Technology Brief 15: Night-Vision Imaging

Either in movies, on television, or when playing video games, most people have seen images taken through night-vision goggles or imaging systems. These are usually monochromatic (single color), green-tinted images of indoor or nighttime environments, such as those shown in Figs. TF15-1 and TF15-2. Historically, two approaches have been pursued to “see in the dark;” one that relies on measuring self-emitted thermal energy by the scene and another that focuses on intensifying the light reflected by the scene when illuminated by very weak sources, such as the moon or the stars. We will explore each of the two approaches briefly.

![Figure TF15-1: A night-vision image taken with military-grade goggles.](image1)

![Figure TF15-2: A full-color thermal-infrared image of a soldier.](image2)
The visible spectrum extends from the violet (wavelength $\lambda \approx 0.38 \mu m$) to the red ($\approx 0.78 \mu m$). As noted in Technology Brief 8 on page 158, the spectral region next to the visible is the infrared (IR), and it is subdivided into the near-IR ($\approx 0.7$ to $1.3 \mu m$), mid-IR ($1.3$ to $3 \mu m$), and thermal-IR ($3$ to $30 \mu m$). Infrared waves cannot be perceived by humans, because our eyes are not sensitive to EM waves outside of the visible spectrum. In the visible spectrum, we see or image a scene by detecting the light reflected by it, but in the thermal-IR region, we image a scene without an external source of energy, because the scene itself is the source. All material media emit electromagnetic energy all of the time—with hotter objects emitting more than cooler objects. The amount of energy emitted by an object and the shape of its emission spectrum depend on the object’s temperature and its material properties. Most of the emitted energy occurs over a relatively narrow spectral range, as illustrated in Fig. TF15-3, which is centered around a peak value that is highly temperature dependent. For a high-temperature object like the sun ($\approx 6000^\circ C$), the peak value occurs at about $0.5 \mu m$ (red-orange color), whereas for a terrestrial object, the peak value occurs in the thermal-IR region.

Through a combination of lenses and a 2-D array of infrared detectors, the energy emitted by a scene can be focused onto the array, thereby generating an image of the scene. The images sometimes are displayed with a rainbow coloring—with hotter objects displayed in red and cooler objects in blue.

In the near- and mid-IR regions, the imaging process is based on reflection—just as in the visible. Interestingly, the sensor chips used in commercial digital cameras are sensitive not only to visible light but to near-IR energy as well. To avoid image blur caused by the IR energy, the camera lens usually is coated with an IR-blocking film that filters out the IR energy but passes visible light with near-perfect transmission. TV remote controls use near-IR signals to

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**Figure TF15-3**: Spectra of power density emitted by ideal blackbodies at $0^\circ C$, $300^\circ C$, and $6000^\circ C$. 

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communicate with TV sets, so if an inexpensive digital camera with no IR-blocking coating is used to image an activated TV remote control in the dark, the image will show a bright spot at the tip of the remote control. Some cameras are now making use of this effect to offer IR-based night-vision recording. These cameras emit IR energy from LEDs mounted near the lens, so upon reflection by a nighttime scene, the digital camera is able to record an image “in the dark.”

**Image Intensifier**

A second approach to nighttime imaging is to build sensors with much greater detection sensitivity than the human eye. Such sensors are called *image intensifiers*. Greater sensitivity means that fewer photons are required in order to detect and register an input signal against the random “noise” in the receiver (or the brain in the case of vision). Some animals can see in the dark (but not in total darkness) because their eye receptors and neural networks require fewer numbers of photons than humans to generate an image under darker conditions. *Image intensifiers* work by a simple principle (Fig. TF15-4). Incident photons (of which there are relatively few in a dark scene) are focused through lenses and onto a thin plate of *gallium arsenide* material. This material emits one electron every time a photon hits it. Importantly, these electrons are emitted at the locations where the photons hit the plate, preserving the shape of the light image. These photoelectrons then are accelerated by a high voltage (∼5000 V) onto a *microchannel plate* (*MCP*). The MCP is a plate that emits 10,000 new electrons every time one electron impacts its surface. In essence, it is an amplifier with a current gain of 10,000. These secondary electrons again are accelerated—this time onto phosphors that glow when impacted with electrons. This works on the same principle as the cathode ray tube (see Technology Brief 6 on page 106). The phosphors are arranged in arrays and form pixels on a display, allowing the image to be seen by the naked eye.

![Figure TF15-4: Schematic of image intensifier assembly and operation.](image-url)
Technology Brief 20: Carbon Nanotubes

Molecules made exclusively from carbon atoms can have very remarkable properties. Diamond, for example, occurs when carbon atoms are arranged in a specific, repeating three-dimensional arrangement (Fig. TF20-1(a)). This particular arrangement leads to a material known for its hardness, light dispersion (i.e., brilliance) and durability. Carbon atoms can be arranged into various other configurations, including flat hexagonal sheets known as graphene sheets (Fig. TF20-1(b)) and closed spheres known as buckyballs (Fig. TF20-1(c)), so named because they resemble the geodesic dome architecture developed by Buckminster Fuller. Carbon atoms can also be arranged into long tubes, called carbon nanotubes (CNTs) with single or multiple concentric walls (Fig. TF20-1(d)). Nanotubes can have radii ranging from 0.4 nm to tens of nanometers and may be several millimeters in length. Each of these arrangements leads to materials with interesting and still not entirely understood properties.

Carbon nanotubes have recently generated much interest in the academic and commercial worlds due to their unique mechanical, electrical, chemical and thermal properties. When pulled along the axis of the tube (i.e., under tensile load), carbon nanotubes are among the strongest materials, about 5 times stiffer than steel! Nanotubes can also be added to polymers to produce composite materials with great strength and durability; several companies are exploring such materials for aerospace, automotive and armor applications. For example, highly resistant automobile collision bumpers made from carbon nanotube composites recently went into production.
Nanotubes can also be modified to alter their electrical properties; they can be made conductive, like metals, or semiconductive, like silicon, via chemical modifications. As conductors, nanotubes can have theoretical current densities along the axis of the nanotube that are 1000 times higher than that of metals. Intensive research and development activities are carried out by numerous institutions aimed at building integrated circuits from combinations of conductive and semiconductive nanotubes. Carbon nanotubes also form the basis of several emerging sensor technologies (Fig. TF20-2).

By exploiting both the mechanical and electrical properties of nanotubes, it has been possible to develop new types of devices and circuits. One such example is shown in Fig. TF20-3, which displays a high-resolution image of the smallest radio transmitter built to date. It consists of a single, nanoscale carbon tube that vibrates mechanically at radio frequencies when placed in a small vacuum chamber. Amazingly, this single nanotube acts as a complete radio, including the antenna, tuner, amplifier, and demodulator!

Figure TF20-2: Flexible hydrogen sensors can be made by transferring carbon nanotubes onto plastic substrates, then adding hydrogen-sensitive palladium nanoparticles to the ends. (Courtesy of Argonne National Laboratory.)
Carbon nanotubes may also enable more efficient organic photovoltaic solar cells. Organic photovoltaic devices (OPVs) are made from thin-films of organic semiconductors (as opposed to semiconductors made of silicon or gallium arsenide). Unlike silicon solar cells, these devices can be fabricated at low relative cost into large, flexible sheets. However, current OPVs are inherently poor in terms of how efficiently they can convert photons into electrons. Because carbon nanotubes can be made into good conductors, researchers have begun adding them to the OVP polymer mix to increase the internal conduction within the photoactive polymer so as to increase the photon-to-electron conversion efficiency. Nanotubes have also been proposed as a less expensive and higher conduction material for OVP electrodes.

Figure TF20-3: A complete radio, including antenna, tuner, amplifier, and demodulator, can be built from a single carbon nanotube suspended from an electrode inside a vacuum chamber (bottom image shows the single nanotube when stationary and when oscillating during operation). (Courtesy Alex Zettl Research Group, Lawrence Berkeley National Laboratory and University of California at Berkeley.)
Although invented in 1956, the hard disk drive (HDD) arguably is still the most commonly used data-storage device among non-volatile storage media available today. It is the availability of vast amounts of relatively inexpensive hard-drive space that has made search engines, webmail, and online games possible. Over the past 40 years, improvements in HDD technology have led to huge increases in storage density, which are simultaneous with the significant reduction in physical size. The term hard disk or hard drive evolved from common usage as a means to distinguish these devices from flexible (floppy) disk drives.

HDD Operation

Hard drives make use of magnetic material to read and write data. A non-magnetic disc ranging in diameter from 36 to 146 mm is coated with a thin film of magnetic material, such as an iron or cobalt alloy. When a strong magnetic field is applied across a small area of the disc, it causes the atoms in that area to align along the orientation of the field, providing the mechanism for writing bits of data onto the disc (Fig. TF21-1). Conversely, by detecting the aligned field, data can be read back from the disc. The hard drive is equipped with an arm that can be moved across the surface of the disc (Fig. TF21-2), and the disc itself is spun around to make all of the magnetic surface accessible to the writing or reading heads. Because writing onto or reading from the magnetized surface can be performed very rapidly (fraction of a microsecond), hard drives are spun at very high speeds (5000 to 15000 rpm) when directed to record or retrieve information. Amazingly, hard-drive heads usually hover at a height of about 25 nm above the surface of the magnetic disc while the disc is spinning at such high speeds! The extremely small gap between the head and the disc is maintained by having the head “ride” on a thin cushion of air trapped between the head and the surface of the spinning disc. To prevent accidental scratches, the disc is coated with carbon- or Teflon-like materials.

Hard drives are packaged carefully to prevent dust and other airborne particles from interfering with the drive’s operation. In combination with the air motion caused by the spinning disc, a very fine air filter is used to keep dust out while maintaining the air pressure necessary to cushion the spinning discs. Hard drives intended for operation at high altitudes (or low air pressure) are sealed hermetically so as to make them airtite.
Technological Advances

Early hard drives performed read and write operations by using an inductor coil placed at the tip of the head. When electric current is made to flow through the coil, the coil induces a magnetic field which in turn aligns the atoms of the magnetic material (i.e., a write operation). The same coil also is used to detect the presence of aligned atoms, thereby providing the read operation. The many major developments that shaped the evolution of read/write heads over the past 50 years have introduced two major differences between the modern hard-drive heads and the original models. Instead of using the same head for both reading and writing, separate heads are now used for the two operations. Furthermore, the writing operation is now carried out with a lithographically defined thin-film head (see Technology Brief 7 on page 135), thereby reducing the feature size of the head by several orders of magnitude. The feature size is the area occupied by a single bit on the disc surface, which is determined in part by the size of the write head. Decreasing feature size leads to increased recording density. The read operation—housed separately next to the write head—uses a magnetoresistive material whose resistance changes when exposed to a magnetic field—even when the field intensity is exceedingly small. In modern hard drives, high magnetoresistive sensitivities are realized through the application of either the giant magnetoresistance (GMR) phenomena or the tunneling magnetoresistance (TMR) effect exhibited by certain materials. The 2007 Nobel prize in physics was awarded to Albert Fert and Peter Grünberg for their discovery of GMR. A consequence of the extremely small size of the magnetic bits (each bit in a 100-Gb/in² disc is about 40-nm long) is that temperature variations can lead to loss of information over time. One method developed to combat this issue is to use two magnetic layers separated by a thin (~ 1 nm) insulator, which increases the stability of the stored bit. Another recent innovation that is already in production involves the use of perpendicular magnetic recording (PMR) as illustrated in Fig. TF21-1. PMR makes it possible to align bits more compactly next to each other. It is estimated that PMR will enable densities on the order of 1000 Gb/in² in the next decade.

Figure TF21-2: Close-up of a disassembled hard drive showing the magnetic discs mounted on a spindle and an actuator arm. The head sits at the end of the arm and performs the read/write operations as the disc spins.