The Microchannel Image Intensifier

It is a glass wafer, perforated by millions of electron-multiplying tubes, resembling a compound eye. It can transform a dim pattern of electromagnetic radiation into a brightened, pointillist image

by Michael Lampton

An amplifier is a device that boosts the power of a signal while otherwise changing it as little as possible. Amplification is usually thought to apply only to signals that vary in time, such as the electrical output of a microphone. A visual scene constitutes a signal that varies in space as well as in time; in order to amplify such a signal it has often been necessary to convert it into a purely temporal pattern. This can be accomplished by scanning the scene in some systematic way, as in a television camera. In the past 25 years, however, several advances in glassworking technology have made it possible to assemble millions of microscopic amplifiers into a geometric array. Each amplifier in the array is a tube or channel about 15 micrometers in diameter that can brighten a small, well-defined portion of the scene. Hence the entire array of amplifiers, operating simultaneously and in parallel, functions as an image intensifier, making faint images brighter without destroying the spatial information of the input signal. Such an array of microscopic amplifiers is called a microchannel plate.

Much of the economic motivation for the development of the microchannel plate has been military. A compact image intensifier that incorporates a microchannel plate can increase the brightness of a scene by a factor of up to 10,000, thereby making possible surveillance at night under darker conditions than ever before. Goggles, binoculars and the like incorporating microchannel intensifiers have become essential in nighttime military operations where, for example, vehicles must be driven without headlights. The U.S. Army Night Vision Laboratory at Fort Belvoir, Va., has been chiefly responsible for the continuing development of these devices. At present such applications account for the production of about 10,000 microchannel intensifiers per year.

The microchannel intensifier has nonmilitary applications as well. In astronomy it can enhance the brightness of an image to the point where individual photons can be detected. As a result an image that would otherwise require a prohibitively long photographic exposure can be recorded in minutes. Image intensifiers have also been made available to people suffering from the form of night blindness called retinitis pigmentosa, although the cost (about $2,700) remains a barrier to their wider distribution.

The microchannel plate is not limited to the intensification of visible images. When it is coupled with suitable electrical and optical systems, it can convert a two-dimensional signal in the near-infrared or the ultraviolet region of the electromagnetic spectrum into a visible image. Moreover, it can directly detect X rays, ions and electrons, making possible a wealth of new applications in such areas as oscilloscope design, electron microscopy and the study of the chemical composition of materials by photometric methods. A microchannel plate is employed in the X-ray telescope aboard the Einstein Observatory satellite and in the ultraviolet spectrometers carried aboard the Voyager missions to Jupiter and Saturn. The European X-ray Observatory Satellite (*EXOSAT*), to be launched next year by the European Space Agency, will carry microchannel plates as part of its complement of X-ray detectors.

What are the principles that underlie the operation of a microchannel plate? It is useful to begin the answer with a description of an image intensifier that does not incorporate a microchannel plate. Such a device depends on an interaction of electromagnetic energy with matter that was first explained by Einstein in 1905. The interaction is the photoelectric effect, and it was one of the first physical processes to be accounted for by the idea that energy comes in quanta, or discrete packets.

When a photocathode, or negatively charged electrode, is exposed to electromagnetic radiation whose wavelength is shorter than some critical value, the photocathode emits a current of electrons that can be collected by a nearby anode, or positively charged electrode. For many metals the critical wavelength lies in the ultraviolet region of the spectrum, although for some substances it lies in the visible region or in the near-infrared region. The rate at which the charge is transferred is proportional to the intensity of the radiation, but whether or not the charge is transferred at all depends only on the wavelength.

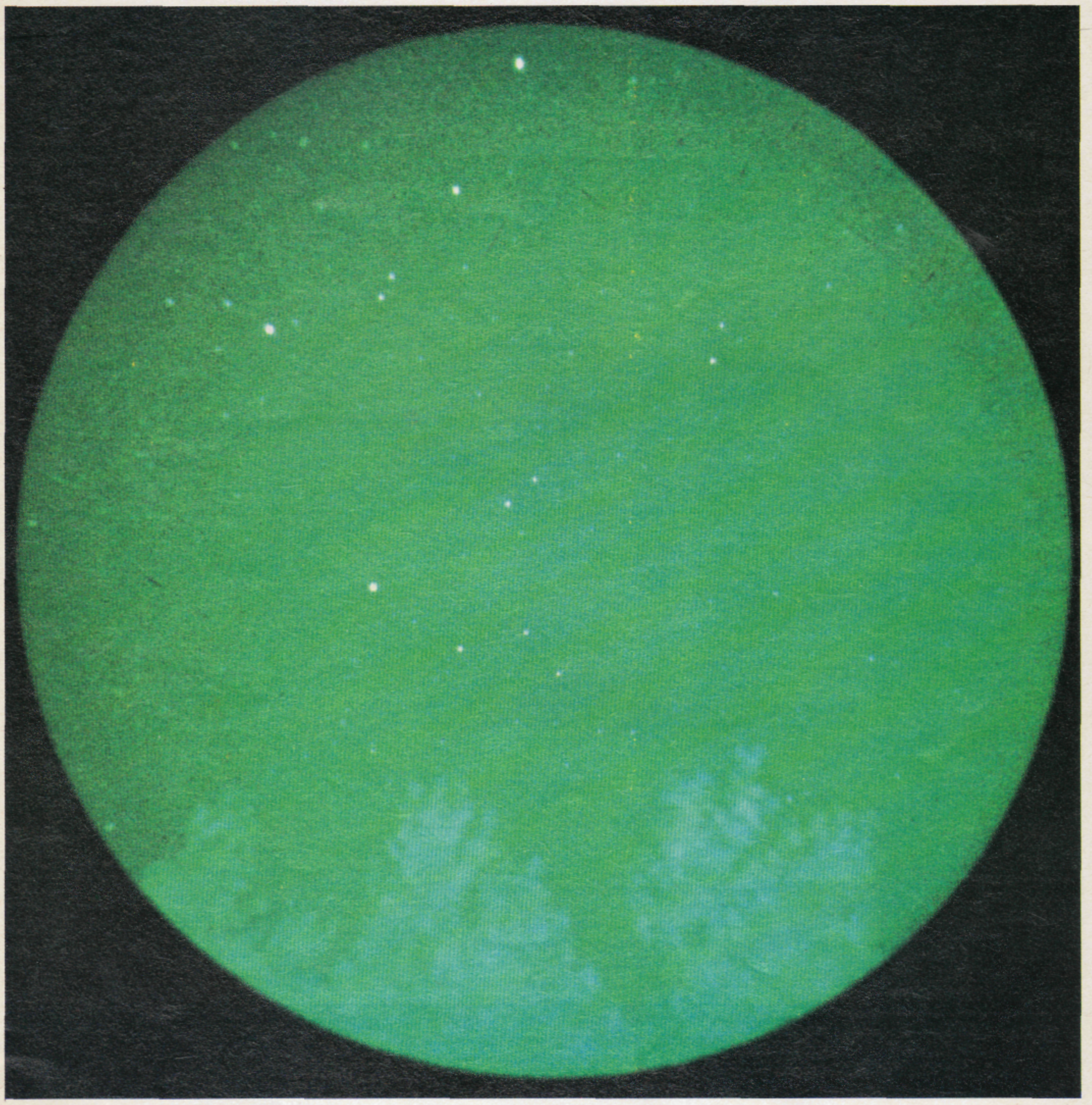
Einstein explained this phenomenon by supposing that an electron bound in matter requires some definite minimum energy to liberate it. Moreover, when the liberating energy is supplied by electromagnetic radiation, it can be absorbed only in the discrete quanta called photons. From the earlier work of Max Planck it was known that the energy of a photon varies inversely with the wavelength of the radiation. Hence a photon with a wavelength longer than the critical wavelength has insufficient energy to knock an electron out of the metal.

An image intensifier exploits the photoelectric effect to convert the stream of photons in electromagnetic radiation into a stream of electrons. Each photon can stimulate the emission of at most one electron, and so it might seem that nothing would be gained by this strategy. What makes possible the amplification of the image is the electric charge of the electron. In an applied electric field the electrons can be accelerated, so that their kinetic energy is increased. In this way the total energy available for forming an image can be multiplied many times.

In its simplest form an image intensifier is a vacuum tube with two electrodes that are connected to an external power supply. No microchannel plate is incorporated into such a device. An image is focused onto the photocathode, and each area of the photocathode emits electrons in numbers determined by the brightness of the image in that area. Each electron is accelerated by an electric field generated by a bias potential of several thousand volts applied between the two electrodes. The accelerated electrons travel across the evacuated gap to the anode, following paths that are approximately straight lines. In this way the flux of electrons that reaches the anode corresponds to the brightness variations of the image on the photocathode. The spatial resolution of the image is well preserved because the photocathode and the anode are close together.

An image tube has a visible output because its anode is made of a fluorescent material. When an electron strikes the anode, it excites and ionizes atoms in the material. A portion of the energy is then released in the form of photons of visible light as the electrons from the excited atoms return to their usual energy levels. The emitted photons constitute the image that is visible on the fluorescent anode.

I pointed out above that each photon striking the cathode can give rise to one electron at most; actually the efficiency of the photocathode is only about 10 percent, that is, only about one photon in every 10 stimulates the emission of an electron. Moreover, at the anode only about 30 percent of the energy conveyed by the accelerated electrons is converted into light. In spite of these inefficiencies there is a net gain, or amplification of the luminosity of the image, because the increase in the energy of each emitted



PHOTOGRAPH OF A NIGHTTIME SCENE illuminated by starlight was made with a 35-millimeter camera fitted with a microchannel image intensifier. The brightness of the photograph approximates the brightness of the scene as it would appear to the eye through the intensifier. The green color of the sky and the treetops in the photograph is the color of the fluorescent light emitted by the screen on which the amplified image can be viewed. The color corresponds to the wavelength of light to which the eye is most sensitive, namely about 540 nanometers. The photograph was made with a daylight color film having an ASA film-speed rating of 400, exposed for one-fourth of a second at a lens-aperture setting of *f*/2.8. Without the image intensifier such a photograph would require from four to eight minutes of exposure. The intensifier was provided by Paul Lighty of the ITT Electro-Optical Products Division in Roanoke, Va.

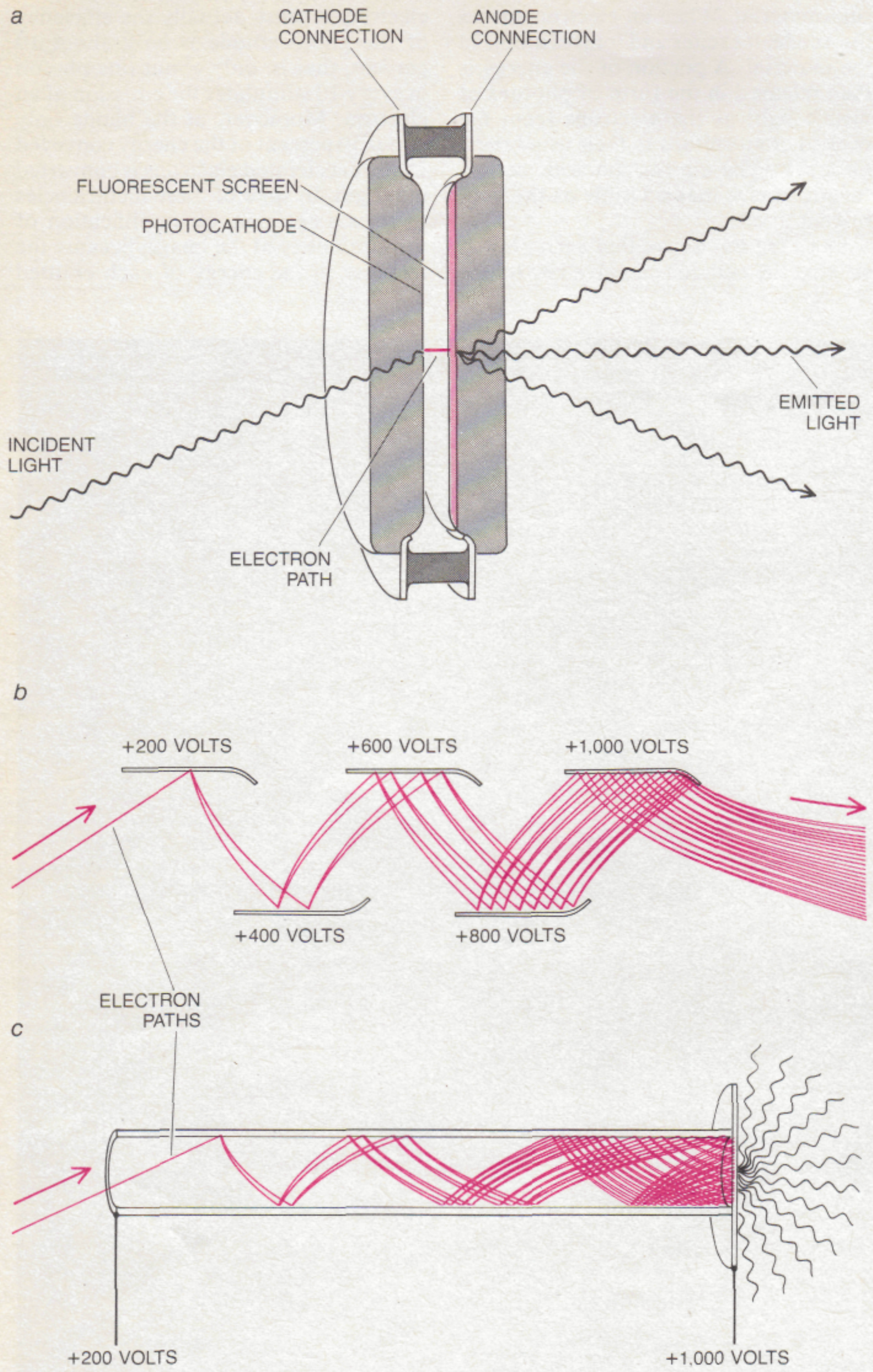


IMAGE INTENSIFIERS exploit the photoelectric effect, whereby the energy of incident photons, or quanta of electromagnetic radiation, is converted into the energy of moving electrons. Because electrons, unlike photons, are electrically charged particles their energy can be increased by acceleration in an electric field. When photons strike a photosensitive metal plate, electrons are ejected into an evacuated region. The electrons are accelerated toward a positively charged fluorescent plate, where their energy is converted again into the energy of visible light. In a two-electrode image tube (*a*) at most one electron is accelerated across the gap for each incident photon, and the electron must travel directly across the gap if the image is not to be blurred. Hence to preserve the sharpness of the image the gap must be narrow. The achievable gain is limited by the voltage that can be applied across the narrow gap without sparking. Electrons that strike certain materials can cause the ejection of additional electrons, and a cascade of electrons can thus be induced by maintaining several electrodes at successively higher voltages (*b*). Although such an electron multiplier can yield high gain, the dispersion of the cascading electrons destroys information about the spatial distribution of the incident photons. A way to achieve both high gain and spatial resolution is to provide one electron multiplier for each pixel, or picture element, in an image, but then the multipliers must be made very small. This can be done with the continuous-channel electron multiplier (*c*), which functions much like the multiple-electrode one but confines the electron cascade to the bore of the channel. Techniques for drawing glass fibers can be employed to make such multipliers that are only a few micrometers in diameter; arrays of the multipliers can then be installed in image tubes.

electron can be several thousandfold.

It may seem that an image signal could be amplified to any level desired by increasing the bias potential that accelerates the electrons. Unfortunately a two-electrode image tube cannot be operated beyond a certain maximum applied voltage. When the voltage exceeds this level, charge begins to flow spontaneously across the small gap between the photocathode and the anode and overwhelms the smaller current of electrons that transmits the image. The effect could be overcome by redesigning the tube to have a larger gap, but then the spatial resolution of the image would deteriorate because of small, random deviations in the path taken by the electrons. By focusing the electrons with electric and magnetic fields it is possible to increase the gap, to operate at a higher voltage and so to increase the gain in image brightness. The electric and magnetic fields must be carefully controlled, however, and such focusing devices can cause geometric distortion of the image or nonuniformities in its brightness. Moreover, for many purposes in physics and astronomy even the more complex intensifiers that focus the electrons have insufficient gain.

The fact that each incident photon can cause at most one electron to be transferred to the anode is a fundamental limitation of such image tubes. In certain materials, however, electrons can be knocked free by an incoming electron just as they can by an incident photon. The effect is called secondary surface emission, and it can be exploited in an image tube to multiply the number of electrons that reach the anode.

Electron multipliers have been employed since the early 1950's as the amplifying components of photomultiplier tubes. Metal electrodes called dynodes are given progressively higher positive potentials and are arranged so that the electrons leaving one dynode are directed toward the next. An incident electron that strikes the first dynode knocks several low-energy electrons out of the metal. The secondary electrons are accelerated to the second dynode, where they are multiplied again. Successive multiplications lead to an exponential growth in the electric charge liberated by the initial electron. Because all the electrons are accelerated by the field, the combined energy of the electrons that finally strike the anode can be enormously greater than it is when a single electron is accelerated.

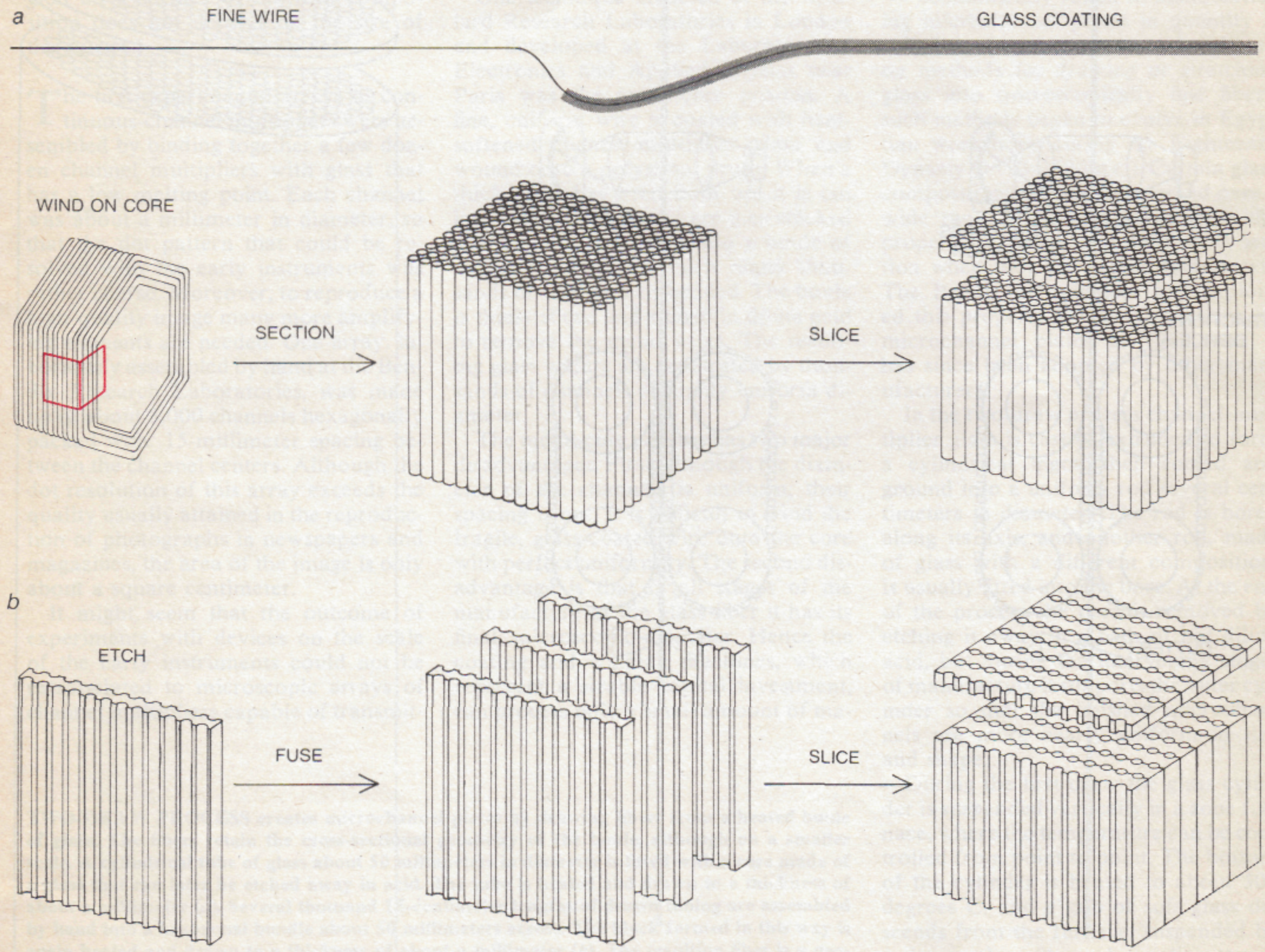
High amplification can be attained in a dynode multiplier structure, but only at the expense of spatial resolution. The geometry of a dynode does not ensure that the electrons travel in a straight line; as a result electrons emitted from a given region of the photocathode do not necessarily land in the corresponding region of the anode. The microchannel plate is a device that combines the gain of an electron multiplier with the spatial resolution of an image intensifier. It consists of millions of independent electron multipliers assembled in a two-dimensional array. There is no attempt to maintain spatial resolution within any one multiplier; instead each multiplier corresponds to a single pixel, or picture element. The intensified image is a pattern of fine dots of varying brightness.

The key step in the development of the microchannel plate was the invention of the continuous-channel electron multiplier. It is a glass tube connected at each end to a source of electric power, supplied with a bias potential of about 1,000 volts and placed in a vacuum. It acts, however, much like a multiplier assembled from dynodes. An incident electron can initiate a cascade of secondary electrons that grows exponentially as it progresses along the inside of the tube. The cascade is entirely confined to the interior of the tube or channel. Such continuous-channel multipliers were first investigated at the Bendix Research Laboratories in Southfield, Mich., by George W. Goodrich, James R. Ignatowski and William C. Wiley from 1959 to 1961.

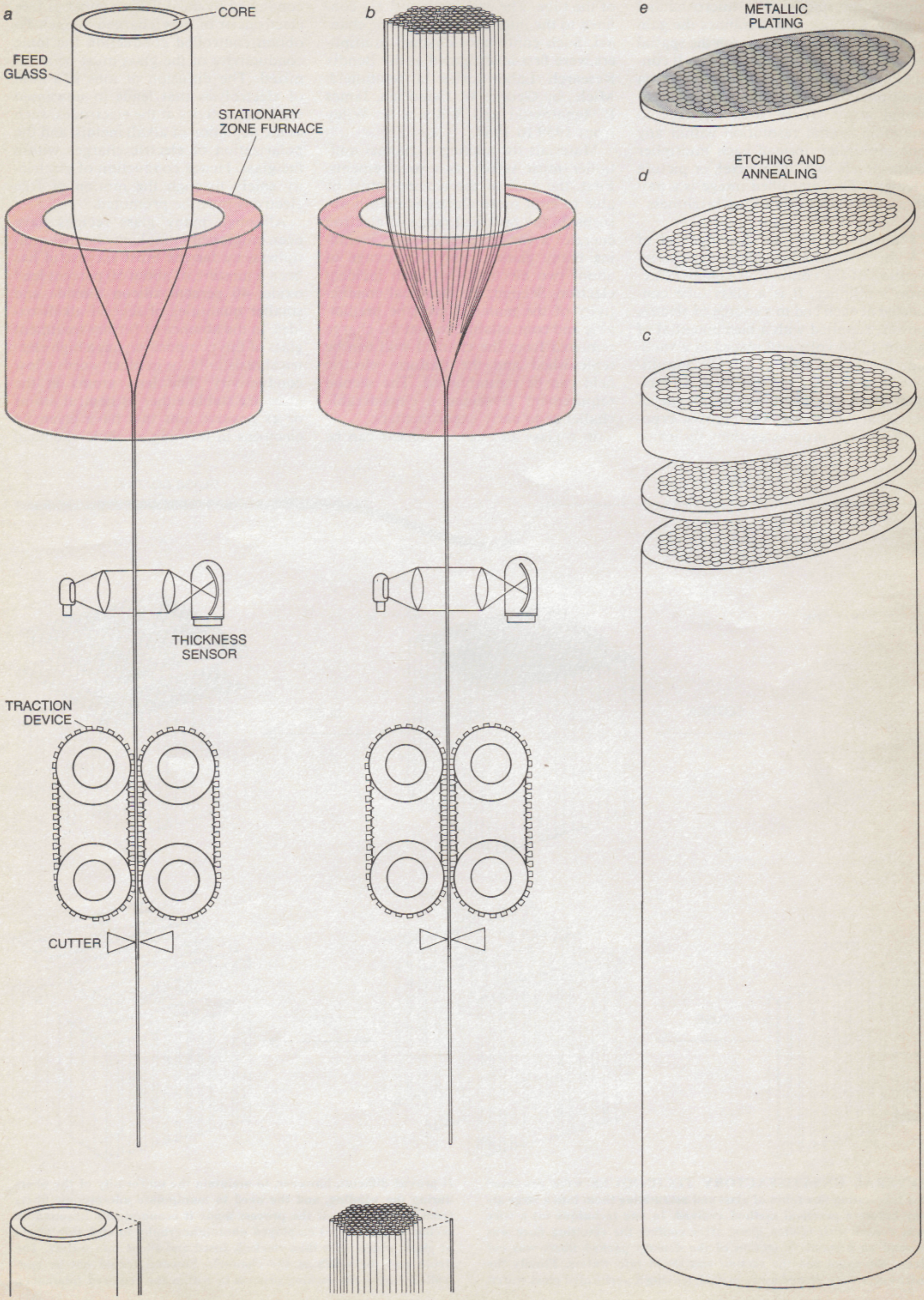
Materials for making a channel multiplier must satisfy two requirements. First, the wall of the channel must be able to emit more electrons than it absorbs. In the practical range of electron energies a variety of materials, including many glasses, emit an average of about two electrons for each incident electron. Second, the electrical conductivity of the material must be predictable and controllable, so that the charge removed from the channel wall can be replenished and the uniform electric field can be reestablished. The second requirement presented a considerable challenge to early experimenters.

In a glass an electric current can be conducted by the diffusion either of free electrons or of ions (charged atoms). To obtain controlled conduction the ionic conductivity of the glass must be minimized. The diffusion of ions is a kind of electrolysis that leads to unwanted chemical activity at the electrodes, such as the depletion of alkali metals, and the polarization of electric charges within the glass. Hence conduction of electricity solely through the motion of free electrons must be promoted.

Although many glass recipes have been employed in making channel multipliers, by far the most successful has been a mixture of about 50 percent lead oxide, 40 percent silicon dioxide and smaller quantities of several alkali oxides. In the absence of further treatment glass of this composition has a high electrical resistivity, or in other words a low conductivity. The lead atoms in the glass are stable either as neutral atoms or as positive ions that have given up electrons in forming an ionic chemical



SEVERAL UNSATISFACTORY TECHNIQUES were proposed for fabricating fine tubes of glass and assembling them into a large array before a practical method evolved. In one technique (*a*) a wire was coated with molten glass; after cooling the resulting fiber was wound on a spool. A section of the densely packed fibers was cut from the spool and the section was sliced into wafers. Finally the wire cores were etched away in acid, leaving a perforated glass wafer. It proved difficult, however, to maintain the uniformity of the fibers during the winding, and the need to manipulate microscopic fibers from the first step of the process made it economically unsound. A second technique (*b*) employed photolithography to etch thin plates of glass, which were then stacked, fused and sliced into wafers. The depth and the width of the channels, however, could not be controlled during the etching process to within the required tolerances.


a
CORE
FEED GLASS
STATIONARY ZONE FURNACE
THICKNESS SENSOR
TRACTION DEVICE
CUTTER
b
e
METALLIC PLATING
d
ETCHING AND ANNEALING
c

bond with oxygen. The conductivity can be improved by removing the oxygen from the lead in the chemical reaction called reduction.

Reduction can be carried out at the surface of the glass by heating it in an atmosphere of hydrogen gas. After several hours at 400 degrees Celsius the reduction of the lead oxide has penetrated to a depth of several tenths of a micrometer and most of the reduced lead has evaporated from the surface. The lead that remains on the surface coalesces into metallic clusters, giving the glass a characteristic black color. The electrons that once formed the ionic bond of the lead oxide are freed to carry electric current, and the surface layer of the glass has become a semiconductor. Its resistivity is from 10^8 to 10^{14} ohms per square, a range suitable for the manufacture of channel multipliers and microchannel plates. (Surface resistivity is expressed in ohms per square, without specifying the dimensions of the square, because the resistivity of a square region on a surface of uniform composition does not depend on the size of the square.)

The first experimental arrays of continuous-channel multipliers were assembled by binding together a few dozen channel multipliers with glass that has a low melting point. Each channel was about a millimeter in diameter, so that the dot pattern that could be resolved with the early instruments was rather coarse. Moreover, to reproduce a high-quality image many more amplifying elements are needed. One array, laboriously assembled by hand at the Bendix Research Laboratories, was made up of about 5,000 channels hexagonally packed with .15-millimeter spacing between the channel centers. Although the dot resolution of this array exceeds the quality usually attained in the reproduction of photographs in newspapers and magazines, the area of the image is only about a square centimeter.

It might seem that the outcome of experiments with devices on the scale of the early instruments could not be extrapolated to microscopic arrays of channel multipliers capable of transmitting high-quality images. The extrapolation is possible in part because for a given applied potential the gain of a channel multiplier does not depend on its size. In a longer channel each electron falls farther under the influence of the force exerted by the electric field, so that it has more time to gain energy. In a shorter channel the electric field is more intense: the force acting on the electron varies inversely with the distance between the electrodes. The two effects cancel each other exactly.

The handmade arrays established that the individual channels in an array respond independently of one another. It was found, however, that the quality of the image is quite sensitive to variations in the diameter of the channels and also somewhat sensitive to nonuniformities in their spacing. In the early 1960's the main challenge to the development of microchannel plates was to devise manufacturing techniques that could maintain high uniformity in the diameter of the channels.

One technique invented at the Mullard Research Laboratories in London and developed at the Laboratory of Electronics and Applied Physics near Paris was the metal-core process. A fine, uniform wire is coated with heat-softened channel-multiplier glass and wound onto a polygonal drum. When a thick layer has been built up, it is cut into blocks. The blocks are then stacked side by side and fused into a boule of multiplier glass in which many thousands of wires are embedded. The boule is thinly sliced and etched in dilute acid to remove the metal wires. The resulting glass wafers are penetrated by thousands of channels of highly uniform diameter.

The metal-core process has two major disadvantages. First, although the diameter of the channels is uniform, their spacing is not. It is difficult to wind the fragile, glass-coated wire onto the core with perfect uniformity. The second disadvantage is that in all stages of the manufacture of the glass fiber it has its final, microscopic diameter. Hence the coating and winding machines, which represent a sizable capital investment, can process only a small amount of material per unit of time. This has proved to be a serious economic obstacle.

Another technique, called the grooved-plate process, was investigated in the U.S. and Switzerland. A large number of fine, parallel grooves are etched by photolithography into each of many thin glass plates. The plates are then stacked and fused to form the block from which the microchannel wafers are cut. The method seemed promising at first because the spacing of the grooves can be precisely controlled in photolithographic etching. Moreover, curved or zigzag channels can easily be made, and such shapes overcome certain limitations of gain inherent in the geometry of straight channels. Controlling the width and the depth of the grooves during etching and fusing proved to be difficult, however, and resulting nonuniformities of gain led to the eventual abandonment of the grooved-plate process.

The technique that has proved to be economically suited to manufacturing microchannel plates in quantity is called the two-draw process. It is based on methods for drawing or stretching glass into microscopically fine fibers; such methods began to evolve in Egyptian workshops during the Eighteenth Dynasty (1570–1320 B.C.). Certain glass compositions that can be worked over a wide range of temperatures have the property of preserving their cross section when they are heated and drawn. The Bendix investigators first exploited this property for the fabrication of microchannel plates in 1960, and it has since been adopted by other manufacturers.

In the two-draw process channel-multiplier glass is cast or extruded to form a cylindrical ingot, then cooled and ground into a uniform rod several centimeters in diameter. The rod is bored along its axis, and another rod, made of glass with a different composition, is usually fitted into the bore. At the end of the process the core is removed by etching it away in a bath of hot dilute acid, but during the intervening stages of manufacture it supports the outer cylinder so that the finished microchannels are more nearly uniform in size and shape.

During the first draw the glass cylinder is suspended vertically in a zone furnace, where the temperature can be controlled from point to point. The bottom of the cylinder is heated to about 500 degrees C. and a gob of soft glass descends from the furnace, suspended by a drawn-glass fiber whose diameter is about a millimeter. By the time the fiber has descended several meters below the furnace it is cool enough to be handled by a traction machine that regulates the speed of the draw. Regulating the speed in turn gives precise control of the diam-

TWO-DRAW PROCESS creates microchannel plates by drawing fibers from a heated boule of glass. The fibers retain the cross-sectional geometry of the boule, although on a smaller scale. A cylindrical tube of glass about 50 millimeters in diameter is fitted with a core made of a glass that can later be etched away in acid. The tube is heated and drawn to a thickness of about a millimeter (*a*). Several thousand 15-centimeter lengths of drawn tubing are assembled by hand into a hexagonal bundle about 50 millimeters across. The block formed in this way is again heated and drawn to a thickness of about a millimeter (*b*). The resulting fiber is a geometrically similar copy of the 50-millimeter hexagon, complete with the fine structure of the assembled glass tubes. The hexagonal fibers are then fused together and sliced at an oblique angle to create wafers about a millimeter thick (*c*). The wafers are etched in acid to remove the glass cores and heated in an atmosphere of hydrogen gas to develop the desired electrical conductivity on the inner walls of the microchannels (*d*). Metal is evaporated onto both surfaces of the wafer so that electrical connections can be made (*e*). The sizes of the tubes packed into the hexagon and the hexagons assembled on the finished wafer have been exaggerated for clarity.

eter of the fiber. Below the traction machine the fiber is cut into segments about 15 centimeters long. Several thousand segments are assembled into a hexagonal bundle.

The second draw is similar to the first. The hexagonal bundle of fibers is suspended and heated in a zone furnace and drawn into a hexagonal compound fiber about a millimeter across. The spacing between the individual cylinders is thereby reduced to a few hundredths of a millimeter, their final spacing in the microchannel plate. Again the drawn glass is cut into segments, which are packed together and fused in a vacuum to form a boule of hexagonal solids. The boule can be as large as 125 millimeters in diameter and can incorporate millions of microchannels.

Microchannel plates are made by slicing the boule into wafers about a millimeter thick and polishing the faces of each wafer. The slice is usually made at an oblique angle to the axis of the microchannels so that in the finished plate electrons will collide with the channel wall near its input end rather than flying straight through to the anode. Grinding, drilling and hot-working can alter the wafer to meet special needs. In the final steps the core glass is dissolved in acid and the plate is heated in hydrogen gas to reduce the lead oxide and give the glass surface the required electrical conductivity. The wafer is finished by evaporating a metal film onto both faces so that electrical connections can be made to all the channels.

There are now two basic kinds of image intensifier that incorporate a microchannel plate. The proximity-focused intensifier resembles a simple two-electrode intensifier into which a microchannel plate has been inserted. The incident image is focused onto the photocathode, the emitted electrons are accelerated across a small gap into the microchannel plate and the more numerous electrons emerging from the plate are accelerated across a somewhat wider gap onto a fluorescent screen. Such a tube is compact, free from distortion and unaffected by magnetic fields. Moreover, like an image formed by contact printing on photographic paper, the output image is flat and always in focus.

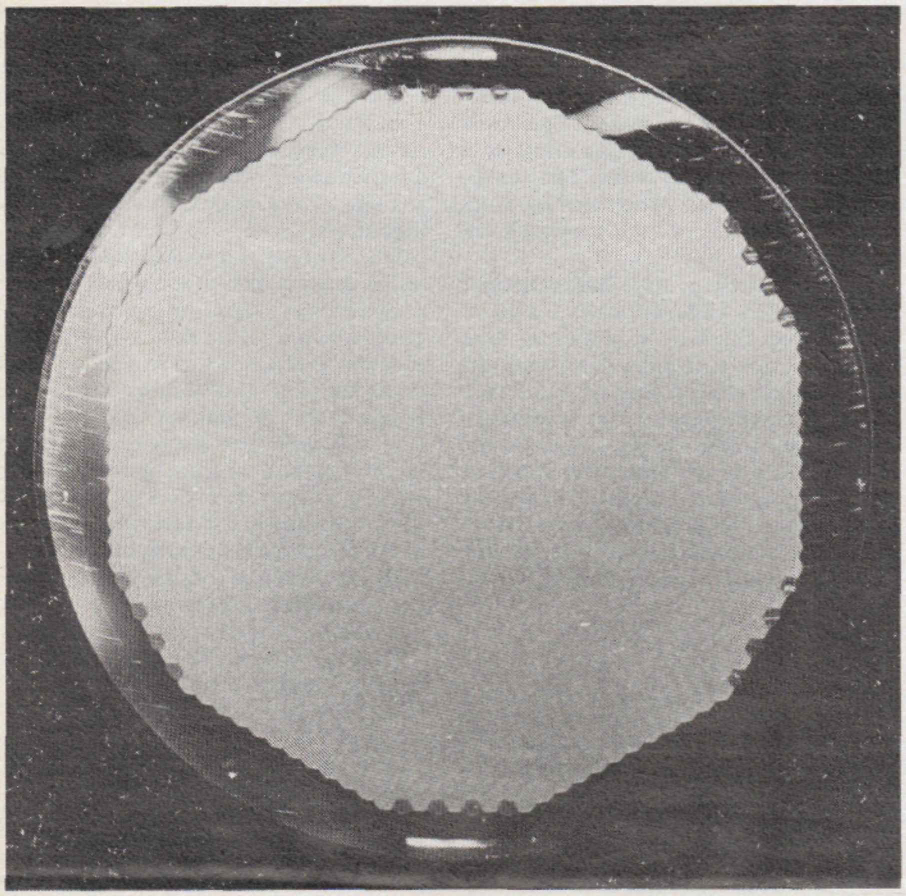
The proximity-focused intensifier is particularly well suited for making photographs of high-speed phenomena. The microchannel plate intensifies the faint image that results from the brief photographic exposure time. In addition the device can serve as a fast camera shutter: the externally controlled voltage difference between the photocathode and the front of the plate provides a means of rapidly switching the intensifier on and off. A proximity-focused intensifier can respond to an electrical shutter pulse lasting for only a few nanoseconds. Hence an unblurred photograph can be made of an extremely short-lived event.

The second kind of image intensifier employs a nonuniform electrostatic field to focus the electrons emitted by the photocathode onto the microchannel plate. Like an optical lens, the tube inverts the image and can also magnify it; in some cases the device can even act as a zoom lens, that is, one that simultaneously adjusts the magnification and the focus. Because of the inversion of the image the electrostatically focused intensifier is particularly useful in conjunction with optical devices that also invert an image. The microchannel plate can replace a complex optical system, such as the one in binoculars, that rights the inverted image formed by an ordinary lens.

Although the microchannel plate has been applied chiefly to image intensification, it can amplify any form of radiation capable of initiating a cascade of electrons in the channels. Ions and electrons as well as photons at wavelengths in the ultraviolet and X-ray regions of the spectrum can all initiate electron cascades in the microchannels. Such forms of radiation can therefore be sensed without a photocathode. The radiation is brought to a focus on the front face of the plate and the cascading electrons are detected at the rear face. If the plate is equipped with a fluorescent anode screen, it can function as an image converter, making visible the spatial pattern of radiation outside the visible part of the spectrum.

Microchannel plates that act as converters as well as intensifiers have been incorporated into laboratory instruments such as high-speed oscilloscopes, transmission electron microscopes, field-ion microscopes and mass spectrometers. In these applications the gain of the microchannel plate makes possible the recording of extremely brief, faint or low-contrast features. Moreover, it allows the instruments to be operated with a lower beam current, which is sometimes an important advantage. In an electron microscope, for example, damage to the material being examined that is caused by the electron bombardment can be reduced.

Four major physical constraints limit the performance of current microchannel plates. First, the average output sig-



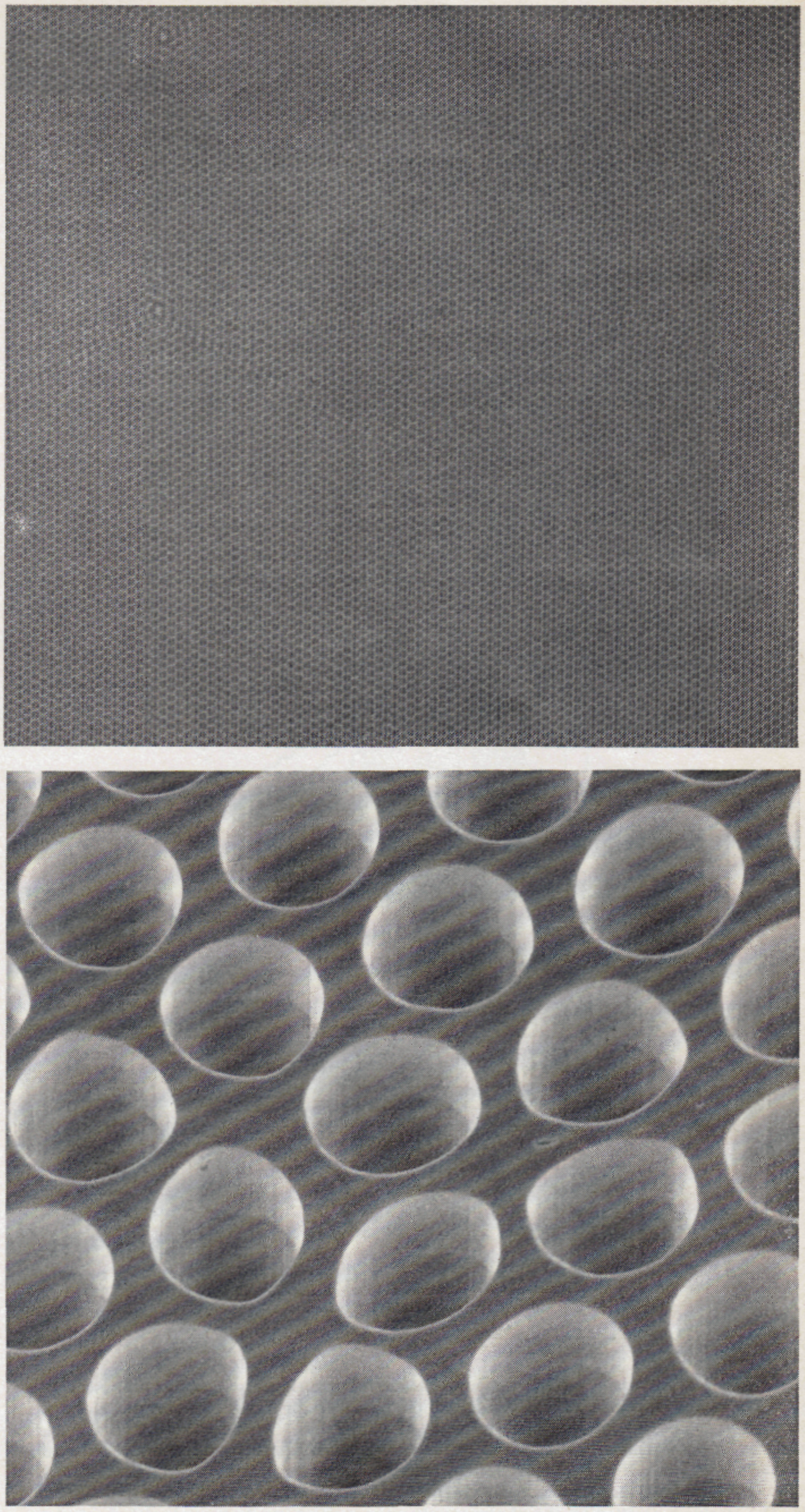
FINISHED MICROCHANNEL PLATE is a thin wafer that can be installed in image tubes of various designs. The standard 25-millimeter microchannel plate shown incorporates some three million microchannels that can brighten an image by a factor of about 10,000. The microchannel plate was fabricated by the Galileo Electro-Optics Corporation in Sturbridge, Mass.

nal cannot exceed the maximum current that can be sustained in the walls of the microchannel. When the flux of electrons is too great, electric charge removed from the glass is not replaced immediately and the field is modified; as a result the overall gain of the channel is reduced. Bright parts of an image can thereby become saturated and the contrast in such regions of the image is lost. Although the effect is undesirable in astronomy, where a well-calibrated dynamic range is required, it can be beneficial in night-vision devices, where high contrast in bright parts of an image might diminish the sensitivity of the observer's eye to darker regions.

A second limitation of channel multipliers is a phenomenon called ion feedback. When the channel is operating at high gain, gas atoms in the channel can be ionized by collisions with the cascading electrons. (At least a few such atoms are present even in the best attainable vacuum.) A positively charged ion formed in this way is accelerated by the electric field toward the input end of the tube, where it may strike the channel wall and initiate a new cascade. The new cascade can cause further ionization and the additional electrons tend to mask the signal. Moreover, ions that strike the photocathode can shorten its life, although damage of this kind is now routinely prevented by depositing a thin film of aluminum oxide, permeable to photoelectrons but not to ions, over the entrance face of the plate.

One way to minimize ion feedback is to make the channels curve or zigzag. Then the electrons easily cascade toward the anode, but the ions are inhibited from moving toward the photocathode by collisions with the walls. Although the simplest way to cut such channels is by photolithographic etching, the process, as I have indicated, is not technically satisfactory. In applications where high gain is needed two or more plates are often stacked and rotated with respect to one another. Since the wafer faces are not cut at a right angle to the channel bore, each resulting microchannel effectively turns a corner partway along its length. Successive cascades of electrons readily follow the path around the corner but ions do not because they do not initiate cascades of other ions. By this strategy the applied voltage (and hence the gain) can be substantially increased before the threshold of regenerative ion feedback is reached.

In an effort to form curved microchannels and so minimize ion feedback groups at several laboratories are exploiting the predictable variation of glass viscosity with temperature. If a glass microchannel plate is sandwiched between metal blocks that are at different temperatures, a uniform tempera-



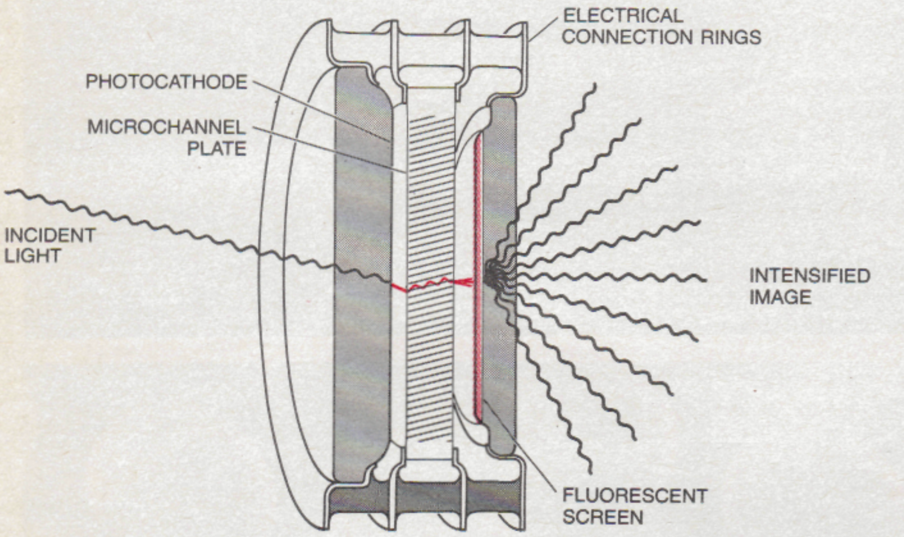
UNIFORMITY OF SIZE AND SPACING of the microchannels is critical to the transmission of high-quality images. A microchannel plate made from drawn-glass fibers exhibits good uniformity, as is shown in the two photomicrographs. In the upper photomicrograph, made by Adolf R. Asam of the ITT Electro-Optical Products Division, a microchannel plate is enlarged 110 diameters; its hexagonal secondary structure is clearly visible. In the lower photomicrograph, made by the author, a second microchannel plate is enlarged 650 diameters. The latter microchannels are 40 micrometers in diameter and are spaced 50 micrometers apart.

ture gradient is set up in the plate. Close to the hotter block the glass is more fluid. If the plate is "ironed" by displacing one of the blocks sideways, the microchannels tilt more near the hotter block than they do near the colder one. Hence each microchannel is bent into a curve. Although curved-channel plates are still experimental devices, they can multiply secondary electrons by a factor of about a million without ion feedback, and they exhibit the same resolution of spatial features as conventional microchannel plates.

A third limitation of a channel multiplier is the charge density of the electrons in the channel, which is called the space charge. When the electron cascade reaches a linear density of about 10 million electrons per millimeter, mutual electrostatic repulsion tends to return additional secondary electrons to the surface of the channel before the field can significantly accelerate them. The result is to limit further growth of the cascade. In many applications the effect is actually beneficial because it makes the output pulses of the multiplier more nearly identical. Random fluctuations in the total charge carried by each cascade are thereby suppressed.

The fourth limitation of the microchannel plate governs its efficiency. The surface area of the entrances to the channels is less than the surface area of the entire plate. If circular channels are employed, the ratio of the total channel cross section to the plate area must be less than 91 percent owing to geometric constraints; because of the thickness of the channel walls the ratio in most microchannel plates is only about 55 percent. Thus about half of the input flux strikes the metal-plated web area between the channel entrances.

Certain strategies can be adopted to reduce this loss. If a strong electrostatic field is applied to the front of the plate, the electrons emitted from the web areas can be pulled into an adjoining channel and so initiate a cascade. The entrances to the channels can also be made funnel-shaped by etching the wafer, raising the ratio of channel area to total surface area. Several laboratories are experimenting with square or hexagonal channels, which pack together more efficiently than channels with a circular cross section.



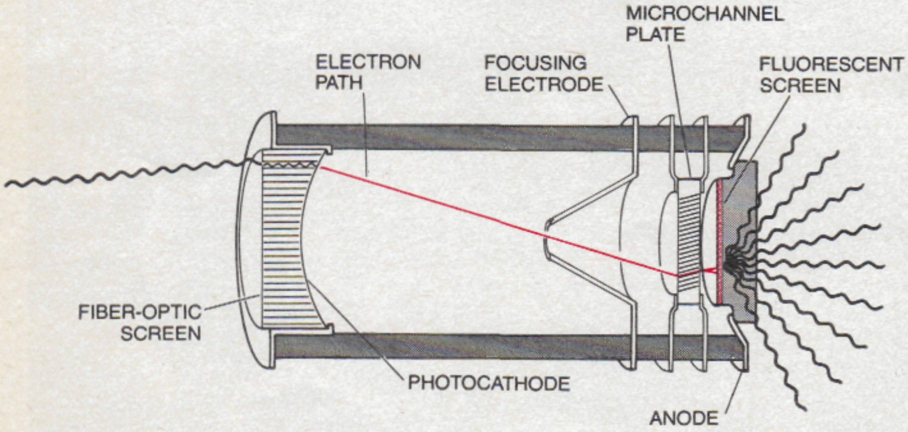
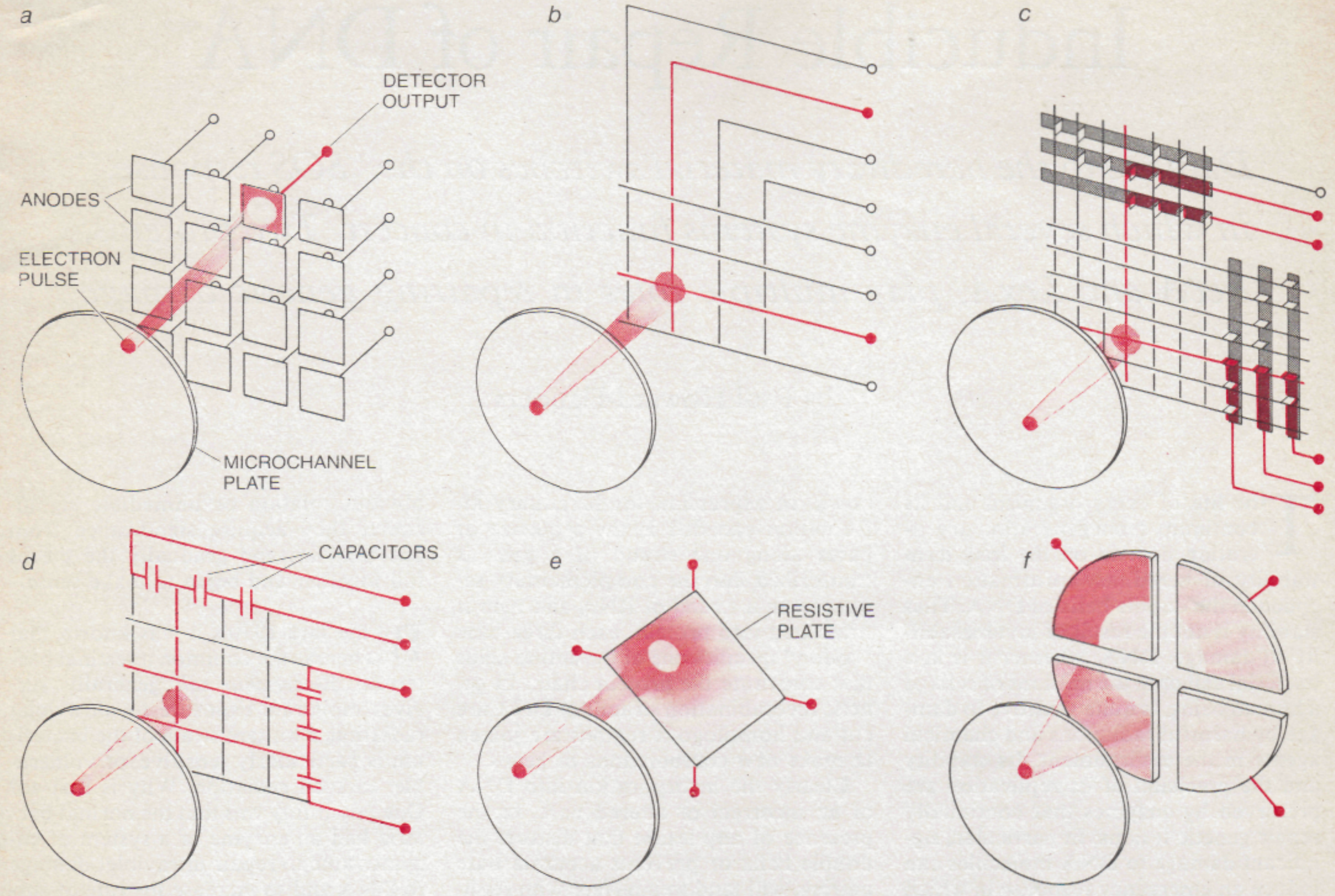


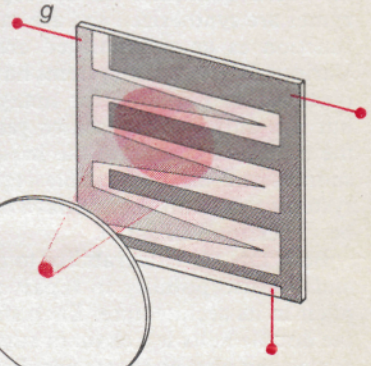
IMAGE TUBES incorporate microchannel plates in two principal configurations. In each configuration the plate is sandwiched between a photocathode, or negatively charged electrode, and a fluorescent anode, or positively charged electrode. The electric potentials of the electrodes on the microchannel plate are intermediate to those of the photocathode and the anode, so that the potentials of the four electrodes become more positive from left to right in the diagrams. The proximity-focused intensifier (*upper diagram*) is similar to a two-electrode intensifier. The electrons emitted by the photocathode cross a short gap to the microchannel plate, where they are accelerated and multiplied. The electrons emerging from the plate strike the anode, again across a short gap. The spatial organization of the input image is preserved because the two gaps are small enough to minimize electron dispersion. Photons enter an electrostatically focused intensifier (*lower diagram*) through a thick fiber-optic window that seals the evacuated interior of the image tube. On the inside of the window is the photocathode; the electrons it emits are focused by an electric field onto the microchannel plate. In this way the brightened image is inverted, so that the image tube can be conveniently mated to additional optical systems that also invert an image. Hence the output image will not be inverted. By changing the focus of the electron beam the image can also be magnified or reduced in size.

The output of a microchannel plate need not be registered on a fluorescent screen. In many applications, such as the remote sensing of photometric data from a spacecraft, there is a need for an electrical rather than a visual output. The simplest such sensor is the microchannel photomultiplier; it resembles a proximity-focused microchannel intensifier in which a simple metal anode replaces the fluorescent screen. An electrical output pulse is obtained from the anode each time electrons cascade through the microchannel plate. Because of the extremely brief delay between the stimulus and the amplified output pulse the microchannel photomultiplier has been employed for counting individual photons and for measuring the flight time of subatomic particles produced in accelerators.

A conventional photomultiplier has only one connection for its electrical output, and so it is not suited to the sensing of images. A microchannel photomultiplier, on the other hand, can be designed so that the position of an output pulse on the anode can be decoded electrically. Conceptually the simplest way to accomplish this is to provide each pixel with its own anode and detecting circuit. The technique is limited to the output of rather coarse images, however, because the number of anode wires and trigger circuits (which must be equal to the number of pixels) cannot be increased indefinitely.

In order to reduce the number of trigger circuits each pulse can be detected simultaneously on overlapping grids of vertical and horizontal wires. If the pulse triggers the nearest vertical and the nearest horizontal wire in the grids, the number of circuits required varies as the square root of the number of pixels. More complex arrangements can yield





ANODES OF DIVERSE DESIGN register the position of a pulse of electrons emerging from a microchannel plate so that image data can be stored and manipulated. Coarse resolution can be obtained by detecting the position of the pulses on an array of separate anodes (*a*). For higher resolution the number of anodes required makes the circuitry prohibitively complex, and other designs are employed. Some of them measure the position of a pulse by depositing charge on a pair of wires in a horizontal and a vertical grid. Each wire in the grid can have its own detection circuit (*b*), or the position of the pulse can be encoded as a binary number (*c*). The latter configuration requires fewer detection circuits for a given image resolution. Other designs detect a cloud of charge on various portions of the anode and determine the position of the pulse by comparing the charge in one circuit with that in another. Charge ratios must be calculated in both the horizontal and the vertical directions so that the spatial coordinates of the pulse can be determined. The charge can be measured at both ends of two capacitor strings (*d*), on the four corners of an electrically resistive plate (*e*), on the four quadrants of a disk (*f*) or on more complex geometrical arrangements of electrically insulated anodes (*g*). In each case the ratios of the charge detected by the various circuits can frequently give the position of a pulse on the microchannel plate to within a few thousandths of the diameter of the field of view.

still more efficient encoding of the positional information. In particular, if the pulse can trigger any combination of wires in the grids, every possible combination of wires can code for some position of the pulse. With such a configuration the number of circuits varies only as the logarithm of the number of pixels.

Another kind of position-sensing anode encodes the coordinates of the electron pulse in an analogue, or continuous, manner. I shall describe one recently developed arrangement that employs only three detecting circuits. The anode is made up of three metal electrodes placed well away from the output face of the microchannel wafer, so that a portion of the electron cloud associated with every electron cascade is intercepted by each of the electrodes. One of the electrodes has a zigzag shape and divides the plane of the anode into two parts [*see illustration above*]. On one side of the zigzag the area of the charge-collecting electrode varies linearly with the x coordinate and is independent of the y coordinate. The area of the electrode on the other side of the zigzag varies linearly with the y coordinate and is independent of the x coordinate. By amplifying and measuring the charge pulses on all three electrodes independently and then calculating the ratios of the pulses received by the x-dependent and y-dependent electrodes to the sum of all three pulses, the position of the output pulse can be accurately determined. The design was originally suggested by Hal O. Anger of the University of California at Berkeley.

My colleagues and I in the Space Sciences Laboratory at Berkeley have adopted Anger's scheme for two spaceflight applications. Four other groups are also seeking to incorporate the detector into photomultipliers that count photons at visible wavelengths. Such a position-sensitive detector can function as the input device for a computer system that can then record and analyze the data. Hence the microchannel plate can serve as an intermediary between incoming radiation and outgoing data of almost limitless variety. Systems of this kind may lead to significant advances in physics and astronomy.