Indicator lamps used in key telephones should be highly visible, use little power, have long life, and be economical to make. A new light-emitting diode made of gallium phosphide outshines the conventional incandescent light bulb in all of these respects.

A Solid Future For Telephone Lamps

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DURING THE PAST TEN YEARS a number of scientists at Bell Laboratories have concentrated on growing crystals of gallium phosphide (GaP) and studying the physics of light generation in GaP semiconductors (see *Luminescence in Semiconductors*, RECORD, *March 1968*). One practical result of this work is a solid-state light source, in the form of the GaP light-emitting diode (LED). The purpose of this article is to examine three questions related to the use of solid-state light sources: Why use solid-state rather than conventional light sources? What design is best? And what does it mean to the telephone business?

The reasons for using solid-state light sources are similar to the reasons for replacing electron tubes with solid-state components. Low power consumption, small size, fast switching speed, low operating temperature, and long life are all common advantages of solid-state devices. Moreover, these devices are extraordinarily reliable and cost relatively little to produce.

Another reason for using solid-state light sources is their compatibility with the existing technology. Today, production of semiconductor components is in full swing, with silicon integrated circuits assuming a major role. These tiny integrated circuits usually operate at low voltages, low power levels, and high speed, and are mounted directly to circuit boards. The wafer size, electrical performance, and processing technology of GaP LED'S are compatible with these integrated circuits, while the power consumption, size, and speed of conventional light sources would present interface problems.

The importance of compatibility can be illustrated on one of our larger telephone systems, the key telephone system. The purpose of key telephone systems, of course, is to extend the service of the conventional telephone. Using a key, or pushbutton, the customer can gain access to any of various telephone lines, talk over a built-in intercom system, or put one line on "hold" while answering another. In most key telephone sets, the pushbutton, when actuated, stays mechanically locked in position until another pushbutton is actuated. With the present key telephone system:

• Service is initiated via a mechanical switching and locking apparatus, the mechanical pushbutton.

• Since all logic functions are wired into the telephone set, a bundle of 50 wires is required for every 6-button set (200 for a 30-button CALL DIRECTOR® telephone).

• Services are assigned to individual pushbuttons by the installer, according to the customer's needs.

• The pushbutton corresponding to an active line is indicated by a light from an incandescent lamp, which consumes 400 milliwatts and is operated on local power.

The advancement of silicon integrated circuit technology and the resulting electronic switching circuits will soon make possible an electronic key telephone system, in which the logic functions and power supply are contained in central control equipment. This new system will greatly extend the services offered by the key telephone. With the new system:

• Nonlocking buttons can be used with little mechanical movement and with electronic switching.

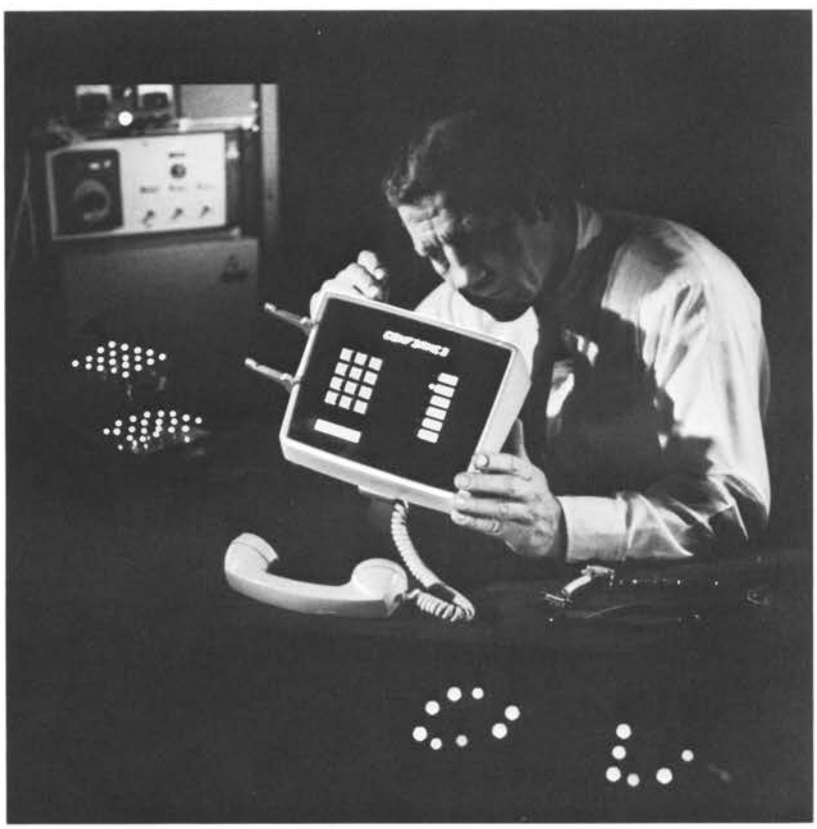
• Since logic functions are to be carried out by the central control unit, the number of wires needed for each set can be reduced to only six, even for the Call Director phone.

• Services can be assigned to a particular button from the central control unit, not at the telephone set itself.

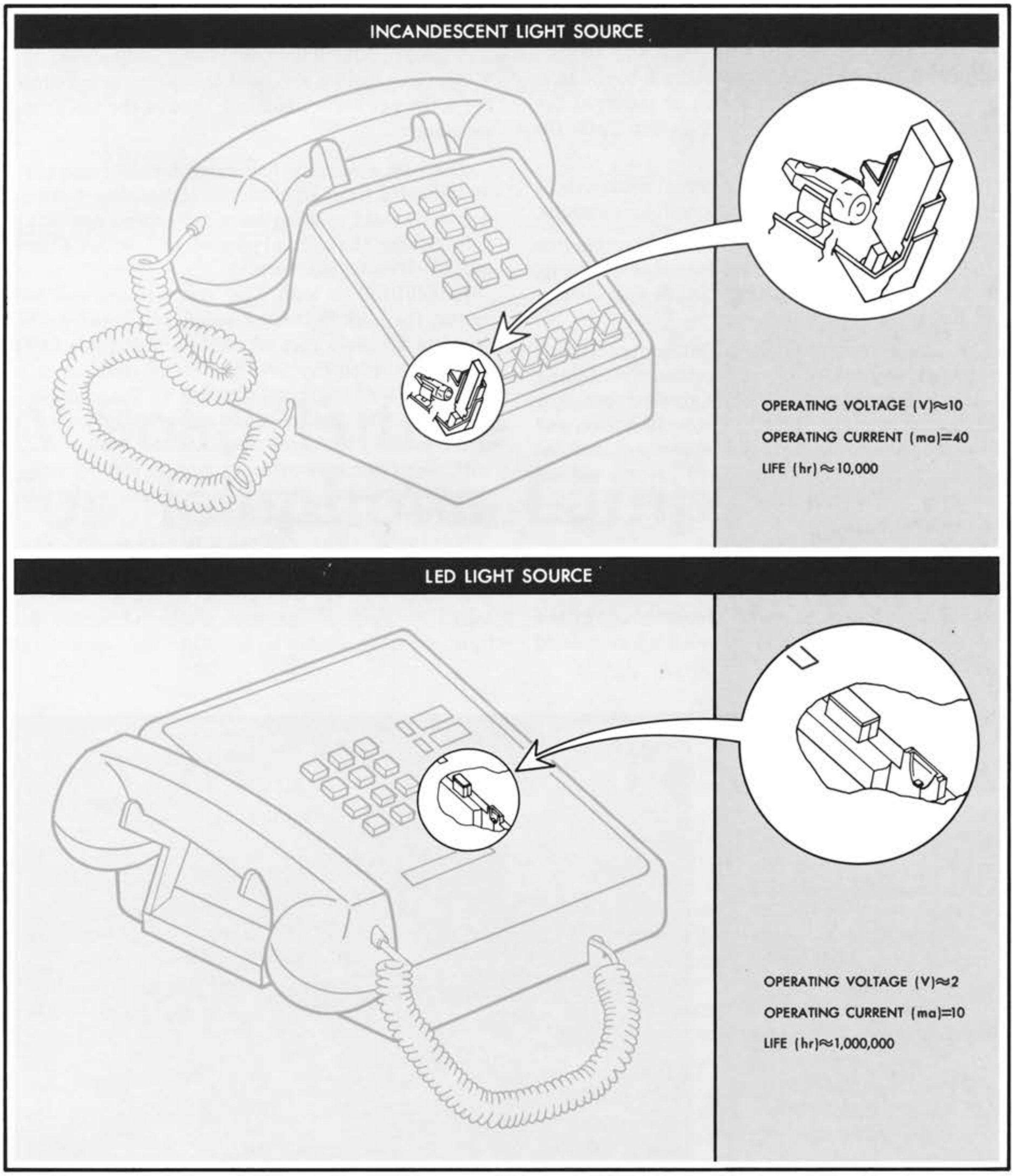
The new system will require a solid-state type of indicator light because the incandescent lamps currently used require more power and operating voltage than the central control unit, with its integrated circuits, can furnish.

In addition to long life, low voltage, and low power, the high switching speed, small wafer size, and low ultimate cost of gallium phosphide LED's may also permit the development of electronically controlled alphanumeric displays on the telephone. Such a display can be used to provide a check for numbers dialed into the telephone, to communicate with electronic memories, or even to display emergency information across the faceplate of the telephone while it is being used.

Having enumerated the advantages of solid-state light sources, let us consider some of the factors that go into designing them. In the key telephone system, the first design objective for light-emitting diodes is to obtain maximum light



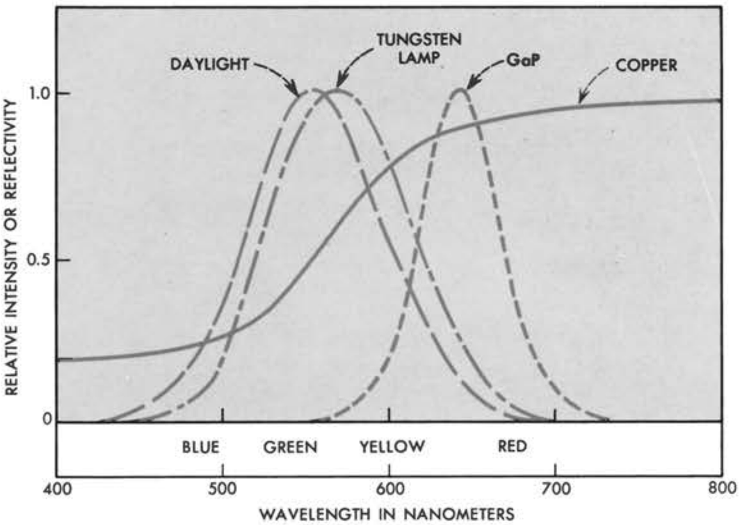
Future multibutton telephone sets, similar to this experimental version, will use LED's, not only as indicator lights, but also in alphanumeric displays that convey messages across the face of the telephone.



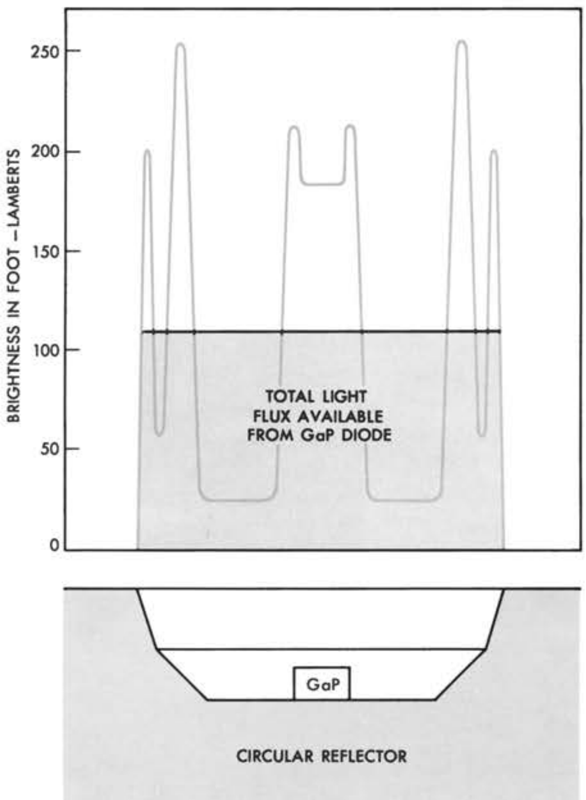
A comparison of the incandescent lamps now being used in multibutton telephone sets and the solid-state lamps planned for future use. Note the substantial reduction in space required by the new LED light source, as well as its superior operating characteristics and extraordinary life expectancy.

intensity per unit cost consistent with high reliability. This, of course, often involves a compromise of contradictory optical, thermal, and electrical requirements. At Bell Labs, computer studies have shown that the highest performance for operation at a current of 10 milliamperes can be expected from a diode approximately 0.2 millimeter on one side. The structure of the indicator light must be designed to distribute the light produced in the best way possible.

Used in a key telephone set, a GaP light-emitting diode approximately 0.2 millimeter in size would produce a brightness level of about 1500 foot-lamberts, when operated at 10 milliamperes, as compared to the usual desk-top level of 100 foot-lamberts in a typical well-lighted room. To make the light pleasing in appearance as well as highly visible, we must trade part of this brightness for area and contrast. This tradeoff is the essence of indicator light design.



An ideal reflector reflects only the light emitted by a specific light source. The curves show how close a copper reflector comes to reflecting all of the light from a red-light-emitting GaP diode.

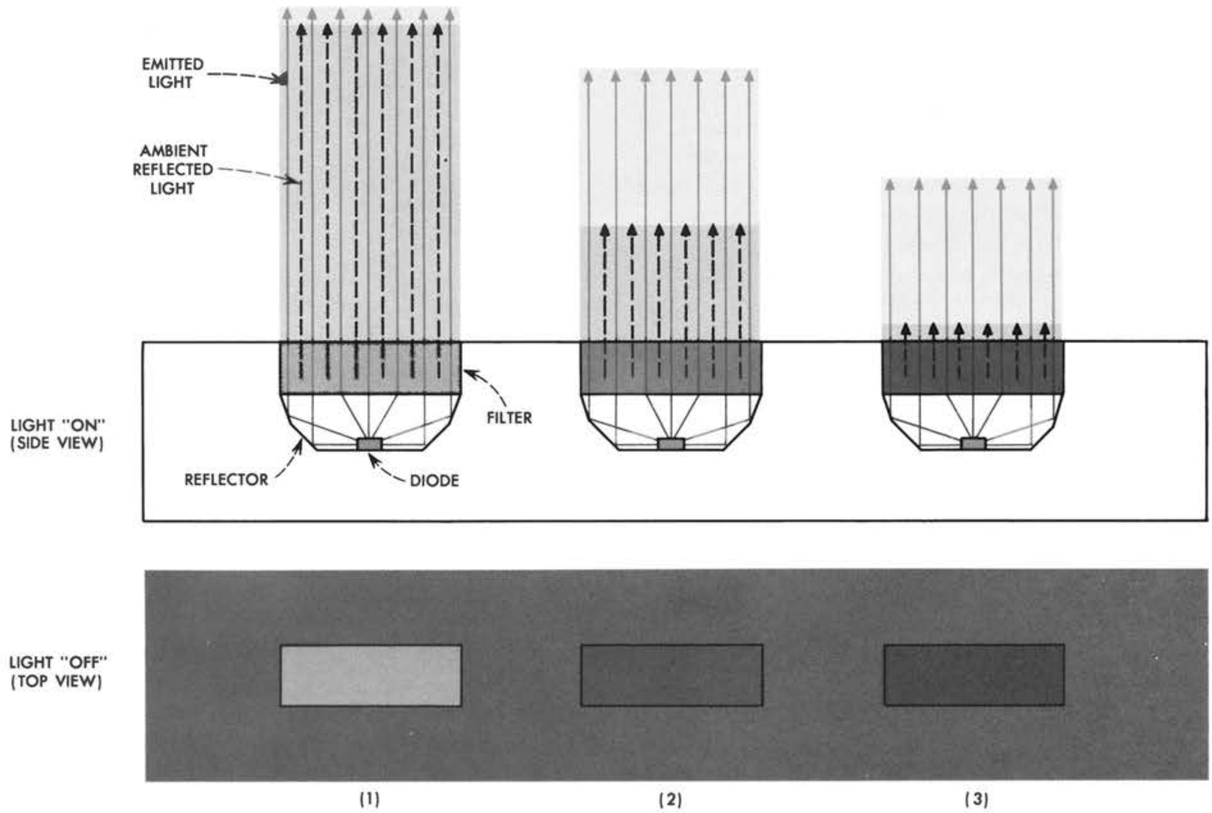


A small GaP light-emitting diode is placed in a circular copper reflector. The total light flux emitted from a 1-percent diode at 10 milliamperes is represented by the shaded area of the graph. This light, if evenly distributed over the reflector, would equal a brightness of about 100 foot-lamberts. The facets of the copper reflector, however, produce an uneven distribution of light as shown by the alternating peaks and valleys in the graph. This enhances the visual impact of the emitted light.

Light emitted from a gallium phosphide LED can be spread over a larger area by using a reflector, fiber optics, or a transparent medium with a high index of refraction. Each of these methods requires that we control the radiation pattern of the semiconductor wafer. By selectively roughening the surfaces of the diode, we can shape its radiation pattern to fit the requirements of the light-spreading medium.

Spreading the light will thus reduce brightness, since brightness decreases as the lighted area increases. From 10 feet away, for example, a 10-milliampere diode, 0.2 millimeter in diameter, is easy to see but too bright. The same amount of light spread over a diameter of about two millimeters is about right for brightness and visual comfort. Beyond this size, the brightness would drop below 100 foot-lamberts, and as a result the lighted area might not be visible enough in a typical well-lighted room.

Other questions now arise. Does this brightness level provide enough contrast? In other words, when the light (a reflector surface containing an LED) is "on," is it visible enough against its background (the faceplate of the telephone) in a well-lighted room? When it is "off," does it pick up reflected light from elsewhere in the room and appear to be "on"? There are three ways of control-



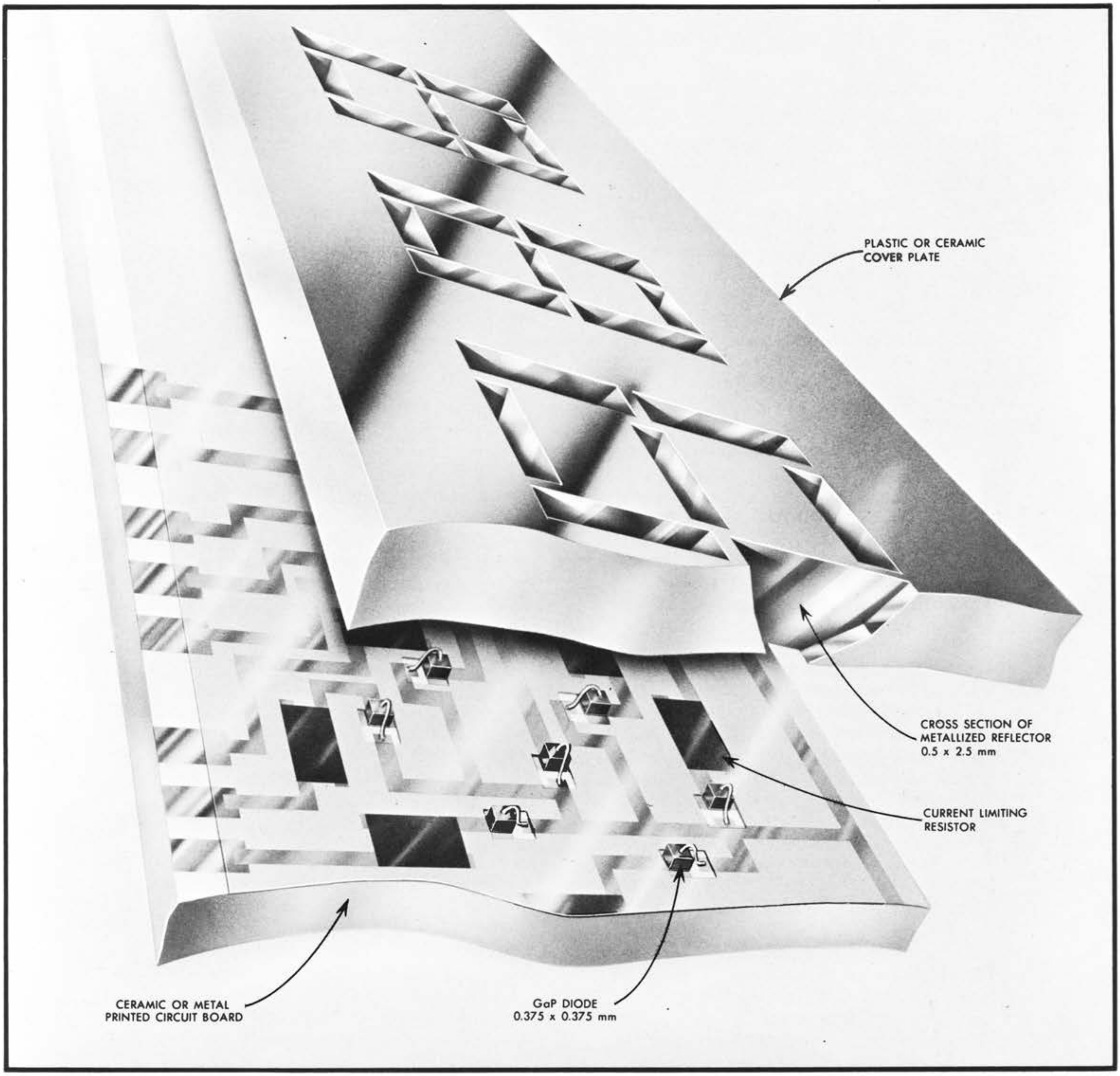
With a very low-density filter (1), the brightness of the light emitted from a diode is comparable to the brightness of reflected ambient light. This makes it hard to tell, for example, which lamp of the array on a key telephone is actually "on." With a denser filter (2), the contrast between emitted and reflected light increases and the distinction between "on" and "off" becomes obvious. The light reflected from the lamp itself is still much brighter, however, than the light reflected from the telephone faceplate around it, if the faceplate is dark. This makes it difficult to tell if all diodes are "on" or "off." A high-density filter (3) cuts the reflected ambient light by as much as 96 percent, thus eliminating the contrast between the lamp and the faceplate when the lamp is "off."

ling contrast. They involve the color and shape of the reflectors and the use of optical filters.

The color of a reflector can take advantage of the difference between the spectral distribution of the light in a room and the light emitted by the LED. An ideal reflector reflects all the light within the spectrum of the source and no light outside of the spectrum. In the case of red-emitting diodes this means that a red or reddish reflector surface should be used, since all but the red light will be absorbed by the reflector. Among metals, therefore, copper comes closest to being the ideal reflector material for red emitters (see illustration, top right, on page 323).

The shape of the reflector is another tool for enhancing contrast. In this case, its use is based on the fact that the eye can be fooled by the proper distribution of light. If the inner surfaces of a circular reflector, for example, are angled in certain ways, narrow concentric rings of light are reflected (see illustration at bottom left on page 323). The reflected light in these rings is three times as bright as the light reflected from other areas of the reflector. At close range, the alternating bright and dark areas present more contrast and better visibility. Viewed from farther away, they tend to fuse, resulting in a brighter looking lamp that appears to be the same size as the outer ring.

Optical filters can also be used to enhance contrast by transmitting the light emitted from the diode and absorbing most of the ambient light reflected from the lamp (diode and reflector). A red filter, for instance, transmits most of the red light



Numeric display assembly. The GaP diodes, along with the corresponding silicon integrated circuits, are mounted on a ceramic or metal printed circuit board. A plastic or ceramic cover plate distributes the light to obtain the 7-bar numeric display format.

while absorbing all the other colors. Thus, if a red filter is placed in front of the reflector, the light emitted from the diode has to compete only with the red part of the ambient light since the other colors are eliminated by the filter.

The use of the red filter reduces the brightness of both the light emitted from the diode and the ambient light reflected from the lamp. The contrast is achieved by reducing the brightness of the reflected light much more than the brightness of the light emitted from the diode (see illustration on page 324). A dark red filter, for example, eliminates as much as 96 percent of the reflected light while absorbing only 70 percent of the emitted light. How far we should go with the light absorption (shade or darkness of the filter) depends on the reflecting qualities of the telephone faceplate. If the solid-state lamp (reflector and filter) looks much brighter in the ambient light than the faceplate, the lamp will appear to be "on" at high levels of illumination, whether the diode is turned on or not. To maintain the "off" appearance at all levels of ambient illumination, darker faceplates generally require a darker red filter.

With their small size and low operating temperature, the new LED's are much more flexible in design than incandescent lamps. Practically any level of brightness can be attained with the proper reflector and filter design. In addition, diode fabrication and assembly techniques are well-advanced. In a key telephone set, for example, six diodes can be mounted by thermocompression bonding to a ceramic circuit board similar to that used for silicon integrated circuits, and the reflectors for these diodes can all be contained in a single metallized cover plate. Similarly, the filters can be made part of the diode assembly, or a transparent section can be molded into the faceplate of the telephone. The resulting assembly is effective as an indicator light up to 10 feet from the telephone at high levels of ambient illumination, using only 5 percent of the power currently required by incandescent lamps.

As mentioned earlier, the attributes of the new LED's can also be applied to a numeric or alphanumeric display, in which numerals and letters are formed by the emitted light. Again, the diodes and drive circuit can be mounted on a printed circuit board, with the reflectors contained in the cover plate (see illustration on page 325).

Along with the work on specific telephone applications, research continues at Bell Laboratories on the physics and the chemistry of the new devices. Gallium phosphide LED's with an external quantum efficiency of approximately 1 percent are now being evaluated in an electronic key telephone system at the Mountain States Telephone and Telegraph Company in Phoenix, Arizona. With their excellent performance, design flexibility, and low cost, the new lamps show a great deal of promise. At the same time, diodes with greater than 7 percent quantum efficiency have recently been fabricated at Bell Laboratories. These diodes are the brightest and most efficient solid-state lamps known today. Their improved performance will be significant in a number of applications for indicator lights and alphanumeric displays in future telephone systems.