CATHODE RAY TUBES

TELEVISION PICTURE TUBES

The cathode-ray tube (CRT) is best known as the display for television and computer monitors. It is a vacuum tube in which electrons move in a beam. Figure 1 shows a cutaway diagram of the interior of a CRT for color television display. Inside the tube, the large, nearly flat, area, called the screen, is covered with phosphor materials that convert the electron-beam energy into light. The beam is rapidly swept over this area, and its intensity is varied, so that a display appears to the viewer, who visually integrates the light. When the display is rapidly changed, the viewer sees motion, as in television.

The CRT is described in this article. In particular, the parts of the CRT, such as the cathode, electron gun, phosphors, deflection system, and shadow mask, are explained. The electrons come from the negative electrode, called the cathode, and form a beam, or ray, inside a vacuum tube, leading to the name cathode-ray tube. Much interesting physics is associated with the beam formation and direction and its conversion to light, as well as with the manufacture of CRTs. CRTs have been used in other display applications, such as oscilloscopes, radar, and photorecording tubes. Some history of the tube, which extends during the last century, is presented.

THE CRT

Figure 1 shows a cutaway diagram of a CRT. The CRT is cut vertically in this diagram to show half the interior. The thick outline is the glass edge. The interior is a vacuum. The external surface of the tube at the right is the portion generally seen by the viewer. The light seen by the viewer originates in the phosphors on the inner surface, called the *screen*. These phosphors are shown by the colored lines. The phosphors are white powders and the color is added to show the color of the light emitted when they are struck by the electron beam. The electron beam is shown by the white band from the neck at the rear of the CRT. For color, three electron beams, shown by red, green, and blue discs, are used. These discs show the color of the light emitted by the phosphor struck by the electron beam. The electron beam comes from the electron gun inside the neck. The electron gun, a very critical part of the CRT, is small compared with the CRT; only its largest parts can be seen in Fig. 1. Pins at the rear of the CRT extend through the glass and provide most of the electrical potentials needed by the gun. Outside the neck and in front of the electron gun, the deflection yoke is used to deflect the electron beams to points on the screen. It is inactive when the beams go to the screen center, as shown in Fig. 1. The blue trapezoidal cross sections represent the ferrite core, and the red surfaces represent the wires of the coil. Red is a typical color of the insulator on the wires. Electric currents in these coils create magnetic fields in the interior of the CRT. The moving electrons in the beam feel the Lorentz force when passing through these fields, and they are deflected by it. The connector at the bottom of the yoke brings in these currents. The circular inset in Fig. 1 shows details of the shadow mask. This mask is the large metal plate immediately behind the phosphor screen. It is supported by the L-shaped frame, and the frame is secured to pins embedded in the glass. The tapered metal structure attached behind the frame is the magnetic shield, needed to exclude the earth's magnetic field. The metal band outside the tube is the implosion band, needed to prevent the earth's atmosphere from violently collapsing the tube. A support for mounting the CRT in a cabinet can be seen near this band at the corner of the CRT. The round structures on the CRT funnel exterior are parts of the anode button. It transmits the highest electrical potential needed for the gun. The inside surface of the CRT is electrically conducting, and the top of the electron gun touches this surface. If this potential were brought in through the socket, arcs to the other pins of the socket would destroy the tube. A wire extends from the end of the electron gun, seen at the bottom of Fig. 1, that has a pan at its other end. This pan contains the getter material.

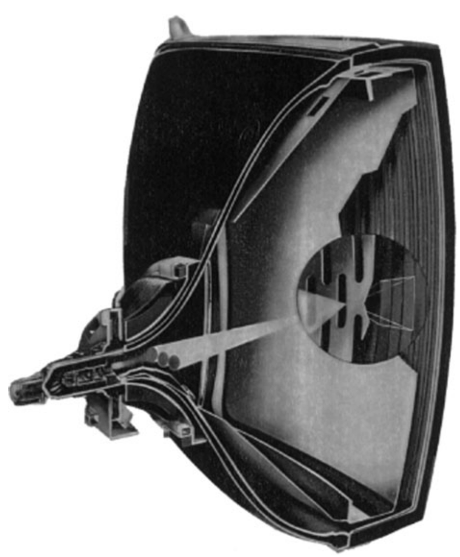

Figure 1. A cutaway diagram of a cathode-ray tube for television or computer monitors.

Gun/Cathode

The electron beams in Fig. 1 originate from the electron gun. A photograph of an electron gun is shown in Fig. 2. The gun is an assembly of metal parts secured by multiform glass rods, often called beads. One rod is visible in the foreground of Fig. 2. In manufacture, the top of the gun is inserted into the rear of the neck of the CRT up to the level of the stem; the stem is the glass disk in the lower part of the figure. The electron gun fits snugly in the neck, held in place by the small leaf springs at the very top of the picture. They also connect the top metal part to the anode potential via an internal coating of the tube. This part is often called the anode grid. Below it lies a large metal part called the focus grid. The diameter of the gun generally ranges from 10 to 50 mm, depending on the application.

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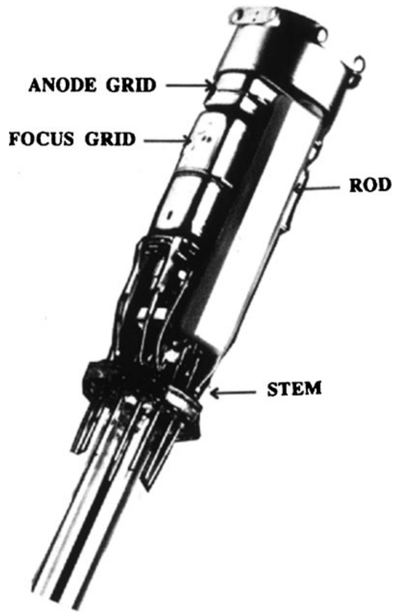

Figure 2. Photo of electron gun.

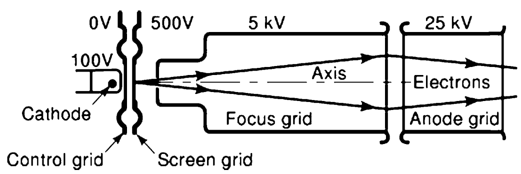

Figure 3. A cross-sectional diagram of the electron gun shown in Fig. 2.

Voltages of 25,000 V and 5,000 V on the anode and focus grids, respectively, create an electron lens in the gap between these grids. This lens focuses the electron beam. The edges of the screen grid and control grid are visible behind the focus grid. The cathode lies inside the small cylinder seen underneath the wire leading to the screen grid. Metal pins pass through the stem to make electrical connections. Wires from the internal ends of these pins lead to the grids, and the external ends of these pins are attached to a socket. The glass stem tube at the bottom of the picture is used for handling the gun before and during insertion into the CRT. Following sealing of the stem to the CRT and air evacuation of the CRT (through this tube), this tube is removed.

A cross-sectional diagram of the electron gun is shown in Fig. 3. Apertures in the control and screen grids allow electrons to pass from the cathode to the electron lens formed by the focus and anode grids. These apertures are very small, generally well below 1 mm in diameter. The lens focuses the electrons. Paths of electrons are shown in Fig. 3 by the lines that have arrows.

Inside the gun, the electron beam originates from a cathode. A picture of a cathode and its parts is shown in Fig. 4. The cathode is a cap on the cathode cylinder. This cylinder is small, frequently less than 2 mm in diameter. Inside this cylinder is a very small heater filament coil whose diameter is about 1 mm. Electric currents in this coil generate heat to raise the cathode temperature to nearly 1000 °C.

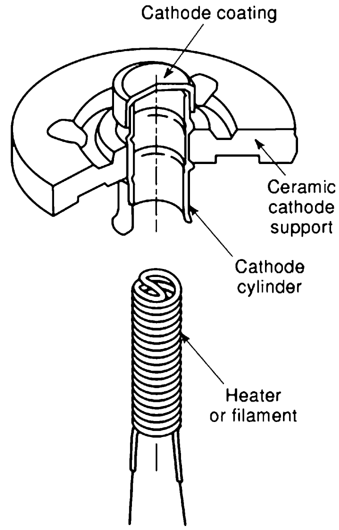

Figure 4. Details of the cathode (1).

Red light from this filament can often be seen at the back of an operating tube. At this temperature, the material of the cathode, typically barium, emits many electrons into vacuum. Positive voltages on the gun electrodes pull the emitted electrons away from the cathode and form them into the beam. Voltage on the control grid in Fig. 3 varies the beam intensity, so that the display will have light and dark regions. Replacement electrons come from the outside through a pin in the stem.

Higher voltages on electrodes further from the cathode accelerate the electron beam. These final electrodes of the gun apply forces to the beam that resemble the action of an optical lens on light, and these forces make the beam very small when it ends on the screen. Because of the similarity of light rays in lenses to electron paths in these forces, the study of this electron motion is often called *electron optics*.

The electrons leave the gun at speeds of 5% or more of the speed of light. This speed is high enough for the theory of relativity to change the electron path perceptibly from that expected from Newtonian physics. The CRT is unusual, perhaps unique, among household objects, in that relativistic effects are significant.

Phosphor

The electron beam in Fig. 1 ends on the screen, where phosphors convert the electron-beam energy into light. Phosphors are semiconductors that frequently contain impurities, which emit light when electrons and holes recombine. Because the beam energy is nearly 25,000 eV and the phosphor band gap is about 5 eV, each electron creates thousands of electrons and holes, causing the emission of thousands of photons of light. Zinc sulfide is a typical phosphor. When it contains cadmium and silver, white light is emitted. From silver alone, the light is blue, whereas it is green with copper.

Deflection

To generate a display of the light from the electron beam, the beam must be swept over the area of the display in

Figure 5. Deflection coils on the neck of a CRT. One pair of coils is shown (2).

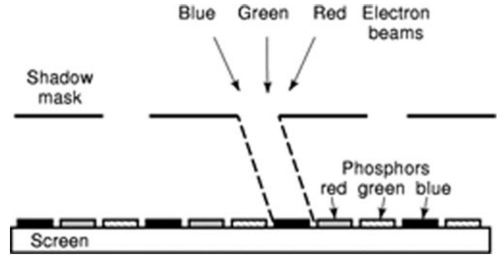

Figure 6. Diagram showing the masking of phosphors by the shadow mask.

synchronization with its intensity variation. Magnetic coils outside the CRT are often used to deflect the beam. These deflection coils are shown in Fig. 1. A more detailed view is shown in Fig. 5. Currents flow in these coils to generate magnetic fields inside the CRT; changing currents sweep the beam over the display area. These coils resemble Helmholtz coils pressed to the outer contour of the CRT. (Helmholtz coils have uniform magnetic flux density in the central region between the coils, the region where the electrons are.). Electric currents flow in the same direction in the portions of the coils in the foreground to create a magnetic field nearly perpendicular to the direction of view. Electrons moving downward are deflected in the view direction. The Lorentz force deflects the beam. (A magnet held near a television screen will distort its appearance due to the Lorentz force on the electrons. Beware: Color CRTs may be permanently distorted if the magnet used for this demonstration is too strong). A ferrite core in Fig. 5, half of which has been removed, concentrates the magnetic field in the neck of the CRT. In operation, two pairs of coils are needed for the two field directions. Many parts of the electron gun shown in Fig. 2 can be seen through the CRT neck in Fig. 5.

Color

Most CRTs in use today display color images. Color is displayed by using three phosphors, one for each of the primary colors to which the eye is sensitive. These additive primary colors are red, green, and blue for emitted light, such as emerges from a CRT. An electron beam is needed to energize each of these phosphors, so the three beams shown in Fig. 1 are required for color. Each electron beam energizes a single color phosphor. To prevent the electron beams from energizing the other phosphors, the shadow mask shown in Fig. 1 is used. The shadow mask contains hundreds of thousands of holes, some of which are shown in Fig. 6. These holes shadow electrons, so that any point on the screen receives electrons from only one of these beams. The electron beams move in the directions of the arrows and have cross sections much larger than an opening in the shadow mask. A portion of each beam passes through the opening and impinges on a single phosphor area. A portion from the blue beam is shown by the dashed lines in this figure. Other portions of the beams are shadowed from the other phosphor areas by the solid mask. In Fig. 6, the angles between the beams are exaggerated, and the distance between the mask and screen is sharply contracted. Typically the angles are less than 1° and the mask–screen separation is 50 to 100 times the mask aperture width. The phosphor area is similar to the mask opening area. An example of the arrangement of the phosphors that emit red, green, and blue colors is shown in the inset of Fig. 1. This phosphor arrangement can also be seen on any home television set. A magnifying glass or optical loop may help in distinguishing it. When seen from afar, the details of the phosphor arrangement blend, giving the appearance of a color image. Contrary to the appearance of the inset in Fig. 1, each beam typically intercepts several mask openings. The beams also come together, or converge, at the screen, not at the shadow mask.

HISTORY AND APPLICATIONS

The basic elements of a CRT, the glass envelope, cathode, deflection, and phosphors, have been described. CRT applications include TV and computer monitors, as well as oscilloscopes and radar tubes. In these applications, the basic elements are not always implemented in the same way as they are in CRTs for TV and monitors. As these applications are described, these differences will be noted. Other vacuum devices, which could be called CRTs but generally are not, include X-ray tubes, electron microscopes, microwave tubes, television camera tubes, and electron-beam lithography, annealing, welding, deposition, etc. They all lack phosphors.

Oscilloscope

The CRT was invented in 1897 by Ferdinand Braun. The oscilloscope was the first application for the CRT. It was developed in the early part of the twentieth century to display the variation of voltage with time. This voltage is taken from a location in an ac circuit. Voltage can vary rapidly with time, so the electron beam must be rapidly deflected to display the variation. Thus, the magnetic deflection coils are replaced by two sequential pairs of plates inside the CRT. Electric fields between a pair of plates deflect the beam. The beam generates a spot on the screen that is swept by the deflection fields to generate a graph of voltage versus time. The time for a horizontal scan is chosen as one or more periods of the ac voltage. The voltage is applied to the vertical scan, so the display resembles the graph of the sine function, if the amplitude is constant and contains only one frequency. Of course, other interesting voltages have many harmonics with different amplitudes that lead to informative displays about the voltage at the circuit location. It became a widely used laboratory tool. Modern oscilloscopes replace the CRT with digital electronics and a flat display. Very high speed modern optics, using pulses of subpicosec duration, uses a CRT similar to the oscilloscope, called a streak tube, to display the pulse. To detect light, a photocathode replaces the thermionic cathode.

Radar Tube

The radar tube was the first application for the CRT outside the laboratory. The screen of a radar CRT is usually round, and a rotating radial line is displayed. Occasional bright spots appear along this line that are associated with targets detected by the radar. The radial line is coordinated with the direction of the radar antenna orientation and the radial distance of the bright spot is coordinated with the distance to the target. There are other, less well-known, radar display formats besides this one, called *plan position indicator*. The radial line is generated by deflecting the electron beam with an external magnetic deflection yoke, such as shown in Figs. 1 and 5. In early versions, only one pair of coils was used, and the yoke was physically rotated around the tube neck in coordination with the rotation of the radar antenna. Later, two pairs of fixed coils provided the required electronic signals to rotate the line. The signal reflected from the target increases the electron-beam current to generate a bright spot. Its arrival time is coordinated with the deflection along the radial line to indicate its distance. The phosphors on the screen are specialized to be persistent, that is, light continues to be emitted for several seconds following the passage of the electron beam. In most displays, persistence results in undesirable blurring of the display, but for radar, this persistence enhances the visibility of the target. The cathode, electron gun, and glass envelope of the radar tube are similar to those of other CRTs. As happened with the oscilloscope, digital electronics in modern radar enable replacement of the radar CRT with a flat display or with a computer-monitor CRT.

TV and Computer Display and Projection TV

Television became popular before and following World War II, and the CRT displayed the visual information. To display a picture, one pair of deflection coils rapidly sweeps the beam across the width of the screen, while another pair slowly sweeps the beam vertically. The pattern of displaced lines is called the raster. Because the beam makes a point of light on the screen, the raster is the composite of these points of light. Thus a CRT display is analogous to the French Impressionist art form called pointillism, where the picture is a composite of dots. The resolution of a CRT display is related to the number of distinct points of light in the composite.

Standard television rasters use about 500 lines, and high-definition television (HDTV), the new television standard, uses more than 1000 lines. To display moving pictures, the raster is changed 30 times a second. In Standard television, alternate lines are often displayed, so 250-line rasters are displayed 60 times per each second. This arrangement, called interlace, reduces the perception of flicker. In HDTV the raster is changed more rapidly, so lines can be displayed successively, called progressive scan; this results in a more pleasing picture.

During the 1960s, color television supplanted monochrome television. CRTs for shadow-mask color television were described earlier. This is not the only way to generate a color image on a CRT. Another way uses a CRT that emits white light. A changing set of color filters lies between the CRT and the viewer. When the green portion of the image is displayed on the CRT, a filter that passes green light is used; when the blue portion is displayed, a filter that passes blue light is used; and when the red portion is displayed, a filter that passes red light is used. To avoid flicker, this must happen very quickly, about 60 times per second. The filters can be changed by arranging them as sectors of a wheel that rotates in front of the CRT. This color wheel method was seriously considered during the development of color television in the 1950s. However, adopting it would have made television inaccessible to owners of the monochrome televisions then in use. The shadow-mask method allows displaying color television signals on both color and monochrome CRTs. Today, the color wheel is replaced by liquid-crystal filters in some specialized applications.

In recent years, CRTs have been used extensively for computer displays. These CRTs are similar to that shown in Fig. 1 and differ from those for television only in the details needed to make the display sharper for text. Brightness is reduced by these changes.

Quite recently, projection television has become popular. Projection systems generally use three CRTs. One monochrome CRT is used for each of the three phosphor colors, and the light from them is projected and combined on the screen.

CONSTRUCTION

Construction of a CRT begins with the flask-shaped glass container. Its top, sides, and base are commonly called the neck, funnel, and panel, respectively. The phosphor, consisting of small grains mixed with water to form a slurry, is added to the flask. After the phosphor settles on the base, which will become the screen, the water is removed. Of course, the construction of the color phosphor screen shown in Fig. 1 is much more complicated than simply settling the phosphor slurry. Photolithographic techniques are used. Even today, each shadow mask must be used to deposit the phosphor on the panel with which it will be used to achieve adequate registration of the openings and phosphors shown in Fig. 6.

An electron gun, shown in Fig. 2, is inserted and flame-sealed to the neck. The tube is sealed after the air in the tube is removed through the cylinder in the stem. A vacuum of 10^{-8} torr is needed, and baking at 400 °C, followed by gettering is necessary to attain it. (A getter material retains molecules that strike it.) Efficient getters are essential to electrically stable CRTs. Electrical connections are made through the pins in the glass stem.

A vacuum inside the CRT is needed for the electron beam to exist. Atmospheric pressure on the evacuated tube can cause violent collapse of a tube that is mishandled. The glass thickness is increased in larger CRTs to prevent collapse of the tube. Increased glass thickness adds weight and limits the maximum size of CRTs.

The electron gun is made by assembling stamped, stainless steel metal parts onto a fixture. They are secured with glass rods heated to softening, which are pressed onto the fixtured assembly. The cathode and its filament are assembled into these metal parts. Pins in the stem are welded to wires that are also welded to the metal parts. The electron current needed for the electron beam enters through one of these pins, filament current enters and exits through two others, and voltages are placed on the electron-gun electrodes through yet other pins. The anode voltage is so high that arcs to the other pins would occur, so it is brought in through the anode button, shown in Fig. 1; the electron current from the beam exits through this connection, too.

The deflection coils are assembled from wires. They are pressed into coils using an arbor with the CRT contour. These coils are surrounded by a ferrite core, separated by insulators, and supported by a plastic housing. This deflection system, frequently called the *yoke*, slides over the neck at the rear of the tube to reach its position against the funnel. Connections between the coils and external transformers provide the currents needed for the magnetic fields that deflect the electron beam. Since deflection establishes the position of the beam on the screen, far fewer external electrical connections are needed, compared to other display technologies.

Deflection is needed to move the electron beam across the screen of the CRT. As the deflection angle is enlarged, the beam paths to the center and edge are different. This limits the deflection between opposite corners to angles of 120° or less. This limit on the deflection angle adds depth to the CRT and prevents manufacture of a very thin CRT.

INDUSTRY—TODAY AND FUTURE

Today most CRTs are made for color and projection television and for computer displays. More than 200 million tubes are sold annually in a market valued at $20 billion. They range in screen diagonal size from 1 inch to 35 inches. Most are made and sold in the Far East.

Many new flat, thin display technologies are emerging. All of them are more expensive than the CRT, but the cost differential is declining. Liquid-crystal displays (LCDs) for computer displays have generally replaced CRTs in many markets. Plasma panels, LCDs, and projection using electronic light valves are displacing CRTs for television displays.

Modern CRTs for TV have flatter and larger screens. Flatter screens greatly reduce glare from ambient light, and they make the CRT appear more like the new flat-panel displays. Larger screens are needed to display the improved resolution associated with digital information transfer; still larger screens will be needed for HDTV.

Growing computer technology drives new applications for electronic displays, many of which will be fulfilled by the CRT. Arcade games, surveillance, banking and vending machines, and so on, all require displays. Most of these needs will be met with the CRT because of its low cost. Medical technology is replacing X-ray film with computer displays. Photography is also becoming digital, and many images are being displayed in softcopy.

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