivered to the target for each laser exposure. For each substrate with nanowires, the data should include the dimensions of the nanowires. The data should also include the spectra of the photoluminescence emitted by the nanowires.

Results

The results should include a correlation of the parameters of the laser exposure (laser wavelength, power per unit area, energy per unit area) with the production of nanowires, a correlation of the nanowire dimensions (length and diameter) with the parameters of the laser exposure, and a correlation of the characteristics of the photoluminescence (at least the position of the peak of the spectrum) with both the conditions of laser irradiation and the dimensions of the nanowires.

Questions

1. What are the best parameters of laser irradiation (laser wavelength, power per unit area, and energy per unit area) for production of nanowires? Why is this so?
2. What is the effect of the parameters of the laser irradiation on the dimensions of the nanowires? Why is this so?
3. What is the effect of the nanowire dimensions on the photoluminescence of the nanowires? Why?

EXERCISES

1. Define *nanophotonics*.
2. Define *quantum dots*.
3. Define *nanowires*.
4. Define *quantum wells*.
5. An electron in a nanowire with a diameter of 40 nanometers has a velocity of 2.5×10^5 cm/sec. What is its de Broglie wavelength? Will it be confined within the wire?
6. Provide at least two examples for the use of photonics in fabrication that are substantially the same as those in the section entitled "Use of Photonics for Fabrication of Nanostructures."
7. Provide at least two examples for the use of photonics in measurement and characterization that are substantially the same as those in the section entitled "*Photonics for Characterization*."
8. Provide at least two examples about how photonic technology and nanotechnology combine to provide useful applications for nanophotonics. The examples should be substantially similar to those in the section entitled "*Photonics and Nanotechnology Joint Ventures*."
9. Define *pulsed laser ablation* and describe how it is used to make nanostructures.
10. Name some of the lasers that have been used in fabricating or characterizing nanostructures.

APPLETS

Quantum Mechanics from Wikipedia, the free encyclopedia
http://en.wikipedia.org/wiki/Quantum.mechanics

QD Vision Manufactures World's First Quantum-Dot Display?
http://www.eeproductcenter.com/showPressRelease.jhtml?articleID=487906

REFERENCES

Kincade, K., Global community charts a course for nanophotonics, *Laser Focus World,* August 2005, p. 72.