Laser Applications

Lasers have become so much a part of daily life that many people may not realize how ubiquitous they are. Every home with a CD player has a laser; hardware stores are now selling a wide variety of laser levels; many, if not most, computers, printers, and copiers are using laser technology. Laser applications are so numerous that it would be fruitless to try to list them all; however; one can give some illustrative examples of how lasers are used today.

INDUSTRIAL APPLICATIONS

High-power lasers have long been used for cutting and welding materials. Today the frames of automobiles are assembled using laser welding robots, complex cardboard boxes are made with laser-cut dies, and lasers are routinely used to engrave numbers and codes on a wide variety of products. Some less well-known applications include three-dimensional stereolithography and photolithography.

Three-Dimensional Stereolithography

Often a designer, having created a complex part on a CAD machine, needs to make a prototype component to check out the dimensions and fit. In many cases, it is not necessary for the prototype to be made of the specified (final) material for this checking step, but having a part to check quickly is important. This is where rapid prototyping, i.e., three-dimensional stereolithography, comes in. The stereolithography machine consists of a bath of liquid photopolymer, an ultraviolet laser, beam-handling optics, and computer control (see figure 36.30). When the laser beam is absorbed in the photopolymer, the polymer solidifies at the focal point of the beam. The component design is fed directly from the CAD program to the stereolithography computer. The laser is scanned through the polymer, creating, layer by layer, a solid, three-dimensional model of the part.

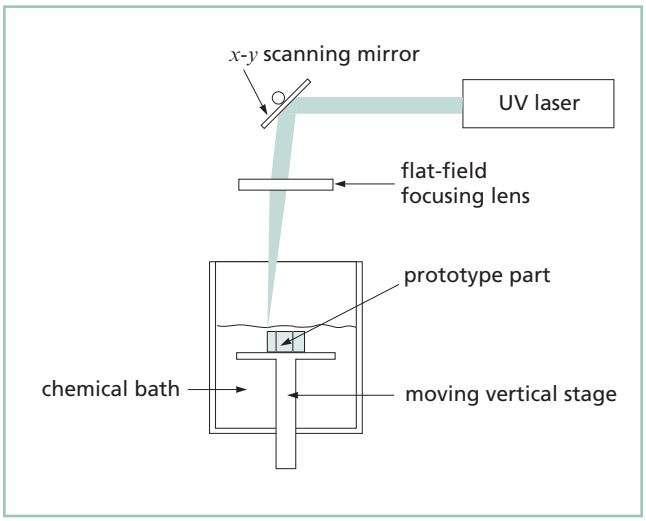

Figure 36.30 **A laser stereolithography system for rapid prototyping of three-dimensional parts**

Photolithography

Lasers are used throughout the manufacture of semiconductor devices, but nowhere are they more important than in exposing photoresist through the masks used for creating the circuits themselves. Originally, ultraviolet mercury lamps were used as the light sources to expose the photoresist, but as features became smaller and more complex devices were put on a single wafer, the mercury lamp's wavelengths were too long to create the features. Approximately ten years ago, manufactures started to switch to ultraviolet lasers operating at approximately 300 nm to expose the photoresist. Manufacturers are now using wavelengths as short as 193 nm to get the resolution needed for today's semiconductor integrated circuit applications.

Marking and Scribing

Lasers are used extensively in production to apply indelible, human and machine-readable marks and codes to a wide variety of products and packaging. Typical applications include marking semiconductor wafers for identification and lot control, removing the black overlay on numeric display pads, engraving gift items, and scribing solar cells and semiconductor wafers.

The basic marking system consists of a laser, a scanning head, a flat-field focusing lens, and computer control. The computer turns the laser beam on and off (either directly of through a modulator) as it is scanned over the surface to make the mark. Depending upon the application, scanning may occur in a raster pattern (typical for making dot-matrix marks) or in a cursive pattern, with the beam creating letters one at a time. The mark itself results either from ablation of the surface of the material, or by a photochemically induced change in the color of the material. Another marking technique, used with high-energy pulsed CO_2 and excimer lasers, is to shine the light through a mask containing the marking pattern and focusing the resulting image onto the marking surface.

Laser scribing is similar to laser marking, except that the scan pattern is typically rectilinear, and the goal is to create microscoring along the scan lines so that the substrate can be easily broken apart.

A wide variety of materials, including metal, wood, glass, silicon, and rubber, are amenable to laser marking and scribing. Each material has different absorption and thermal characteristic, and some even have directional preferences due to crystalline structure. Consequently, the type of laser used depends, to some extent, on the material to be marked (e.g., glass transmits the 1.06 μm output from a YAG laser but absorbs the 10.6 μm output from a CO_2 laser). Other considerations are the size of the pattern, the speed of the scan, cosmetic quality, and cost.

Currently, most volume marking applications are performed with lamp-pumped YAG-based pulsed or Q-switched lasers. Pulsed and cw CO_2 lasers make up the bulk of the remainder. However, DPSS and fiber lasers are encroaching on this field owing to their higher reliability and lower operating cost. Because of their very short

wavelengths (100–300 nm), excimer lasers are used in applications requiring extremely high resolution, or whose materials would termally damage at longer wavelengths.

Noncontact measurement

There are many types of laser-based noncontact measurement techniques in use today including scatter measurement, polarimetry and ellipsometry, and interferometric measurement.

Scatter Measurement: In the semiconductor industry, patterns of material are deposited on a wafer substrate using photolithographic processes. Defects on the wafer can result in poor reliability, disconnects in circuitry, or complete circuit failure. Consequently manufacturers need to map the wafer to determine the defects' location and size so that they can either be eliminated or avoided. To do this, they scan the wafer with a laser and measure backscatter with a very sensitive photodetector array.

Lasers used in this application have to have excellent pointing stability, constant wavelength and power stability to calculate the correct size of the defects through complex algorithms, and low noise so the little scatter the defect makes can be distinguished from the background laser light. Blue 488-nm argon ion lasers have been the laser of choice for many years. However; as lithography has shifted to shorter and shorter ultraviolet wavelengths, however, we are beginning to see the metrologic techniques for wafer defect measurement also moving to shorter wavelengths. Ultraviolet diode and solid-state lasers are likely to replace the ion laser in the next generation of instruments.

Polarimetry and Ellipsometry: The optical phase thickness of a thin film can be carefully measured using polarimetry or ellipsometry. A beam of known polarization and phase state enters the thin film layer at an angle. The thin film has a known index of refraction. The measured phase change in the reflected beam is then correlated to an optical phase thickness for that layer using the known index of refraction. This technique can also be used with a thicker transparent media, such as glass, where changes in the polarization and phase state of a beam scanned across the substrate indicate variations in index of refraction due to inclusions or stress-induced birefringence. The most common lasers used in these applications are violet, red and near infrared single-emitter laser diodes and mid-visible diode-pumped solid-state lasers owing to their cw output, low noise, and compact sizes.

Interferometric Measurement: Interferometric measurement can be used for high-resolution position measurement as well as for measuring waveform deformation of optical beams as they pass through a component or system.

The technique uses the wave periodicity of the light beam as a very fine ruler. The position of an object in the path of the beam is computed from the phase of the light reflected from it. Interference between the object beam and a reference beam provides measureable intensity variations which yield this phase information. Distance and velocity measurement can be performed for moving objects as long as the fringe-recording mechanism is paced with it.

Typical applications of this technique include positioning of masks for the lithography process, mirror distance correlation within an FTIR spectrometer, optical feedback in many high-resolution positioning systems, and determining the alignment and flatness of hard disk drive heads.

For applications requiring measurement over a long path length, lasers with a single longitudinal mode and long coherence length are often required. In these cases, frequency-stabilized helium neon lasers or a solid-state lasers with frequency selective elements are used.

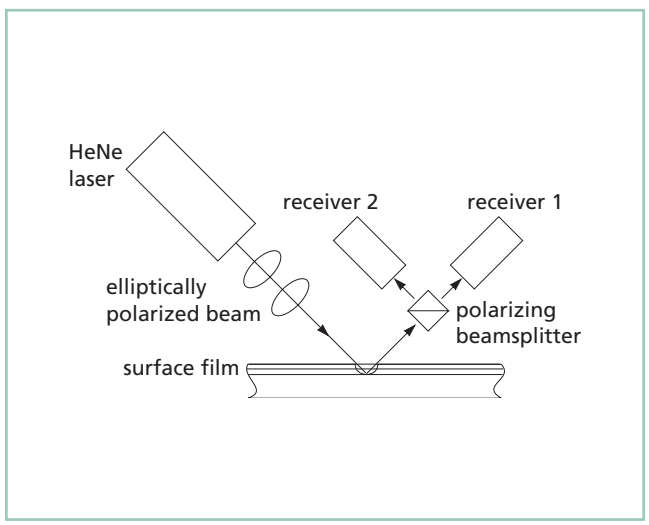

Figure 36.31 **Surface film thickness measurement**

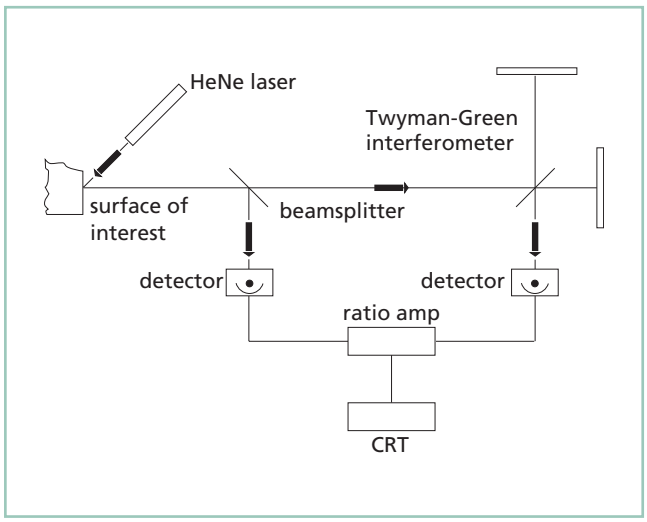

Figure 36.32 **Interferometric measurement**

SCIENTIFIC APPLICATIONS

Lasers are used extensively in the scientific laboratory for a wide variety of spectroscopic and analytic tasks. Two interesting examples are confocal scanning microscopy and time-resolved spectroscopy.

Time-resolved spectroscopy

Time-resolved spectroscopy is a technique used to observe phenomena that occur on a very short time scale. This technique has been used extensively to understand biological processes such a photosynthesis, which occur in picoseconds (10^{-12} seconds) or less. A fluorescing sample is excited by a laser whose pulse length is much shorter than the time duration of the effect being observed. Then, using conventional fluorescence spectroscopy measurement techniques, the time domain of the fluorescence decay process can be analyzed. Because of the speed of the processes, mode-locked lasers are used as the exciting source, often with pulse compression schemes, to generate pulses of the femtosecond (10^{-15} sec) time scale, very much faster than can be generated by electronic circuitry.

Confocal scanning microscopy

Scanning microscopy is used to build up a three-dimensional image of a biological sample. In standard light microscopy, a relatively large volume of the sample is illuminated, and the resultant light gathered by the objective lens comes not only from the plane in focus itself, but also from below and above the focal plane. This results in an image that contains not only the in-focus light, but also the haze or blur resulting from the light from the out-of-focus planes. The basic principle of confocal microscopy is to eliminate the out-of-focus light, thus producing a very accurate, sharp, and high-resolution image. A schematic of a confocal microscope is shown in figure 36.33. A visible laser is used as the light source to produce a distinct and spatially constrained point source of illumination. This light is then focused on the sample. A pinhole is placed in front of the detector at an optical distance that is exactly the same as the optical distance between the focus point and the illuminating source point (the confocal condition). Consequently, only the light generated at the illuminating point will, upon reflection or scattering from the sample, pass through the pinhole in front of the detector; out-of-focus light will be blocked by the pinhole. The signal from the detector is then digitized and passed to a computer. The complete image is digitally built up by scanning the sample in the x and y directions.

TIR and Fluorescence Correlation Spectroscopy

Fluorescence correlation spectroscopy measures the variation in fluorescence emission at the molecular level as fluorochromes travel through a defined field. The data can then used to determine binding and fusion constants for various molecular interactions. Because the measured volumes are so small, measurements are typically made using single-photon or two-photon confocal microscopy techniques (see above). In many cases, the region of interest for fluorescence correlation spectroscopy is the first 100 to 200 nm of the sample's surface. However, the excitation depth (vertical resolution) for conventional confocal spectroscopy is 1 to 1.5 μm, leading to low signal-to-noise ratios and diminished accuracy.

One means of reducing the excitation volume is to use total internal reflection (TIR) techniques. If a laser beam, passing through a high index material (e.g., glass at $n\cong1.5$) strikes an interface with a lower index sample material (e.g., an aqueous solution at $n\cong1.3$) at an oblique angle, there is an angle of incidence (the *critical angle*) at which all of the light will be completely reflected at the interface, and none will pass into the lower-index material. The critical angle is given by

$$\theta_c = \arcsin\left(\frac{n_t}{n_i}\right) \qquad (36.26)$$

where n_t is the index of the transmitting (lower index) material and n_i of the incident material.

Because the beam is completely reflected at the interface, there is no energy flux across the interface; there is, however, an electromagnetic field generated in the lower index material, determined by the boundary conditions on the electric and magnetic fields at the interface. This transmitted wave is evanescent, propagating along the surface of the interface, but decaying in intensity exponentially with depth, limiting excitation to a few hundred nanometers—five to ten times better resolution than with confocal techniques alone.

Various techniques have been used to obtain TIR. Most commonly, the laser beam is brought in through a prism, as shown in figure 36.34. Another technique is to bring the beam in through

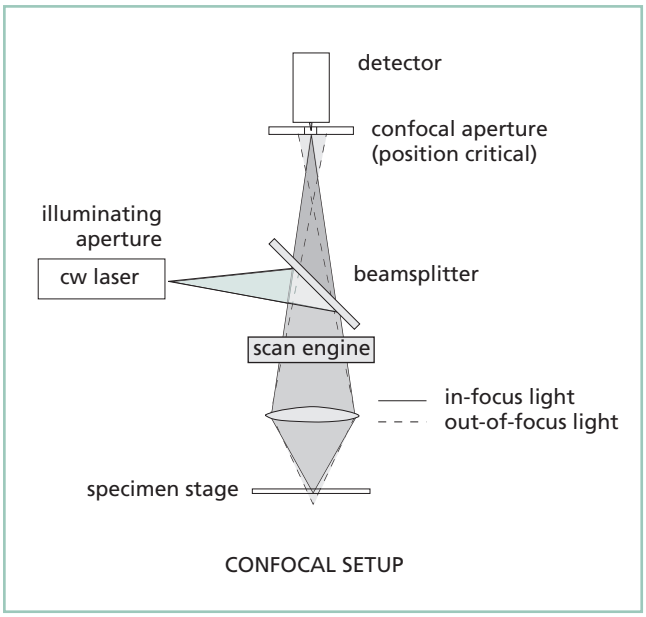

Figure 36.33 **Optical schematic of a confocal microscope**

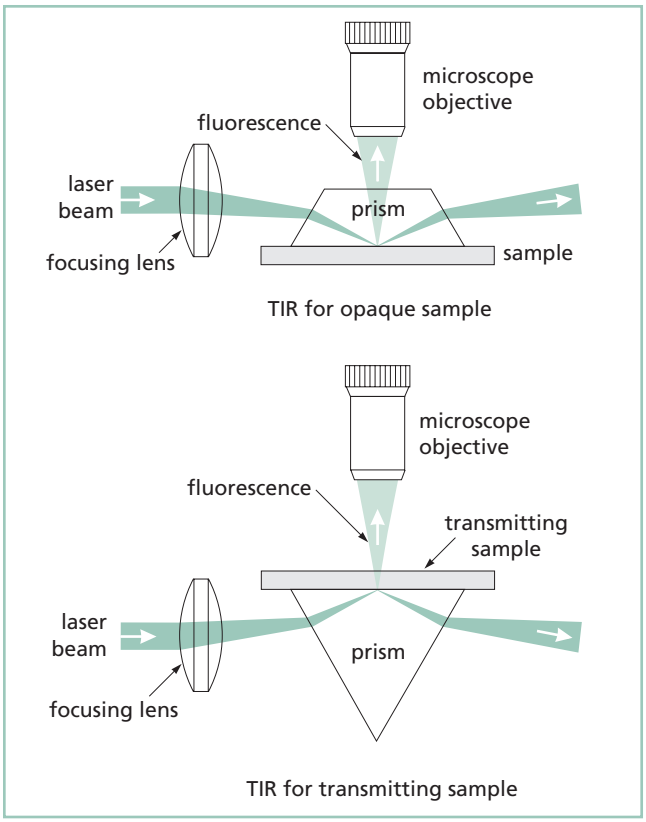

Figure 36.34 **An example of TIR spectroscopy**

the steeply curved edge of the observing microscope itself, and then filtering out the returning beam with a dichroic mirror.

Microarray scanning

In DNA research, a microarray is a matrix of individual DNA molecules attached, in ordered sets of known sequence, to a substrate which is approximately the size of a microscope slide. A single array can contain thousands of molecules each tagged with a specific fluorochrome. The array is then put into a microarray reader where each individual site of the matrix is individually probed by a variety of laser wavelengths at, or near, the excitation band of specific protein tags. The resulting fluorescence is measured and the fluorescence, position, and sequence data are stored in a computer database for later analysis.

Microarrays and microarray readers have had a dramatic impact on the speed by which data can be taken. Previously experiments were conducted one or two molecules at a time; preparation and setting up could take hours. With microarray readers, the raw data for analysis of thousands of molecules can be taken in minutes.

The main driver for microarrays is the pharmaceutical industry. If one can identify the differences in the way genes are expressed in a healthy organ and in a diseased organ, and then determine the genes and associated proteins that are part of the disease process, it may be possible to synthesize a drug that would interact with the proteins and cure or reduce the effect of the disease.

The optical system for a typical microarray scanner is shown in figure 36.35. The beam from a laser is focused onto a well (molecule) on the molecular matrix. If the appropriate fluorescent tag is present, the resulting fluorescence is measured by a detector. A filter in front of the detector separates the laser wavelength from the fluorescence signal. The laser beam is then moved to the next well.

Today's microarray scanner systems use two or more cw lasers, each with a different wavelength. Output power typically ranges from 10 to 50 mW, a power level that allows scanning without damaging or changing the material under test. Laser pointing stability is important as the microarray wells are quite small and repeatability is needed to relocate cells. Power stability and low noise are also extremely important due to the small sample size and the resulting weak fluorescence signal.

The most common lasers in use today for excitation are the blue solid-state (473–488 nm), green solid-state (532 nm) and red diode (650–690 nm) lasers. Solid-state and semiconductor laser technology is chosen primarily for its compact size, reliability, and power efficiency. Other wavelengths, including violet (405 nm) and ultraviolet (375 nm) from diode lasers, are currently being tested for application in microarray-reading applications.

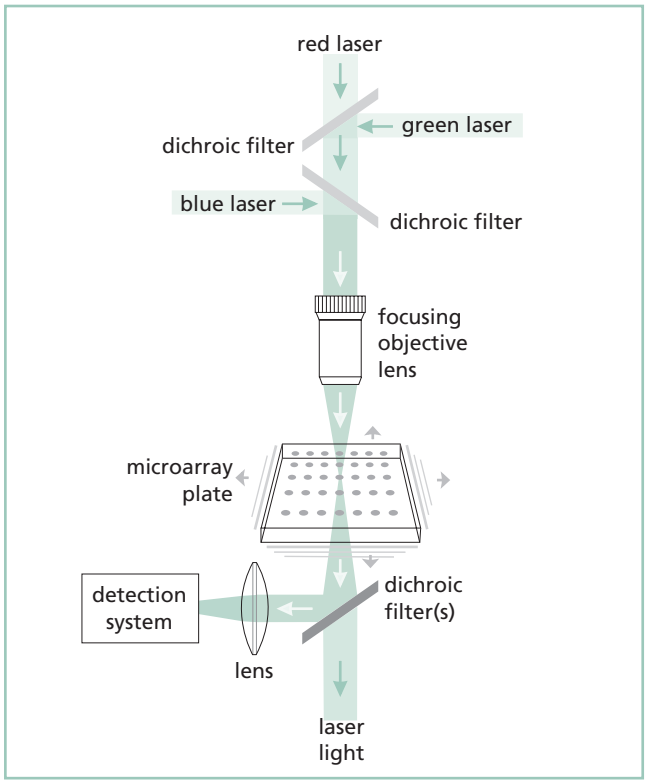

Figure 36.35 **Microarray scanning**

CLINICAL AND MEDICAL APPLICATIONS

One of the earliest applications of lasers in medicine was photocoagulation, using an argon-ion laser to seal off ruptured blood vessels on the retina of the eye. The laser beam passed through the lens and vitreous humor in the eye and focused on the retina, creating scar tissue that effectively sealed the rupture and staunched the bleeding. Today, lasers are used extensively in analytical instrumentation, ophthalmology, cellular sorting, and of course, to correct vision.

Many types of lasers are used in clinical applications including CO_2, solid state, and diode lasers, as well as array of gas lasers covering the spectrum from the ultraviolet to the infrared.

Flow cytometry

Flow cytometry is a technique used for measuring single cells. Not only is it a key research tool for cancer and immunoassay disease research, but it is also used in the food industry for monitoring natural beverage drinks for bacterial content or other disease-causing microbes.

In a basic cytometer, the cells flow, one at a time, through a capillary or flow cell where they are exposed to a focused beam of laser light (see figure 36.36). The cell then scatters the light energy onto a detector or array of detectors. The pattern and intensity of the scattered energy helps to determine the cell size, and shape. In many cases the cells are tagged with a variety of fluorochromes designed to selectively adhere to cells or cell components with specific characteristics. When exposed to the laser light, only those with the tag fluoresce. This is used in many systems to assist with separation or sorting of cells or cellular components.

The most popular lasers used in flow cytometry are the 488-nm (blue) argon-ion laser and the 632-nm (red) and 594-nm (yellow) HeNe lasers. However, new violet, blue and red diode lasers and a variety of new DPSS lasers are entering the field.

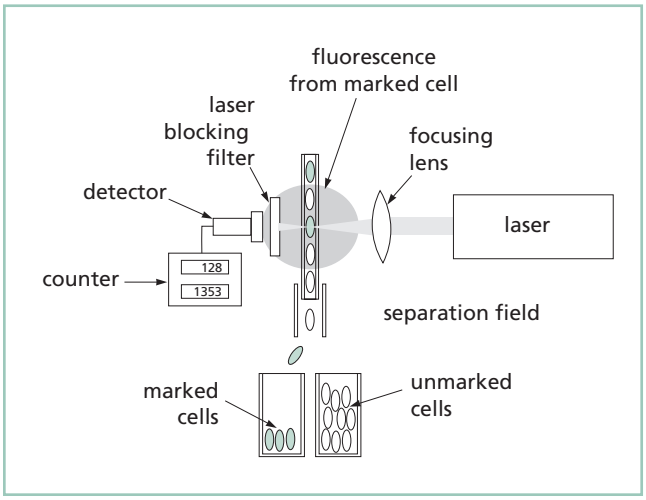

Figure 36.36 **Schematic of a laser cell sorter**

Surgical Applications

Lasers are used in a variety of surgical and dental procedures from cutting tissue, vaporizing tumors, removing tattoos, removing plaque, removing cavities, removing hair and follicles, resurfacing of skin and of course, correcting vision. In many ways, medical applications are like materials processing applications. In some cases material is ablated. In others tissue is cut or welded, and in yet others, photochemical changes are caused in blood vessels to encourage shrinkage and absorption. Understanding tissue absorption characteristics and reaction to wavelength and power are key.

Ultraviolet excimer lasers are used for vision correction because they can ablate material from the lens of the eye without causing thermal damage which could blur vision or make the lens opaque. Ruby lasers are used for tattoo removal because many of the dyes break down when exposed to 694-nm radiation, yet the skin tissue is left undamaged.

Cosmetic treatment of wrinkles, moles, warts, and discolorations (birth marks) is often accomplished with near infrared and infrared lasers. These procedures are often assisted by topical or injected photosensitive chemicals that assist with selective absorption at specific sites.

Lasers are also used to treat macular degeneration, an overgrowth of veins and scar tissue in the retinal region, a condition associated with advancing age. In this procedure, the patient is injected with a selective dye, which enhances the absorption of laser light by the blood in the blood vessels. When the blood vessels absorb laser energy, they wither in size, uncovering the active retina. A multiwatt green DPSS laser is most commonly used for this application because the green wavelength is not absorbed by the lens or aqueous portion of the eye, which allows the laser to affect only the targeted veins.