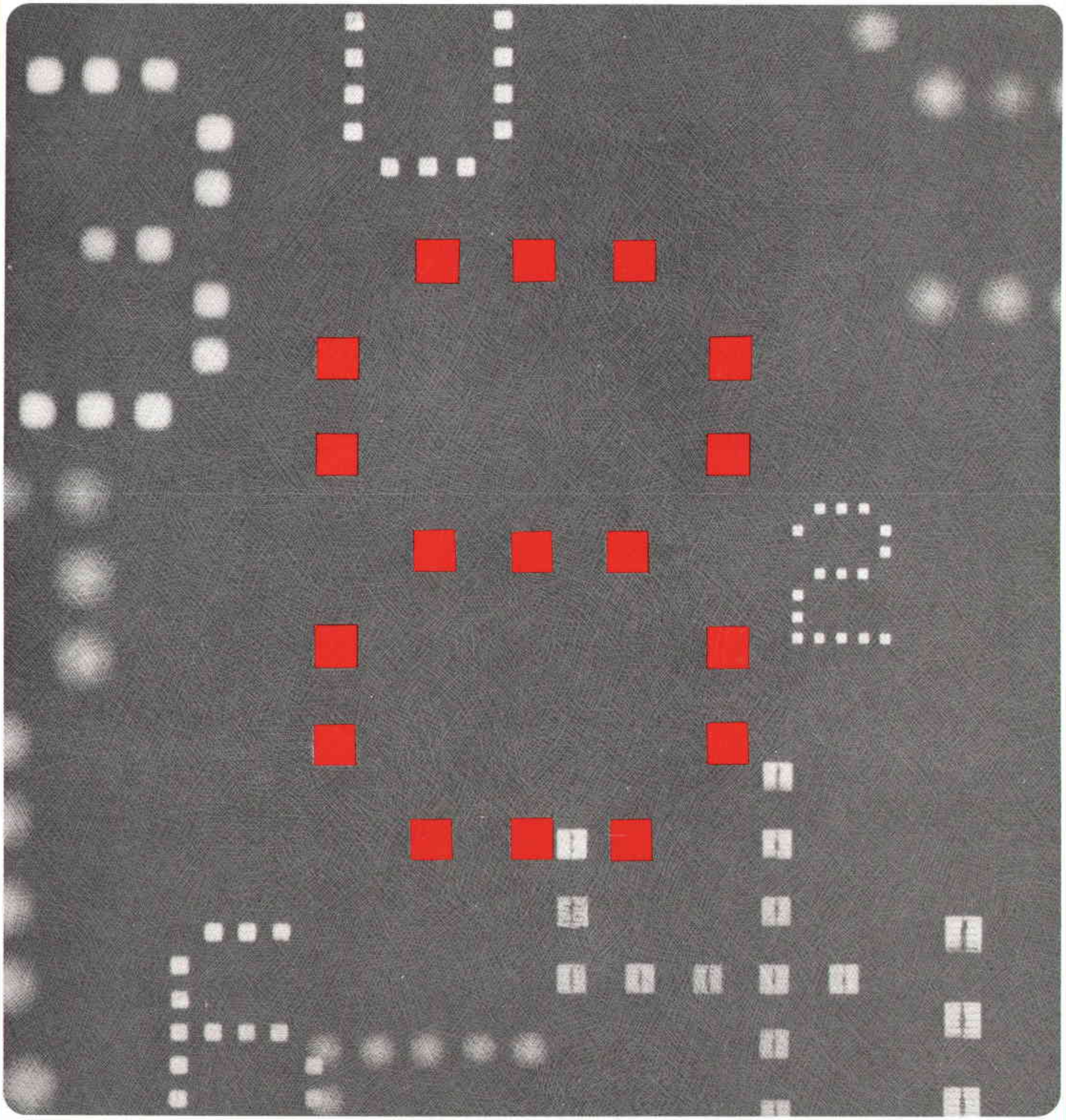
HEWLETT-PACKARD JOURNAL



FEBRUARY 1969

First in a line of solid-state display devices are these one- and three-digit numeric indicators. Compatible with integrated circuits, they need only BCD input signals and five-volt power to display any numeral from 0 to 9 in an array of bright red dots.

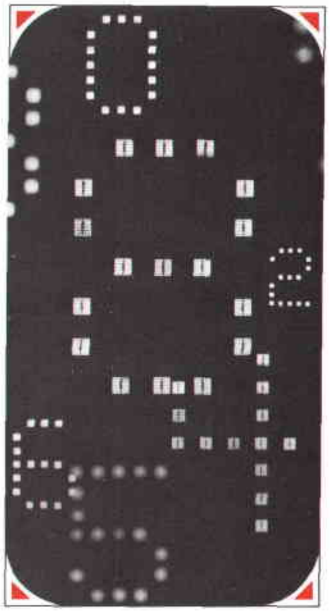
Solid-State Displays

By Howard C. Borden and Gerald P. Pighini

SOLID-STATE DISPLAYS ARE HERE. Developing them has taken more than six years of research and development in light-emitting materials, plus Hewlett-Packard's resources in solid-state technology, integrated-circuit design and manufacture, ceramic metallization and etching, and optoelectronic packaging. The result is the new HP Model 5082-7000 Numeric Indicator, a small, low-power, all-semiconductor module which accepts four-line binary-coded-decimal input signals and displays the corresponding digit, 0 through 9, as an array of brightly glowing red dots (Fig. 1). A similar but larger module, Model 5082-7001, displays three digits in line.

Compatibility with integrated circuits is a significant advantage of the new solid-state indicators over other types of display devices. They need only five-volt power and logic levels of 0 and 5 volts (nominal), compatible with transistor-transistor logic (TTL) and diode-transistor logic (DTL).

IC compatibility, in fact, was the principal motivating factor in the development of the solid-state display. However, it wasn't the only one. The list of advantages of solid-state displays is impressive. Among them are thin single-plane presentation, ruggedness, and high 'solid-state' reliability. Because they are free from fundamental degradation mechanisms, they are expected to have long life. They don't generate RFI, and they are amenable to low-cost, high-volume production using semiconductor batch fabrication techniques.



The new solid-state indicators have other advantages as well. They have a surface light distribution which gives constant brightness over wide viewing angles. They have high contrast and color purity, both of which contribute to readability. They are free from parallax because they produce all numerals in the same plane, and they respond in less than one microsecond to input-code changes; hence they are useful as readout devices when test results are being photographed with high-speed cameras. The brightness of the solid-state indicators is voltage-variable; it can be adjusted for optimum readability under widely varying ambient light conditions.

Obvious uses of the new indicators are in instrument panels, status boards, and information displays, or anywhere a need exists for a compact, IC-compatible, variable-brightness readout module that can perform both the decoding function and the readout function. The possibilities for these indicators and for future solid-state displays are intriguing; some are discussed on page 4.

Itself an instrument manufacturer, Hewlett-Packard may eventually become its own best customer for solid-state readouts, especially where a large character font is needed. Limited character font is a disadvantage of gaseous display tubes. Where greater flexibility in alpha-numeric and symbolic display is needed, as in the

PRINTED IN U.S.A.

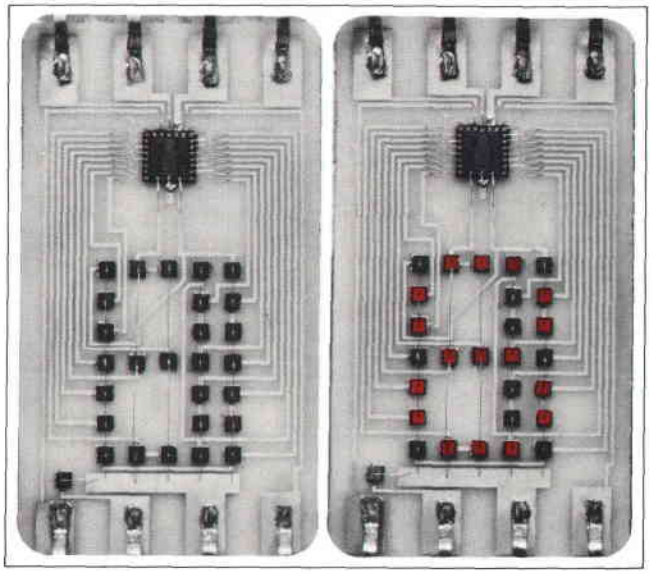


Fig. 1. *Model 5082-7000 Solid-State Numeric Indicator accepts four-line BCD and displays any numeral from 0 to 9 in an array of bright red dots. It takes five-volt power and logic levels compatible with integrated circuits. Shown here is the bare module; mounted behind red glass, only the numeral is visible.*

HP Model 9100A Calculator, HP has used cathode-ray-tube displays. CRT's are still the most economical solution to the type of display requirements found in the calculator. However, CRT's are large, need high voltages, and must have circuits to generate and recirculate the characters. Although we don't have it yet, an all-solid-state alternative to the CRT seems to be desirable. The new numeric indicators are a first step in that direction.

Optical Characteristics

A display is an interface between a machine and a man. The man is affected by the optical characteristics of the display. Character font, size, color, viewing angle, brightness, and contrast all contribute to the subjective effect of the display on the man.

Character Font. Fig. 2 shows the character font of the new numeric indicators. The numerals 0 through 9 are produced by selectively energizing a matrix of gallium arsenide phosphide [Ga(As,P)] light-emitting diodes. There are 28 diodes: 27 are arranged in a 5 x 7 rectangular array (not all of the 35 matrix locations are occupied by diodes) and the 28th is offset at the lower left to serve as a decimal point.

The characters are designed to preclude ambiguity. It is unlikely that one number will be mistaken for another, even if one or two diodes should fail to light.

In this Issue: *Solid-State Displays;* ***page 2.*** *Solid-State Displays — Present and Future;* ***page 4.*** *Measuring Luminance;* ***page 10.*** *Hybrid Hot Carrier Diodes;* ***page 13.*** *Hybrid Technology Produces Many Useful New Devices;* ***page 16.***

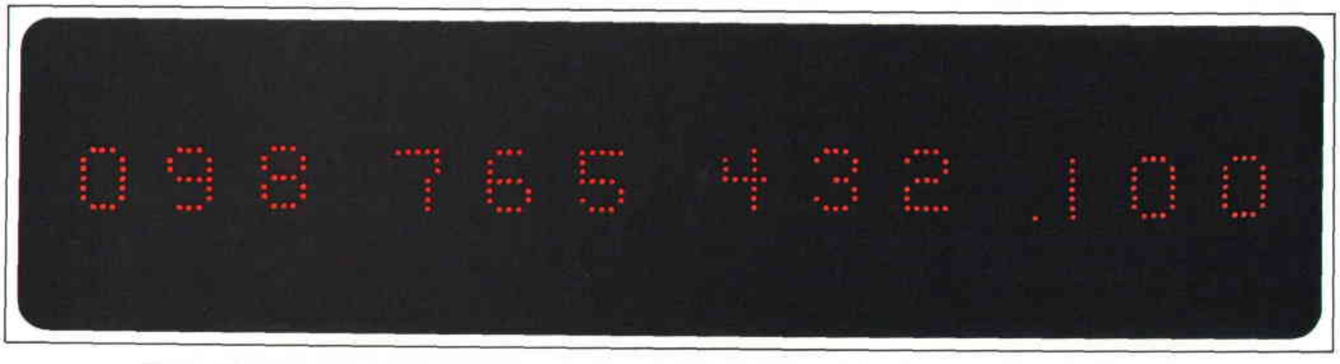


Fig. 2. *The new solid-state indicators come in one-digit and three-digit modules. Here four three-digit modules display the full character font, which includes the numerals 0 through 9 and a decimal point.*

Solid-State Displays, Present and Future

The new one-digit and three-digit solid-state numeric indicators are only a beginning. Larger and smaller characters, larger character sets, more colors, and discrete light sources are under development. Different kinds of displays are in the future.

Using What's Available Now

Small size, low power, low voltage, and high brightness make the presently available ¼ inch numeric indicators suitable for a wide range of applications in commercial and military equipment. Displays with as many 250 to 275 characters per square foot can be assembled using one-digit and three-digit modules. An obvious use is for numeric readouts from instruments and electronic data processing equipment. In telemetered or computer-driven status boards, the modules' small bulk and high image definition should prove valuable. The numeric indicators have no sealed-in toxic gases and operate at low voltages, and so are particularly well suited for closed environments, or for environments where there are explosion hazards. Their red color makes them useful for displays in darkrooms or in areas where personnel must be dark-vision adapted.

Color TV Still Years Away

Although it will surely happen, perhaps another ten years will pass before solid-state display technology is sufficiently advanced to make a wall-mounted color television set practical. Red, blue, and green light-emitting diodes will be needed to produce the visible spectrum with acceptable color fidelity, and at present we lack the means for producing the blue ones. Cost is another problem. About a quarter-million points would be needed for a standard TV presentation. At today's production costs, the chips alone would cost nearly $25,000 for a five-inch-wide screen. Power requirements are also a problem. A five-inch-wide screen, 25% saturated to a luminance of 75 footlamberts, would need about 100 watts. A square foot of diodes driven solidly to a brightness of 50 footlamberts would draw about one kilowatt, at the electroluminous efficiencies that are typical of today's materials. For all these reasons, a solid-state color TV seems to be years away.

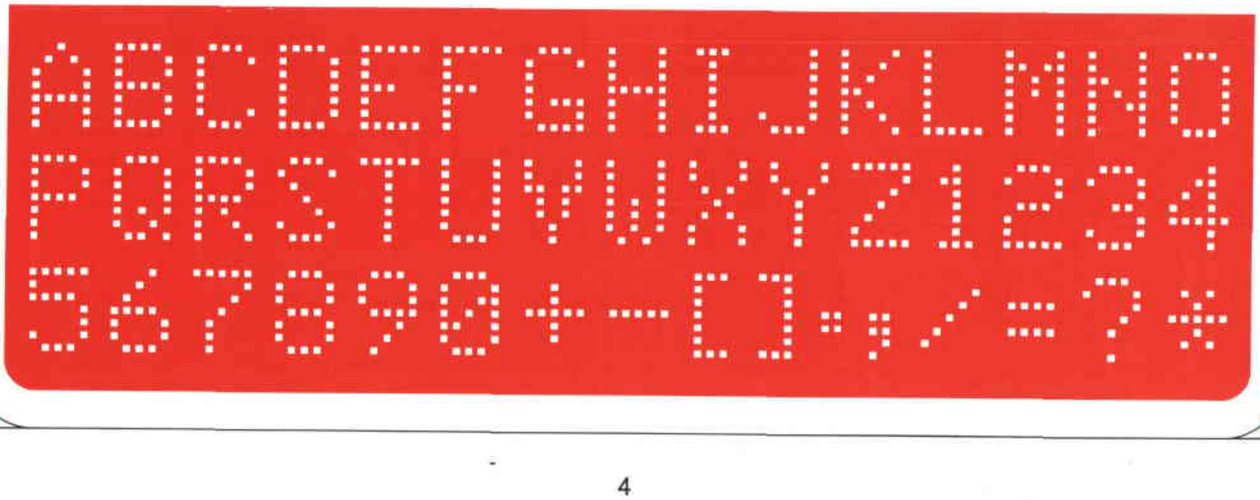
What About the Near Future?

Somewhat nearer to reality than solid-state television displays are smaller solid-state characters and symbols which can be incorporated in probes, micrometers, and other tools, so the tools themselves will become digital measuring instruments. Small displays can also be head mounted, say in a pilot's helmet. Character densities of 50,000 to 250,000 characters per square foot are feasible, the size reduction being limited only by the human side of the *man-machine interface.*

Small displays are potentially useful as markers in optical instruments, too. One such application arises when recording data on film. An 18 x 32 dot pattern is sometimes used to identify frames for automatic scanning equipment. With their nanosecond turn-on and turn-off times, light-emitting diodes could easily supply the dot pattern, which could then be transmitted to the film by fiber optics.

Alphanumeric Modules Are Imminent

Almost ready for production at HP are alphanumeric indicators which use the same 5 x 7 dot matrix as the new numeric indicators, with all 35 positions in the matrix occupied by diodes. Six-bit ASCII code controls the indicators. The character font, illustrated below, includes the letters A through Z, the digits 0 through 9, and the symbols +, −,), (, ·, *, ?, =, /, and ,. Two integrated-circuit chips decode the inputs and drive the diodes. The IC's are designed so they can be modified easily and economically whenever a change of font is wanted.



Character Size. The characters are ¼ inch high. However, because of an unexplained subjective phenomenon, the characters appear larger by at least 50%. The apparent character height is about ⅜ to ½ inch. This phenomenon isn't visible in the photographs in this article, so the reader should be aware when looking at these photographs that a 'living display' would have a substantially different subjective effect. After a study of larger and smaller sizes in various display applications, it was decided that ¼ inch characters are quite satisfactory for general instrumentation display, and this size was selected for the initial products. People with normal vision can read the characters at distances up to 8 feet.

Both the one-digit and the three-digit indicators are intended primarily for mounting in a horizontal line. The minimum center-to-center spacing between characters in separate modules is limited by the package width to 0.570 inch. Within the three-digit module the character spacing is 0.400 inch, center-to-center. The minimum vertical center-to-center spacing is slightly more than one inch. Large displays in which each character is individually replaceable can be constructed out of one-digit modules; such displays can have as many as 250 characters per square foot.

Color. The color of the light emitted by the numeric indicators is red. It has a dominant wavelength of 655 nm and is of high purity. Although alloys of gallium, arsenic, and phosphorus can be made to emit any color between infrared and green, the luminance (i.e., visual brightness) of HP's Ga(As,P) alloy is greatest, for a given input energy, when the light has a wavelength of 655 nm. Red is also well suited for use in darkrooms, ready rooms, and other dark environments, since it impairs the eye's dark-adaptation considerably less than other colors.

Brightness. Typical Ga(As,P) diodes used in the numeric indicators produce luminances of 75 footlamberts with 4.0 Vdc applied to the module. At 50 fL brightness, the characters appear quite bright under normal factory lighting. Brightness can be varied between 5 and more than 50 footlamberts by adjusting the dc voltage applied to the 'LED+' terminal of the module. As shown in Fig. 3, the luminance variation is nearly linear from three to four volts.

Reduced display brightness is desirable in dark rooms, or where power is at a premium. The power input to the light-emitting diodes varies roughly linearly with LED+ voltage, as does the power dissipated in the current-limiting circuits in the module. Power to the logic circuits in the module remains constant at about 150 mW.

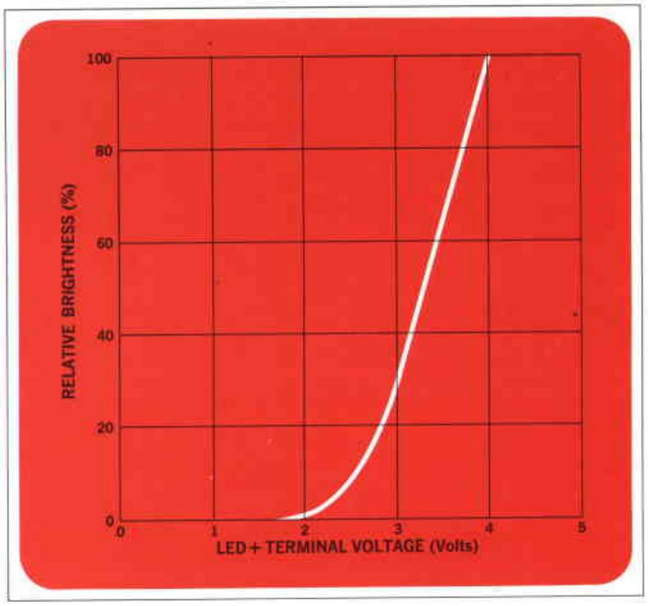


Fig. 3. *The brightness of the solid-state indicators can be adjusted by varying the voltage applied to the LED+ terminal of the module. Variable brightness and red color make the indicators useful in dark working environments.*

Contrast. Contrast is the ratio of the luminance of a lighted diode to the luminance of the surrounding area, which in this case is a white ceramic substrate with gold metallic striping. For optimum contrast, the numeric indicators should be viewed through a red 'notch' filter. (The filter isn't supplied with the indicators.) Ideally, the filter should transmit 100% of the red light from the diodes (density = 0) and 0.1% or less of the rest of the visible spectrum (density ≥ 3.0). Rohm and Haas' Plexiglas #2423 as it is presently manufactured isn't quite this good, but it is effective and inexpensive.

Viewing Angle. There are two general display situations. One is typified by bench-mounted instruments; here wide viewing angle is important, either so several instruments can be observed by one operator, or so a group of people can observe the same display. In such applications the new numeric indicators can be viewed from angles as great as 60° from the normal in a horizontal plane and as great as 70° in a vertical plane. They have a cosine, or Lambertian, surface light distribution, meaning their light is equally dispersed in all directions; this makes their brightness independent of viewing angle.

The second display situation is typified by an aircraft instrument panel, where the observer's head is in a relatively fixed position with respect to the display. In these situations it's often desirable to trade off wide-angle viewability for minimized light reflection or for the higher

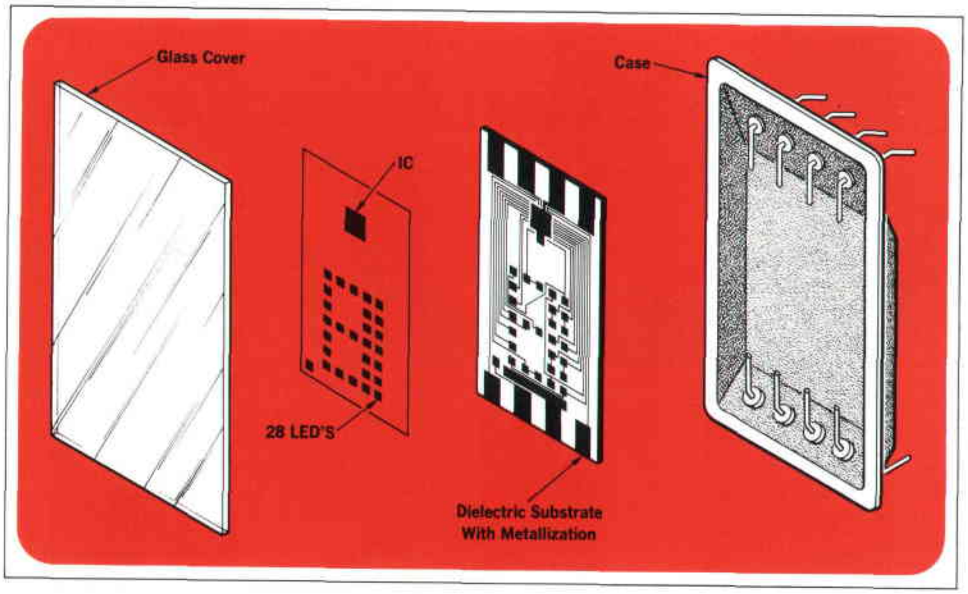


Fig. 4. *Model 5082-7000 Solid-State Numeric Indicators consist of 28 gallium arsenide phosphide red-light-emitting diodes and an IC chip containing some 400 circuit elements, all mounted on a ceramic substrate and sealed in a case designed for wide-angle viewability. On the substrate is a metal interconnection pattern.*

efficiency possible with narrow-lobe light emission. The radiation pattern of the numeric indicators can be modified by appropriate filters, lenses, and shades.

Electrical Characteristics

While the optical characteristics of the man/machine interface are important to the man, the machine is more interested in the electrical characteristics of the display.

Each digit of the solid-state indicators has eight inputs. They are:

- one line for a 5 Vdc filtered power supply for integrated-circuit logic operation. This supply should be regulated to prevent overvoltage conditions and should be able to provide about 30 mA per digit.
- one line (LED+) for a 4.0 Vdc light-emitting-diode power supply, capable of providing up to 200 mA per digit.* If brightness variation is required, this supply should be variable from about 2.0 to 4.0 volts.
- four lines for 8-4-2-1 BCD negative logic, 3.5 V < '0' < 5.0 V, 0 V < '1' < 1.5 V. The BCD coding, Table I, conforms to ASCII coding.
- one line for decimal point control. A 10 mA, current-limited source is needed. It is turned on to illuminate the decimal point.
- one line for ground, common to all signals and power supplies.

The decoding circuitry has no memory, so the display will conform to the input code within less than a microsecond — typically less than 200 ns. The modules also have no overvoltage protection. Transients exceeding 6 V on the BCD lines or the integrated-circuit power-supply lead, or exceeding 5 V on the LED+ lead, may cause damage, so protection should be provided.

Table I. Binary Code Truth Table

X_8	X_4	X_2	X_1	Display
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	Blank
1	0	1	1	Blank
1	1	0	0	Blank
1	1	0	1	Blank
1	1	1	0	Blank
1	1	1	1	Blank

Note: Negative Logic '0' = Line High: $3.5 \leq V \leq 5.0$
'1' = *Line Low:* $0.0 \leq V \leq 1.5$

Mechanical and Thermal Characteristics

At 50 fL average diode brightness, and with the numbers 5 or 8 illuminated (17 diodes lighted), the light-emitting diodes dissipate about 250 mW. Another 250

---

* The LED supply may also be a full-wave-rectified unfiltered source of frequency 50 Hz or higher. Lower frequencies can be used if noticeable flicker is not objectionable.

mW is dissipated by the decoding circuitry. Hence the modules are rated at ½ watt per digit. Heat sinking should be adequate to dissipate this amount of power with a temperature rise of 10°C or less above ambient.

In mounting the display modules, care should be taken to protect their glass front windows. The indicators don't need a vacuum, so they'll continue to operate even with substantial package damage. However, the hermetic seal will be lost if the front window is broken, and this may reduce the life of the module.

The leads of the indicator modules are 0.100 inch apart, compatible with current printed-circuit-board practice.

How They're Made

Five basic elements make up the one-digit solid-state numeric indicators, as shown in the exploded diagram Fig. 4. All the parts except the case are manufactured by Hewlett-Packard. Tekform Products Company manufactures the case. The five elements are:

- A ceramic substrate. The front of the substrate is thin-film metallized and photolithographically etched to form an interconnection pattern consisting of 8 input pads and 18 output drive lines. The back of the substrate is also metallized so the thermal resistance between the substrate and the case will be low.
- Twenty-eight gallium arsenide phosphide red-light-emitting diode chips. Twenty-seven are arrayed in a 5 x 7 matrix and one is offset to serve as a decimal point. The cathodes of the diodes are bonded to the metal interconnection pattern on the substrate. The light is emitted from the anode side of the diodes. All of the anodes are wired togther and connected to the metallized substrate by ultrasonic lead bonding, using 0.001 inch aluminum wire.
- A monolithic silicon integrated-circuit chip. The chip translates standard 8-4-2-1 binary-coded-decimal input codes into 18 current-limited outputs which drive the 27 diodes in the 5 x 7 matrix. (A separate external source drives the decimal point.) The IC chip has only 18 outputs because certain combinations of the 27 diodes are always lighted together. The IC terminals are connected to the metal layer on the substrate by ultrasonic bonding, using 0.001 inch aluminum wire.
- A tin-plated Kovar® case with glass-to-metal-sealed leads. The case is designed for wide-angle readability of the characters. The ceramic substrate is soldered to the case.
- A glass window cover whose coefficient of thermal expansion is matched to that of the case. The glass is joined to the case with epoxy to form a hermetic seal.

® Westinghouse Electric Corporation

Ga(As,P) Light-Emitting Diodes

Each light-emitting diode chip is a simple mesa structure (see Fig. 5). An n-type alloy of gallium arsenide phosphide is grown epitaxially on a gallium arsenide substrate. The p region is then diffused and capped with a comb-type metal anode. The comb-type anode distributes the diode current evenly over the diode's cross-section while masking less than 25% of the light.

When forward bias is applied to the diode, the potential barrier at the junction is reduced so current can flow. Electrons are injected into the p region and holes are injected into the n region. Eventually these minority carriers recombine, and in some of the recombinations energy is given off as photons. Most of the light is generated in a space charge layer about 0.5 μm wide on the p side of the junction, where several percent of the recombinations result in near-edge photons — that is, photons whose energy is near the bandgap energy.

Since the anode surface is very close to the junction, most of the light generated internally reaches the surface. However, only a few percent of the photons escape. The loss is caused by internal surface reflection, which is a result of the difference between the refractive index of the Ga(As,P) alloy ($n \approx 3.5$) and that of its surroundings ($n \approx 1.0$).

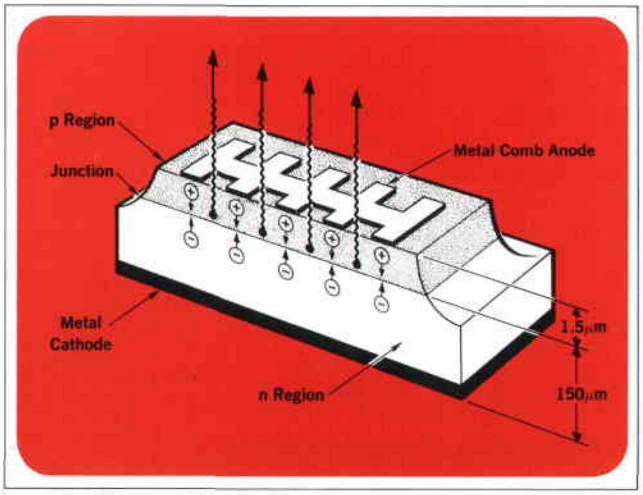


Fig. 5. *Each light-emitting diode chip is a mesa-type p-n junction diode. Light is given off in recombinations of minority carriers, predominantly on the p side of the junction. The comb anode gives even current distribution while blocking less than 25% of the light.*

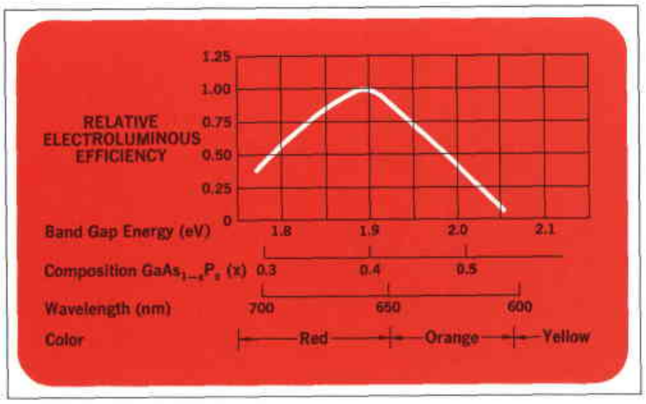


Fig. 6. *Red was chosen as the color of the light emitted by the new solid-state indicators because the electroluminous efficiency of HP's gallium arsenide phosphide alloy is highest for that color. Electroluminous efficiency is a measure of visual brightness per unit diode current. It is a function of the alloy composition, that is, the value of x in the formula* $GaAs_{1-x}P_x$.

At very low diode currents, that is, currents in the nanoampere range, only a small fraction of the total diode current contributes to light emission. As the current is increased into the milliampere range, the electroluminous efficiency also increases. Electroluminous efficiency, expressed in footlamberts per unit current density, is a measure of the perceived brightness that results from a given amount of current. Electroluminous efficiency becomes constant, and diode luminance increases nearly linearly, for diode currents of 3 mA to 100 mA. Typical diodes have junction areas of 0.002 cm^2 and electroluminous efficiencies of 15 footlamberts per ampere per square centimeter; this is equivalent to a brightness of 75 fL at 10 mA. Efficiencies as high as 100 $fL/A/cm^2$ have been observed in some diodes.

The light-emitting properties of the diodes are very stable with time. The diodes' half-life, the time required for the luminance to decrease to 50% of its original value, appears to be more than 100,000 hours. This estimate is based on presently available data, straight-line extrapolated to the 50% point.

Composition Determines Electroluminous Efficiency

Gallium arsenide phosphide has the formula $GaAs_{1-x}P_x$, where x is between 0 and 1. The value of x determines the optical bandgap energy, which in turn determines the radiation wavelength for near-edge emission (photon wavelength is inversely proportional to energy, and the energy of near-edge photons is approximately the bandgap energy). We have found that the electroluminous efficiency of the Ga(As,P) we are now producing is highest for a composition in which x is 0.4 (see Fig. 6). This corresponds to a bandgap energy of 1.9 electron-volts and a wavelength of 655 nm, and gives the diode its characteristic red color. Although the eye's response to this wavelength is only 10% of its peak response

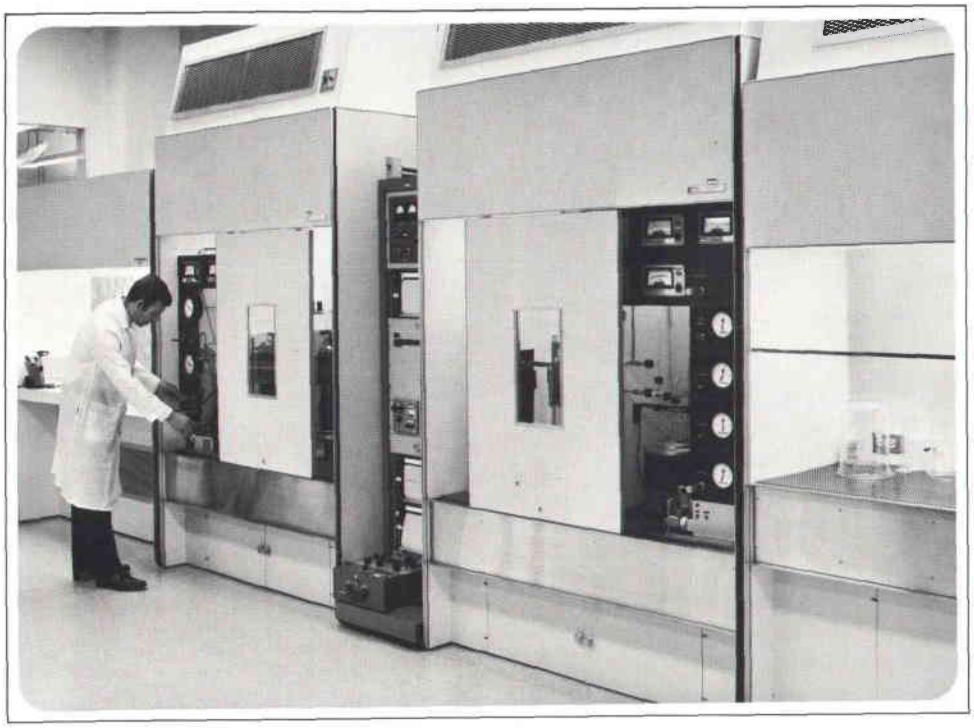


Fig. 7. *Ga(As,P) wafers up to two inches in diameter are grown in this HP-designed vertical-flow, RF-heated, cold-wall, dual-reactor, vapor-phase epitaxial system. The light-emitting diodes are made from these wafers. All parts of the solid-state indicators except the case are made by HP.*

(which occurs at 555 nm), it isn't possible to generate a brighter light for a given current at wavelengths shorter than 655 nm. This is because the number of photons generated per unit current drops more sharply with decreasing wavelength than the eye's sensitivity increases.

The tradeoff between the eye's response and the efficiency of photon generation, which is controlled by varying the value of x in the formula $GaAs_{1-X}P_X$, was only one of many tradeoffs that had to be decided upon as the light-emitting diodes were developed. Material was the first variable. Ga(As,P) was selected because its bandgap energy is high enough to provide visible light, its doping profile can be closely controlled, and its near-edge recombination mechanism is relatively strong compared to competing energy-dissipating recombinations. Another tradeoff was how to optimize the injection of electrons into the p side of the junction. This is controlled by the dopants and the doping profiles that are used in the diodes. The six years that were required to develop the diodes were largely spent in unravelling the complex physics and determining the tradeoffs involved. [1]

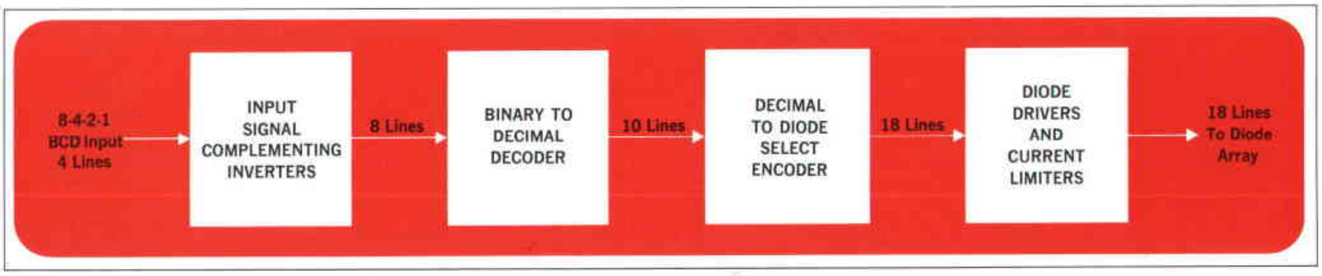


Fig. 8. *The IC chip decodes BCD input signals into ten signals representing the digits 0 through 9. These signals are then encoded into signals which drive groups of diodes. There are 18 groups, and the diodes in each group are always lighted together. A two-step decode/encode process was chosen so the input code or character font could be changed simply by changing the interconnections between the logic elements.*

Special Manufacturing Facility

It was necessary to create a source of Ga(As,P) that would be capable of maintaining sufficiently close control over composition, doping profiles, and dimensions. Therefore, a special reactor [2] was designed and built by HP (Fig. 7). It is a vertical-flow, RF-heated, cold-wall, dual-reactor, vapor-phase epitaxial system capable of growing wafers of Ga(As,P) up to two inches in diameter. The system holds the phosphorus-to-arsenic ratio constant within ±1% across the growing epitaxial layer. Because of this precise control, the entire wafer of Ga(As,P) can be used to make diodes, and light-emitting properties are quite uniform from diode to diode. (A typical wafer had a mean luminance of 291 fL at 10 A/cm^2 and a standard deviation of only 25 fL.)

RF induction heating was chosen for the reactor instead of resistance heating for the following reasons.

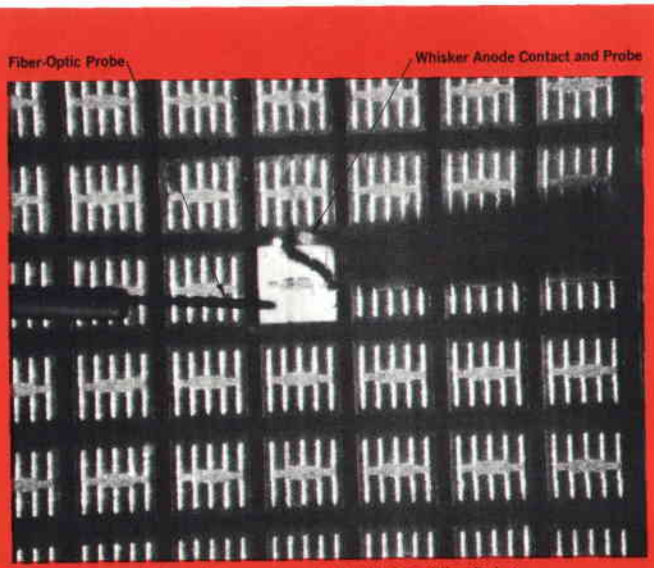
- It is possible to keep all of the glass portions of the apparatus at temperatures well below those of the reaction zone, thereby minimizing a possible source of contamination.
- The thermal mass of an induction heated system can be made small, thereby reducing the total time required for the growth process.
- Sharp temperature profiles, desirable for high deposition efficiency, are easily achieved.
- The volume of the system for a given substrate area can generally be made smaller than a comparable resistance-heated unit. This gives shorter system time constants when time-variant gas flow rates are used.

Heating is accomplished by the inductive coupling between an RF solenoid and a high-purity graphite susceptor. Since the skin depth of the RF field in graphite is a few millimeters at the operating frequency (450 kHz), the interior of the chamber is heated primarily by radiation from the outer walls of the susceptor.

GaAs substrates are placed on a horizontal pedestal within the susceptor so the growth surface is normal to the gas flow. Gas flows are measured with electronic flowmeters to ensure the required degree of control and reproducibility in the growth process. The phosphorus (in the form of PH_3) flow is automatically programmed by an electromechanical valve to achieve the desired profile of phosphorus within the epitaxial layer. Flow

Measuring Luminance

At HP, diode luminance is measured by optically imaging the diode's light-emitting surface on a fiber-optic probe. The fiber-optic probe transmits the light through a filter. From the filter the light goes to a photomultiplier tube, and the tube's output is measured by a digital voltmeter which reads directly in footlamberts. The system is calibrated using a 100 fL standard source. Matched photopic-filter/photomultiplier-tube assemblies and certified sources, traceable to N.B.S., are purchased from Gamma Scientific Corporation. The electrical response of the filter/photomultiplier assemblies to photon excitation matches the response of the human eye.



(Note comb-type anode contacts of light-emitting diodes)

rates can be changed very quickly, so a wide variety of compositional profiles can be obtained.

Substrate temperature is controlled to ±1°C or better by a closed-loop control system whose thermocouple sensing element is located within the substrate pedestal. Temperatures elsewhere in the susceptor are measured by optical pyrometry. The temperature of the arsenic (in the form of $AsCl_3$) reservoir is controlled by a thermoelectric cooling unit.

The initial capacity of the light-emitting-diode production facility is about 1.5 million diodes per year.

The integrated circuits and ceramic substrates for the solid-state numeric indicators are also manufactured by HP. An automatic machine is now being developed to sort and test the diodes and IC chips, then orient them and attach them to the substrates. Testing is done by a data acquisition and processing system controlled by an HP 2116A Computer.

IC Decode-Encode Logic

Some 400 circuit elements are contained in the IC chip used in the solid-state numeric indicator modules. Four basic functions are performed in the chip (Fig. 8). Incoming four-line BCD signals are first complemented. Then the eight signals — the four BCD input signals and their four complements — are decoded into ten mutually exclusive line signals, each of which will excite one of the ten decimal digits 0 through 9. Of the sixteen possible binary input codes, the six that don't represent a decimal digit produce blanks. Complementing the BCD inputs was done to minimize the overall complexity of the IC chip; it greatly simplifies the decoding circuitry.

The third function performed in the IC is to encode the ten mutually exclusive line signals into signals that select the proper diodes to produce each character. Diodes that are always lighted together are excited by a single output from the IC chip. The number of diode groups required to produce ten digits is eighteen, so the chip has eighteen outputs. Each of the ten mutually exclusive line signals activates a subset of the eighteen outputs. These diode drive signals then go through combination power amplifiers and current limiters, and excite the light-emitting diodes.

The two-step decode-encode organization was chosen to allow some flexibility in changing the input and output options of the chip. The chip is the electrical equivalent of a ten-position, eighteen-gang switch which has series resistors in all of its outputs and is operated by four BCD signal lines. By simple changes in one of the masks used in making the IC, either positive or negative BCD inputs can be accommodated, and any 10 of the 2^{18} possible output combinations can be selected. Therefore, changes in character font, presentation of special symbols, or changes in input code can be accomplished quite easily.

Each of the four binary input lines is connected to twenty grounded-collector pnp transistors in the decoding area of the IC chip. It is connected to the bases of ten of these directly. Between the input and the other ten transistors is an npn emitter follower, which drives an inverter; the input line is connected to the base of the emitter follower, and the inverter output is connected to the bases of the ten pnp transistors. Thus there are eighty pnp transistors in the decoding area of the IC chip. However, not all are operational. Only those needed for the desired decoding function are given emitter connections. The direct-connected pnp transistors that have emitter connections are active when the binary input signal is in the low state (0V). The emitter follower, the inverter, and the remaining pnp transistors that have emitter connections are active when the binary input signal is in the high state (5V). Emitter connections are made by etching holes in the oxide layer of the chip. When the metal interconnection layer is added, the metal comes in contact with the emitter of a transistor only where there is a hole in the oxide. Thus the chip can be made to respond to either positive logic or negative logic simply by changing the oxide cut mask used in making the IC.

The same technique allows flexibility in changing the output code of the IC chip. Each of the ten lines going from the binary-to-decimal decoder into the decimal-to-diode-select encoder is connected to eighteen npn emitter-follower OR gates. However, not all of the 180 npn transistors are connected. Oxide cuts are made for emitter connections only where connections are needed to turn on one of the eighteen diode drive lines. Any drive line is turned on when one of the ten mutually exclusive decimal lines is turned on *and* the encoding npn transistor for the drive line has an emitter connection.

Diode Drive Circuit

From the decimal-to-diode-select encoding circuitry, each of the eighteen diode drive lines goes to an npn grounded-emitter inverter which drives a pnp emitter follower. Between the pnp emitter and the output connection to the light-emitting diode is a current-limiting resistor. The resistor is connected to the n side (cathode) of the light-emitting diode, and the p side (anode) of the diode is connected to the LED+ terminal of the module. Between this terminal and the ground terminal of the module is the external light-emitting-diode power supply, its positive side connected to the LED+ terminal. When the diode is forward biased (turned on), about 1.6 volts appear across the diode, and less than one volt appears across the saturated pnp emitter follower. The remainder of the power supply voltage appears across the current-limiting resistor. As the power supply voltage is varied,

Howard C. Borden

Howard Borden is manager of solid-state displays at HP Associates. He began his 28 year career in 1939 as a mechanical engineer. Following a tour of duty with the U.S. Navy and further work as a mechanical engineer, he decided to go into business for himself. He bought an appliance store, introduced television, and saw it grow to become the largest part of his business. For the past 18 years he has been in research and development in the field of electro-optical-mechanical systems. He joined HP in 1966.

Howard studied mechanical engineering at the Massachusetts Institute of Technology and electronics at the U.S. Navy Radio Materiel School. In 1961 he received the BA degree in economics from Stanford University, where he also minored in industrial engineering. He is a member of IEEE, the American and Western Economic Associations, the Optical Society of Northern California, and the Society for Information Display.

Gerald P. Pighini

Gerry Pighini has been in the solid-state electronics field since 1955, when he received his BS degree in metallurgical engineering from Brooklyn Polytechnic Institute. He has been with HP since 1965, first as chief engineer of HP Associates and then as production manager for semiconductors before assuming his present responsibilities as manager of solid-state displays. Before coming to HP, Gerry was chief manufacturing engineer for a producer of semiconductor devices.

Gerry is co-author of a paper on growing large gallium arsenide phosphide wafers for light-emitting-diode production. He is a member of the Society for Information Display.

the diode and emitter-follower voltage drops remain nearly constant. The voltage across the resistor, and therefore the diode current, varies nearly linearly with the power supply voltage. This makes the brightness of the diode vary almost linearly with the supply voltage. All of the current-limiting resistors are closely matched (a characteristic of IC's) so the brightnesses of the individual diodes are very nearly equal.

The total time required for a change in input code to travel through the IC is about 100 ns. The response time of the light-emitting diodes is about 10 ns, so the total response time of the display is typically about 110 ns.

The IC chip is a low-resistivity p^+ substrate with a p-type epitaxial layer. The output currents flow through the substrate, thereby minimizing the current density in the aluminum interconnecting metal. This construction is a departure from the conventional IC, which is grown on an n^+ substrate.

Acknowledgments

The authors wish to acknowledge the contributions of people from several HP divisions which have made this product possible. Developmental work was done in John Atalla's solid-state laboratory, which is part of Hewlett-Packard Laboratories, the corporate research and development facility. Materials work was under Paul Greene and Robert Burmeister, Jr., device work under Robert Archer, and IC development under John Barrett. Ed Hilton's integrated-circuit department of the Frequency and Time Division is producing the IC chips, with James Grace overseeing the transition from the solid-state laboratory. The ceramic substrates are a product of George Bodway's metal-film facility in the Microwave Division. Light-emitting-diode production, component testing, and final assembly of the pieces is done by the solid-state-display group at HP Associates.

References

[1]. 'Solid state module makes for light reading,' Electronics, September 2, 1968.

[2]. R. A. Burmeister, Jr., G. P. Pighini, and P. E. Greene, 'Large Area Epitaxial Growth of $GaAs_{1-x}P_x$ for Display Applications,' to be published in Transactions of the AIME.

SPECIFICATIONS

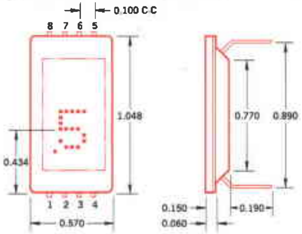
HP Model 5082-7000
Numeric Indicator

ABSOLUTE MAXIMUM RATINGS
POWER SUPPLY: All power and logic inputs referred to common (ground).
IC LOGIC VOLTAGE: 5 Vdc
LED (LIGHT EMITTING DIODES) VOLTAGE: 4.5 Vdc
STORAGE TEMPERATURE RANGE: −65° to +95°C
OPERATING TEMPERATURE RANGE: −55° to +95°C

TYPICAL CHARACTERISTICS
LUMINANCE AT 4 V LED +: 75 fL.
POWER DISSIPATION AT 50 fL: 500 mW.
PEAK WAVELENGTH: 655 nm.
SPECIAL LINE HALFWIDTH: 30 nm.
CHARACTER RESPONSE TIME ('on' or 'off'): <1 μs
IC LOGIC CURRENT AT 5 Vdc (logic + to ground): 25 mA
LED CURRENT AT 4 Vdc (LED + to ground): 200 mA.

PIN ASSIGNMENT

1. Logic 1	5. Logic 4
2. Decimal Point	6. Ground
3. LED +	7. Logic +(5 Vdc)
4. Logic 8	8. Logic 2



PRICES:	1–9	10–99	100–499	500–999	1000–4999
	$75.00 each	**$60.00** each	**$50.00** each	**$45.00** each	**$42.00** each

MANUFACTURING DIVISION: HP ASSOCIATES
620 Page Mill Road
Palo Alto, California 94304

Reliability

The following cumulative test results have been obtained from reliability testing performed at HP Associates in accordance with the latest revision of Military Semiconductor Specification MIL-E-5400, MIL-STD-202 and MIL-STD-750. The following results were obtained with solid state displays (5082–7000) sampled from the production line.

END POINTS:

1. Generate proper character font 0–9 and decimal points.
2. No change in average unit brightness (fL) within limits of measurement accuracy (±10%).
3. Seal Hermeticity. Meets MIL-STD-883, Method 1014, Test Condition A and D (at PE = 20 P.S.I. and T_1 = 2 hours).

Test	Reference	Test Conditions	Units Tested	Failed
Humidity	MIL-STD-202C Method 106	24 hr. cycles from 25°C to 65°C @ 95% R.H., 5 cycles	38	0
Altitude (Nonoperating)	MIL-STD-202C Method 105C Condition B	30 min. @ 50,000 ft.	38	0
Temperature (Nonoperating)	MIL-STD 202C Method 107B Condition A	−65°C to +85°C 5 cycles	38	1
Shock	MIL-STD-202C Method 213 Condition C	5 drops, 6 orientations 100 g, 6 ms	37	0
Vibration Variable Frequency	MIL-E-5400 Curve IV	±10 g, 70-500-70 Hz	37	0
Thermal Shock	MIL STD-750 1056.1	0°C to 100°C 5 cycles	37	0

Test	Reference	Test Conditions	Units Tested	Total Unit Hours	Failed
High Temperature Life	MIL-STD-750 1031.1	500 hrs. storage at 85°C	10	5,000	0
Steady State Operating Life	MIL-STD-750 1026.1	1000 hrs. @ 4 V LED + cycling 0–9 at ½-s rate	10	10,000	0

Hybrid Hot Carrier Diodes

These unique combinations of p-n junctions and Schottky barriers have the high breakdown voltage and high-temperature characteristics of silicon, the low turn-on voltage of germanium, and the speed of Schottky barrier devices. What's more, they can be produced at low cost.

By Robert A. Zettler and A. Michael Cowley

SCHOTTKY BARRIER DIODES, also called hot carrier diodes, have a combination of characteristics that make them hard to beat as switching devices in high-speed computers and as microwave mixers, detectors, and rectifiers. They have the high-frequency characteristics of point contact diodes, but have much higher reverse breakdown voltages. They have uniformity, reproducibility, and reliability approaching those of p-n junction diodes, and they have low noise and nearly ideal diode I-V characteristics.

One thing that has been missing, however, is low cost. It has been difficult to make high-reliability Schottky barrier diodes economically. If the devices are passivated to make them easier to produce and to give them high storage temperatures, they have low reverse breakdown voltages—typically 5 to 10 volts. If the devices aren't passivated, they have higher reverse breakdown voltages — 30 volts or more — and are more reliable, but they have maximum storage temperatures of only 125°C and they are harder to produce and therefore more expensive.

The approach taken in our laboratory has been to combine planar p-n junction technology with passivated Schottky barrier techniques to produce a hybrid diode.[1] The first device of this type to reach full production is Model 5082-2800, which has a reverse breakdown voltage greater than 70 volts, 200°C operating and storage temperature, effective minority-carrier lifetime less than 100 picoseconds, and turn-on voltage of only 410 millivolts at 1 mA. It also has low leakage current and will withstand 20,000 g shock. Most important, it can be produced at less than one-fifth the cost of older hot carrier diodes. It is, in fact, comparable in cost to p-n junction diodes.*

Other hybrid devices are now near production or in development (see page 16). In some, the reverse breakdown voltages have been lowered to 15 or 20 volts to get higher forward conductance and lower capacitance. In others, parameters have been optimized for power rectification. All of these hybrid diodes are rugged, can withstand high temperature, and have low turn-on voltages and low cost.

Passivated and Unpassivated Diodes

The Schottky barrier diode is a rectifying metal-semiconductor junction. Any of several metals (gold, molybdenum, titanium, chromium, nickel, nichrome, aluminum, and others) can be used in conjunction with either n-type or p-type silicon. N-type silicon is nearly always preferred because it gives better high-frequency performance (electrons, the majority carriers in n-type silicon, have higher mobility than holes, the majority carriers in p-type silicon).

Fig. 1 compares passivated and unpassivated Schottky barrier diodes. The unpassivated diode is made by depositing a matrix of metal dots on a bare silicon surface. Then, by random probing with a metal whisker, contact is made to one of the dots. Reliability is normally high, but the maximum storage temperature is low, and the cost is high because of the random-probing technique.

The passivated Schottky barrier diode is made by first forming a passivating layer of silicon dioxide, SiO_2, on the silicon surface, then etching a hole in the passivating layer and depositing a layer of metal over the hole and the surrounding area. One technique for making contact with the metal is to deposit a gold button on the metal, using standard photoresist and plating techniques. Contact with the gold button is easily made in one try with a metal ribbon. Alternatively, contact can be made directly to the relatively large metal area, using a metal whisker.

In the passivated diode, the layer of SiO_2 protects the edge of the diode and improves yield. Standard mass-

---

*The p-n junction guard ring-Schottky barrier or hybrid approach was first disclosed for patent purposes by R. W. Soshea of Hewlett-Packard Associates in 1965, and was later independently conceived by Lepselter and Sze of Bell Telephone Laboratories (see reference 2).

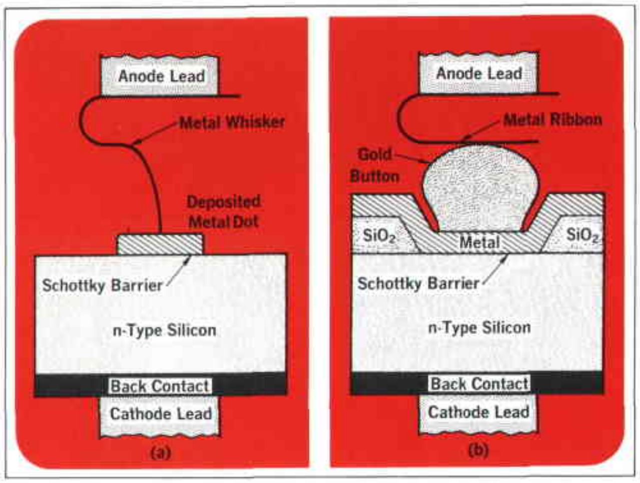


Fig. 1. *Two types of Schottky barrier diodes that preceded the new hybrid type.* **(a)** *Unpassivated Schottky barrier diode is expensive to produce and has relatively low maximum storage temperature.* **(b)** *Passivated diode is less costly and has higher storage temperature, but has low reverse-breakdown voltage (typically 5 to 10 V).*

production techniques can be used, and this combined with higher yield brings costs down. However, it has been observed that this type of diode seldom has a reverse breakdown voltage as high as 20 V. Usually it is much lower. It is believed that the reason for this lies in the complex interface of the metal, silicon, and SiO_2 at the edge of the Schottky barrier formed in the hole in the oxide layer. Besides the usual effects of surface states and oxide charge associated with the passivating film, there may be finite-thickness oxide films extending over the semiconductor around the periphery of the hole. Even if there are no oxide films, the interface can be viewed as a degenerate case of a p-n junction which has nearly zero radius of curvature. In this type of junction there would be very high electric fields which would produce avalanche currents at relatively low applied voltages.[3][4]

Another problem with passivated Schottky barrier diodes on n-type silicon is excess low-frequency noise. This, too, is believed to arise at the edge of the Schottky barrier.

Hybrid Diodes

The new hybrid device, sketched in Fig. 2, is basically a passivated Schottky barrier diode. The essential feature of the device is a diffused guard ring of p-type silicon which extends in planar fashion under the passivating oxide. The Schottky barrier is formed in the interior of the ring and makes electrical contact with the p-n junction. The guard ring reduces the edge effects mentioned above to such an extent that hybrid diodes can have reverse breakdown voltages of several hundred volts. Our first hybrid diode, the HP 5082-2800, has a reverse breakdown voltage of 70 V. Similar devices which are optimized for certain receiver applications have reverse breakdown voltages of 15 or 20 V; these are the HP 5082-2811 and the HP 5082-2810.

I-V Characteristics

A possible equivalent circuit for the hybrid structure is shown in Fig. 3(a). It consists of two diodes in parallel, one representing the p-n junction and one representing the Schottky barrier. Fig. 3(b) is a sketch of the anticipated forward I-V characteristics of the two diode components alone, and of the total forward I-V characteristic. The composite characteristic is dominated by the p-n junction at the higher voltages, where the p-n junction injects appreciable minority-carrier charge and hence modulates the conductivity of the n-type silicon layer. If permitted to happen, injection by the p-n junction will limit the switching speed at high current levels, because it results in minority-carrier charge storage. At low levels the I-V characteristic is essentially that of the Schottky barrier, so the low-level switching speed will not be limited by storage effects. Nevertheless, a loss of switching speed at high current levels, if allowed to happen, would seriously limit the usefulness of the hybrid structure, especially in applications such as computer core drivers and high-frequency modulators. However, it is possible to avoid this loss of speed at high current levels.

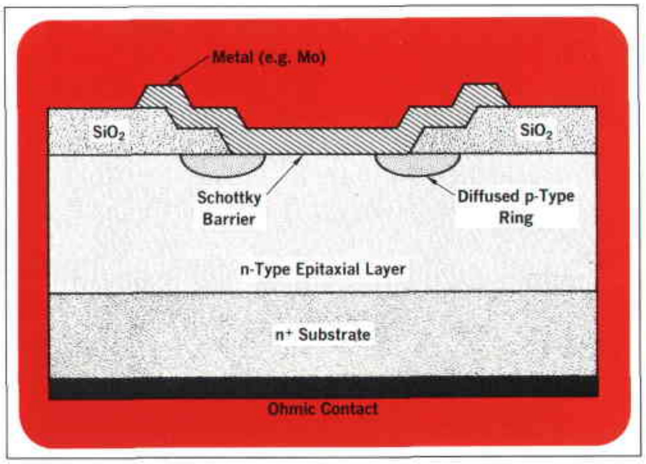


Fig. 2. *Hybrid Schottky barrier diode has a diffused p-n junction guard ring under the metal and the passivating oxide layer. Proper choices of metal and diffusion profile give the new diodes high reverse breakdown voltages, low noise, and nearly ideal I–V characteristics.*

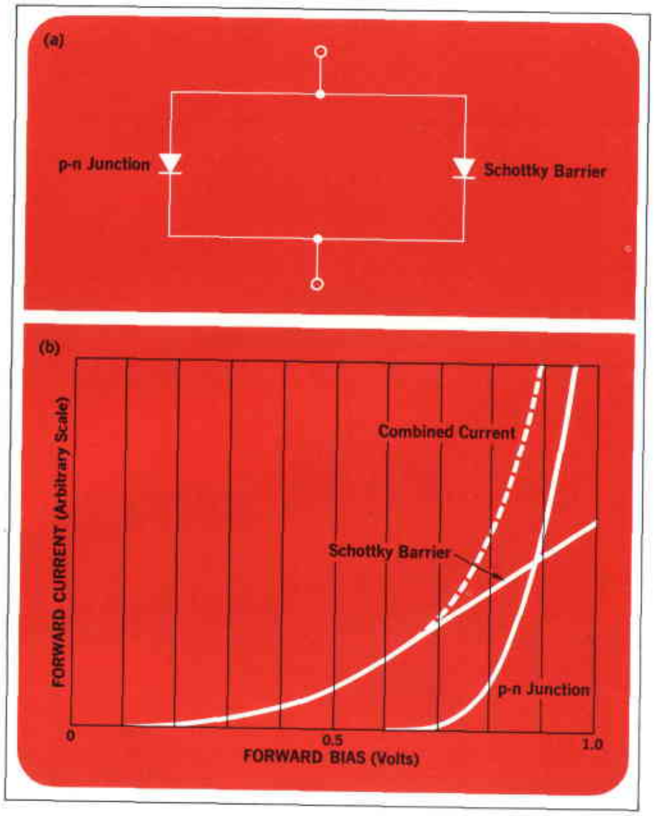


Fig. 3(a) *Hybrid diode equivalent circuit, assuming the contact between the metal and the diffused ring is ohmic, or non-rectifying.* **(b)** *I–V characteristic expected from this structure. Shape is typical of gold/silicon and platinum-silicide/silicon hybrid diodes.*

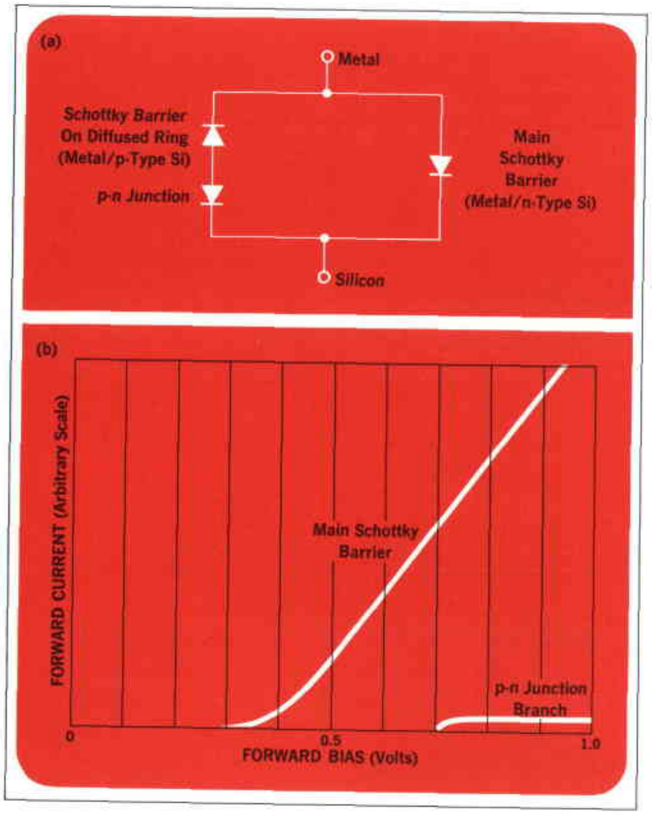


Fig. 4(a) *Equivalent circuit of hybrid diode, assuming a rectifying contact between the metal and the diffused ring. Molybdenum/silicon and titanium/silicon hybrid diodes behave like this. The new HP 5082–2800 is a molybdenum/silicon diode.* **(b)** *I–V characteristics of the two branches in* **(a).**

Another Equivalent Circuit

The model shown in Fig. 3(a) implicitly assumes that the metal used to form the Schottky barrier with the n-type silicon forms an *ohmic* (non-rectifying) contact to the diffused p region. This is true for a p^+ diffusion and virtually any metal, since the current flow can proceed by a tunneling mechanism. An ohmic contact can also occur if the metal has a high barrier height on n-type silicon, because it then has a low barrier height on p-type silicon. In this case the ohmic contact is the result of a very high saturation current for the reverse-polarity Schottky barrier diode formed on the diffused p-type region.

However, ohmic contact need not exist for properly chosen combinations of metals and diffused region surface concentrations. This can be seen as follows. It has been established that the sum of the barrier heights of a given metal on n-type and p-type samples of a given semiconductor should equal the bandgap of the semiconductor, excluding the effects of image-force lowering.[5] A metal having a barrier height of, say, 0.6 V on n-type silicon will, to a good approximation, have a barrier height of about $1.1 - 0.6 = 0.5$ V on p-type silicon. (The bandgap of silicon is 1.1 V.) Using a metal like this, it is possible to form opposite-polarity, rectifying Schottky barriers over a diffused p-n junction *provided that the concentration at the surface of the diffused region is not so high as to permit large tunneling currents.* The equivalent circuit of Fig. 3 should then be modified to the three-diode model shown in Fig. 4(a). The third diode represents the rectifying contact between the metal and the diffused region.

The essential feature of this modification is that the metal-to-p-type Schottky barrier in series with the p-n junction is reverse biased when the main Schottky barrier and the p-n junction are forward biased, so that most of the applied forward voltage on the left branch in Fig. 4(a) appears across the reverse biased Schottky barrier. The amount of current that the p-n junction can inject, Fig. 4(b), is limited by the reverse current of the metal-to-p-type Schottky barrier. Therefore, the rectifying contact to the p region can be used to reduce or eliminate the charge storage under heavy forward bias. This technique is responsible for the new hybrid diodes' high switching speed even at high current levels.

Choosing the Metal and Diffusion Profile

It has been our experience that Schottky barrier diodes which have good reverse characteristics are difficult to fabricate on n-type or p-type silicon which has a surface concentration greater than about $10^{18}/\text{cm}^3$. Therefore, the surface concentration of the diffused ring must be limited to a value lower than 10^{18} if the equivalent circuit of Fig. 4(a) is to apply. Also, the dependence of the reverse current on the choice of metal must be considered.

The saturation current of a Schottky barrier is given in the emission model by[6]

$$I_S = A\,A^*T^2 e^{\frac{-q[\phi_{BO} - \Delta\phi(V)]}{kT}} \qquad (1)$$

where A is the area of the diode, A^* is the effective Richardson constant (which is approximately the free

Hybrid Technology Produces Many Useful New Devices

Hybrid hot-carrier-diode technology has made possible a number of new semiconductor devices now in or near production at HP. These devices are expected to be widely useful, either because they cost much less than older devices, or because they have much improved performance characteristics. The hybrid process puts hot carrier diodes on a nearly equal footing with p-n junction diodes in such areas as reliability, ruggedness, and economics, and the hybrid diodes have all the advantages of Schottky barrier devices as well.

High Voltage, High Temperature

The first hybrid diode to be produced is the HP 5082–2800, which has a reverse breakdown voltage greater than 70 V and a maximum operating and storage temperature of 200°C. Its low cost, high-temperature capability, reliability, and rugged contact structure have led to its use in high-volume projectile fuze production and in other applications requiring similar characteristics. Low cost also makes it a practical replacement for ordinary p-n junction diodes in many RF and digital applications in a wide range of military and commercial equipment. It is particularly useful in digital circuits which call for low forward turn-on voltage or sub-nanosecond switching times. In fast sampling gates its high reverse breakdown voltage gives wide dynamic range, its low turn-on voltage gives low offsets, and its negligible charge storage gives high sampling efficiency and further freedom from offsets.

Resistance to burnout, high reverse breakdown voltage, and negligible charge storage make the 5082–2800 an efficient rectifier or high-level detector through UHF. It can also be used as a wide-dynamic-range UHF mixer or modulator at high local-oscillator levels.

Microwave Mixers and Detectors

Other hot carrier diodes are being made by the same hybrid process that is used in the 5082–2800. In some of these diodes, the epitaxial-layer thickness and resistivity, the active-area size, and other characteristics are optimized to produce, for example, a higher forward conductance and a lower barrier capacitance at the expense of a lower reverse breakdown voltage. This tradeoff gives the diodes optimum characteristics for receiver applications at frequencies well into L band. They can be used as mixers or detectors, and they have the same resistance to burnout, ruggedness, reliability, high operating temperature, and low cost as the higher-voltage version. Two of these diodes, the HP 5082–2810 and the HP 5082-2811, are now in the early phases of production. Other types (HP 5082–2818 and HP 5082–2819), which have microwave mixer noise-figure and detection-sensitivity specifications, are well along in development and will be announced later this year.

Rectifiers Under Development

Hybrid hot-carrier-diode technology can also be applied to the problems of high-frequency power rectification, and high-current, fast-rise pulse switching and clamping. Currently under development are large-area high-breakdown hybrid hot carrier chips, packaged in low-thermal-resistance, high-dissipation enclosures. They have demonstrated an ability to handle average currents of 10 amperes or more at working inverse voltages over 50 volts. Their rectification efficiency at one ampere peak forward current is as good at 1 MHz as that of most p-n junction 'fast-recovery' rectifiers is at 10 kHz, yet they are just as rugged as the p-n junction devices and have the same sharp, clean, reverse avalanche breakdown characteristics.

Efficient rectification at higher frequencies means that switching regulators and dc-to-dc power converters can be designed with smaller and lighter filter components. An additional benefit of hybrid hot carrier power rectifiers is freedom from reverse-recovery transient spikes caused by stored charge; such spikes frequently produce substantial radio-frequency interference when p-n junction rectifiers are used.

Where low-voltage, high-current dc power supplies are needed, such as for systems employing quantities of integrated circuits, a hybrid hot carrier rectifier can provide a lower forward turn-on voltage; this improves the rectification efficiency, since the principal losses are due to the forward voltage drop of the rectifier. As a result, smaller, more compact, more reliable power supplies for computer applications should be possible. An additional benefit is freedom from reverse transients, which eliminates the high-level, fast-rise noise spikes often generated by p-n junction rectifiers.

electron value for silicon),[7] and ϕ_{BO} is the barrier height for zero field. $\Delta\phi(V)$ is the image force correction to the barrier height and is given by [8]

$$\Delta\phi(V) = \left[\frac{q^3 N_{D,A}}{8\pi^2 \varepsilon_S{}^3}\left(V_{BO} + V - \frac{kT}{q}\right)\right]^{1/4} \qquad (2)$$

where $N_{D,A}$ is donor or acceptor density, ε_S is the semiconductor dielectric constant, and V_{BO} is the diffusion potential of the Schottky barrier (ϕ_{BO} minus the Fermi energy).

According to (1) and (2), the reverse current of the Schottky barrier depends only weakly on the carrier density or applied voltage (neglecting tunneling) but depends very strongly on ϕ_{BO}. For electron-beam evaporated molybdenum, $\phi_{BO} \simeq 0.42$ on p-type silicon; saturation current I_S for a diode of area 10^{-5} cm^2 and $N_A = 5 \times 10^{17}/\text{cm}^3$ would be about 160 μA. Under the same conditions a gold barrier ($\phi_{BO} \simeq 0.3$ V on p-type silicon) can provide a current at 1 V reverse of about 17.5 mA. For platinum silicide, with $\phi_{BO} \simeq 0.25$ on p-type silicon, the saturation current is about 120 mA. Thus, the gold and platinum silicide contacts to the diffused ring, because of their high saturation currents, are essentially *ohmic,* while the molybdenum contact is a fairly good *rectifier* which limits the current in the p-n junction, thereby preventing charge storage to a great extent.

We have chosen molybdenum as the metal to be used in the new hybrid diodes.

Characteristics Agree With Theory

Fig. 5 shows a forward I-V characteristic of a typical molybdenum hybrid diode formed on n-type silicon. The value of 'n' (sometimes called the 'ideality factor') in the relation

$$I = I_S(e^{qV/nkT} - 1)$$

was 1.01. This agrees with the value of n calculated from the image force effect.[9]

The reverse characteristics of this diode are shown in Fig. 6. The diode breakdown at 10 μA is approximately 87 V and sharp. The reverse characteristics are plotted on a semi-logarithmic scale vs $(V + V_{BO} - kT/q)^{1/4}$ to show that the increase of reverse current with voltage follows the $V^{1/4}$ dependence expected from image force lowering. The slope of the curve expected from Eqs. (1) and (2) using a dielectric constant of $\varepsilon = 11.7\ \varepsilon_O$ is 2.52 $\text{V}^{1/4}$/decade. The measured value is 2.47 $\text{V}^{1/4}$/decade.

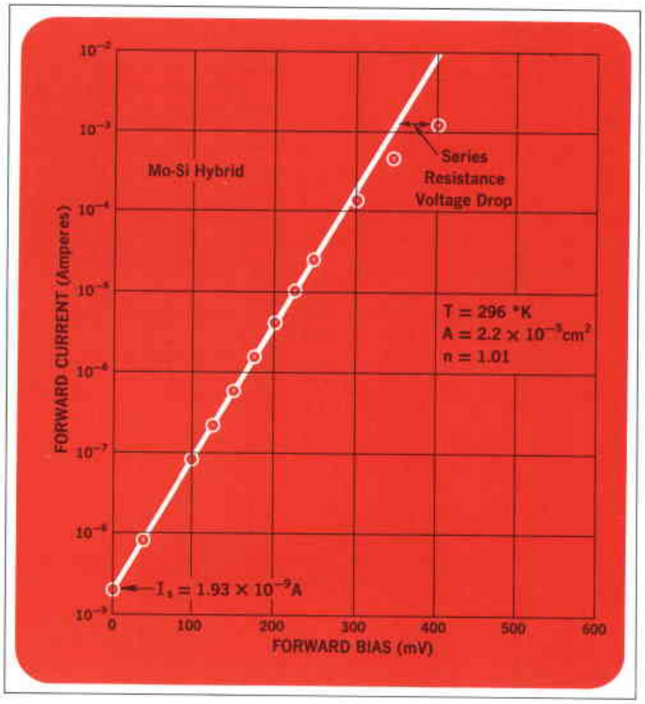


Fig. 5. *Forward I–V characteristic of typical Mo-Si hybrid diode conforms closely to theory.*

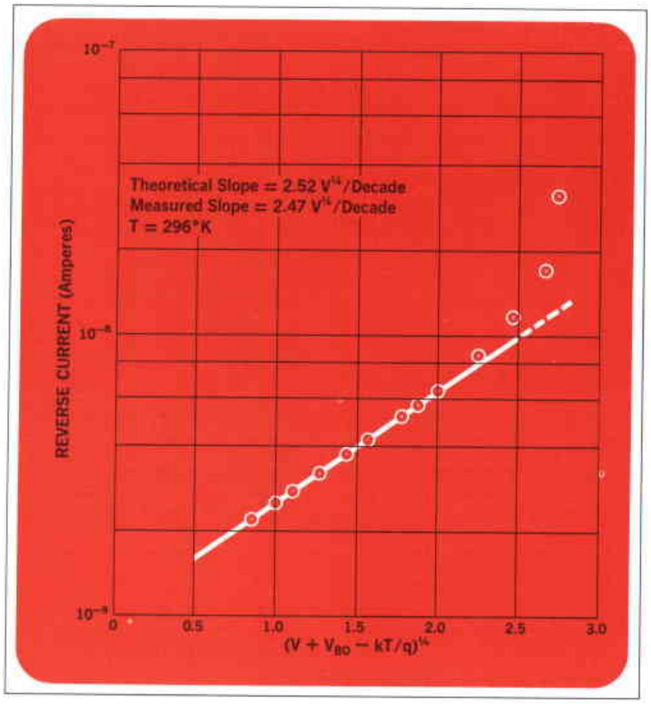


Fig. 6. *Reverse I–V characteristic of typical Mo-Si hybrid diode, showing essentially exact agreement with image force lowering theory.*

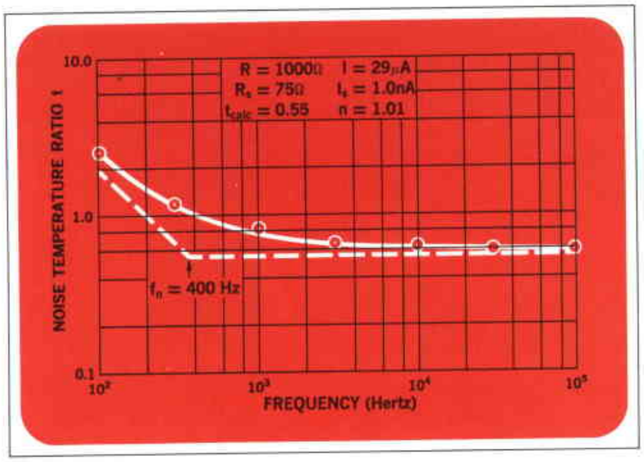


Fig. 7. *Noise temperature ratio for typical Mo-Si hybrid diode, biased to total dynamic resistance of 1000 Ω.*

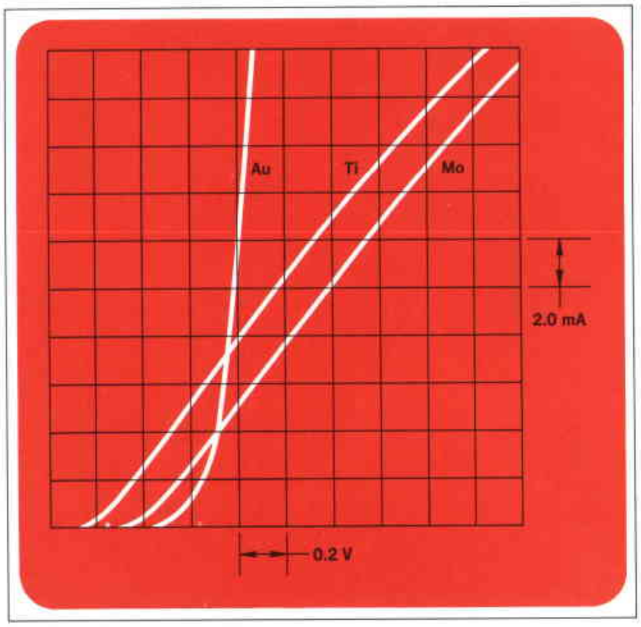


Fig. 8. *Au, Mo, and Ti hybrid diode forward I–V characteristics. Diodes were all made on the same silicon wafer. Au diode shows very strikingly the additional current due to hole injection by the p-n junction. This p-n junction current for the Mo and Ti diodes is essentially absent because of the limiting effect of the reverse biased rectifying contact to the diffused ring.*

Both the forward and the reverse characteristics agree very well with simple Schottky barrier diode theory. There is no need to invoke complex theories involving interfacial films and/or surface states to explain measured deviations from more simple theory. We suggest that in many of the experiments reported in the literature the true Schottky barrier diode electrical characteristics have been obscured by serious edge effects, and that the hybrid structure eliminates these effects.

Noise Suppressed

The noise theory of Schottky barrier diodes has been discussed in another paper.[10] It was shown there that silicon Schottky barriers with space charge fields of the order of 10^4 V/cm or greater have a noise temperature ratio t_B given by

$$t_B = \tfrac{1}{2}\left(1 + \frac{nI_{SO} + (n-1)I}{nI_{SO} + I}\right) \qquad (3)$$

where I_{SO} is the saturation current of the diode extrapolated to zero applied voltage, n is the 'ideality factor,'[9] and I is the forward bias current. The noise temperature ratio of a device biased to a dynamic resistance R is defined as the ratio of available noise power from the device to the available noise power of a resistor R, for the same bandwidth.

For a practical diode consisting of a barrier region and a parasitic series resistance R_S, the noise temperature ratio t of the composite structure is

$$t = \frac{R_B t_B + R_S}{R_B + R_S} \qquad (4)$$

where R_B is the dynamic resistance of the barrier and $R_B + R_S$ is the total dynamic resistance of the device, which we denote by R. In a hybrid diode structure, the noise properties of the diode at moderate forward bias levels should be dominated by the Schottky barrier, so (3) and (4) should apply. This has generally been found to be the case, apart from a small amount of excess noise at low frequencies. Some typical data are shown in Fig. 7. The relevant parameters were $I_{SO} \simeq 10^{-9}\ A$, $I \simeq 2.9 \times 10^{-5}\ A$, $n \simeq 1.01$, $R_S \simeq 75\ \Omega$, and $R_B \simeq 925\ \Omega$. The resultant ac diode resistance was 1000 Ω, and the calculated noise temperature ratio was 0.55. The data are in agreement with this value above 30 kHz, while at lower frequencies, there is a small excess noise component which varies approximately as 1/f.

A convenient quantity commonly used to indicate the severity of the excess noise in these diodes is the 'noise corner frequency,' or simply 'noise corner.' We will denote it by f_N. It is defined as the frequency at which the excess component of the diode noise is equal to the sum of the thermal and shot noise components. The diode in Fig. 7 has an f_N of about 400 Hz. The amount of excess noise has been found to vary somewhat from diode to diode; the diode of Fig. 7 was judged to be typical and was selected after examining several dozen diodes from four fabrication runs. Diodes selected for lowest noise have noise corner frequencies well below 100 Hz under the same conditions.

In contrast to the data shown in Fig. 7, it has been observed in our laboratories that passivated Schottky barrier diodes fabricated by simply depositing metal in an oxide window on a silicon wafer have noise corner frequencies ranging from about 50 kHz to over 1 MHz under similar bias conditions. The noise is generally observed to have 1/f spectrum.

We have concluded from this comparison, and from other data, that the excess noise arises at the periphery of the planar passivated Schottky barrier, and it is apparent that the p-n junction guard ring has significantly suppressed this excess noise.

Charge Storage Reduced

Hybrid diodes made with three different metals — gold, molybdenum, and titanium — were studied to determine their charge-storage characteristics. Fig. 8 shows the forward I-V characteristics of the three diodes. It is apparent from the non-constant series resistance that the p-n junction on the gold diode is injecting at somewhat less than 1 volt, while the diodes with molybdenum and titanium barriers are not injecting heavily even at 1.5 or 2 volts. This difference is to be expected, because the gold barrier on the p-type diffused ring is so low that its saturation current permits the p-n junction to conduct large currents and hence store significant amounts of charge. Molybdenum and titanium, on the other hand, with their much higher barrier heights on the diffused ring, have merely to avoid breakdown below 1 or 2 volts to ensure relatively small amounts of stored charge. The Schottky barriers on the diffused ring are not very close to ideal, since they have the same oxide-interface problems as Schottky barriers without the guard ring, but they can typically be made to withstand 2 volts before breakdown, and occasional units will require 5 to 6 volts for breakdown. This is adequate to prevent charge-storage problems over the normal operating range of the hybrid diodes.

A. Michael Cowley

Mike Cowley taught electrical engineering at the University of California at Santa Barbara and worked as a consultant in physical electronics before joining HP in 1965. At HP, Mike has been concerned with the technology and microwave properties of Schottky barrier diodes. Currently, he is studying microwave generation using avalanche effects in silicon and the Gunn effect in gallium arsenide.

Mike received BS and MS degrees in electrical engineering from the University of Notre Dame in 1959 and 1961, and the Ph D degree in electrical engineering from Stanford University in 1965. He has published a number of papers on solid-state devices. He is a member of IEEE, Tau Beta Pi, Sigma Xi, and the American Physical Society.

Robert A. Zettler

Bob Zettler received the AB degree in physics and mathematics from Brown University in 1960. After a year of designing low-frequency transistor circuits, he moved to the Massachusetts Institute of Technology, where he worked as a research assistant. He received the MSEE degree from MIT in 1963, and joined HP the same year.

At HP, Bob has been concerned with research and development of electroluminescent diodes, tunnel diodes, avalanche transistors, and Schottky barrier devices. Now supervisor of applied research at HP Associates, he is responsible for projects in silicon epitaxy, GaAs Gunn oscillators, avalanche diode oscillators and Ga(As,P) electroluminescence. He has co-authored several papers on Schottky barrier devices. He is a member of IEEE and Sigma Xi.

Direct measurements of charge storage in the three types of diodes were made at forward currents of 5 mA and 15 mA. At 5 mA, the molybdenum and titanium diodes stored less than 1 picocoulomb (the estimated accuracy of the measurement) while the gold diode stored approximately 16 pC. At 15 mA, the gold diode stored more than 100 pC. At this same current, which corresponds to about 1.5 volts across the diode, the molybdenum diode stored approximately 1.4 pC and the titanium diode still did not store any measurable charge.

HP 5082-2800 hybrid diodes, made with molybdenum, typically store less than 4 pC at 15 mA and have effective minority-carrier lifetimes less than 100 ps.

Acknowledgments

We wish to thank E. Petherbridge and R. D. Patterson for their assistance in fabricating and characterizing the experimental devices, and C. Forge for the design of our charge-storage test set. We also acknowledge many helpful discussions with R. W. Soshea, J. L. Moll, and M. A. Clark.

References

[1]. R. A. Zettler and A. M. Cowley, 'PN Junction-Schottky Barrier Hybrid Diode,' IEEE Transactions on Electron Devices, Vol. ED-16, January 1969. (The material in this article is derived primarily from this reference.)

[2]. M. P. Lepselter and S. M. Sze, 'Silicon Schottky Barrier Diode with Near-Ideal I-V Characteristics,' Bell System Technical Journal, Vol. 47, pp. 195-208, February 1968.

[3]. C. Leistiko, Jr., and A. S. Grove, 'Breakdown Voltage of Planar Silicon Junctions,' Solid State Electronics, Vol. 9, pp. 847-852, 1966.

[4]. S. M. Sze and G. Gibbons, 'Effect of Junction Curvature on Breakdown Voltage in Semiconductors,' Solid State Electronics, Vol. 9, pp. 831-845, 1966.

[5]. C. A. Mead and W. G. Spitzer, 'Fermi Level Position at Semiconductor Surfaces,' Physical Review Letters, Vol. 10, pp. 471-472, 1 June 1963.

[6]. H. K. Henisch, *Rectifying Semiconductor Contacts,* Oxford University Press, London, 1957, pp. 196-201.

[7]. M. M. Atalla, 'Metal-Semiconductor Schottky Barriers, Devices and Applications,' Proceedings of the Microelectronics Symposium, pp. 123-157, Munich, 1966.

[8]. S. M. Sze, et al., 'Photoelectric Determination of the Image Force Dielectric Constant for Hot Electrons,' Journal of Applied Physics, Vol. 35, pp. 2534-2536, August 1964.

[9]. C. R. Crowell and S. M. Sze, 'Current Transport in Metal-Semiconductor Barriers,' Solid State Electronics, Vol. 9, pp. 1035-1048, 1966.

[10]. A. M. Cowley and R. A. Zettler, 'Shot Noise in Silicon Schottky Barrier Diodes,' IEEE Transactions on Electron Devices, Vol. ED-15, p. 761, 1968.

SPECIFICATIONS

HP 5082–2800 Series Hot Carrier Diodes

$T_A = 25°C$

		Single Diode		Matched Pair, Unencapsulated, Unconnected		Matched Quad, Unencapsulated, Unconnected		Single Diode		Single Diode		Matched Bridge Quad, Epoxy Encapsulated		Matched Ring Quad, Epoxy Encapsulated		Matched Quad, Unencapsulated, Unconnected			
CHARACTERISTICS	Symbol	HP5082-2800		HP5082-2804		HP5082-2805		HP5082-2810		HP5082-2811		HP5082-2813		HP5082-2814		HP5082-2815		UNITS	TEST CONDITIONS
		min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max		
BREAKDOWN VOLTAGE	V_{BR}	70	—	70	—	70	—	20	—	15	—	*		*		15	—	V	$I_R = 10\mu A$
REVERSE CURRENT at V_R = ( )	I_R	—	200 (50V)	—	200 (50V)	—	200 (50V)	—	100 (15V)	—	100 (8V)	*		*		—	100 (8V)	nA	V_R = ( )
FORWARD VOLTAGE	V_{F1}	—	410	—	410	—	410	—	410	—	410	—	410	—	410	—	410	mV	$I_{F1} = 1.0mA$
FORWARD CURRENT	I_{F2}	15	—	15	—	15	—	35	—	20	—	20	—	20	—	20	—	mA	$V_{F2} = 1.0V$, Note 1
FORWARD VOLTAGE MATCH**	ΔV_F	—	—	—	20	—	20	—	—	—	—	—	20	—	20	—	20	mV	I_{F2} = 1.0 to 10mA (04, 05: 0.5 to 5 mA)
CAPACITANCE	C_0	—	2.0	—	2.0	—	2.0	—	1.2	—	1.2	*		*		—	1.2	pF	$V_R = 0$, f = 1.0 MHz
EFFECTIVE MINORITY CARRIER LIFETIME	τ	—	100	—	100	—	100	—	100	—	100	*		*		—	100	ps	$I_F = 5.0mA$

* Breakdown voltage, reverse current, capacitance, and effective minority carrier lifetime cannot be readily verified after assembly and encapsulation because of the shunting effect of the other diodes. The encapsulated quads have the same parameter values as the HP 5082-2815 unencapsulated quad prior to assembly and encapsulation.

** Quads and pairs having additional and/or tighter matching are available upon request. Please contact the local HP field sales office.

Note 1: The test condition and specification are interchanged to make the tabulation easier to read. The actual test condition is forward current; the actual specification is forward voltage. The forward current is limited to prevent thermal runaway.

PRICES:

	1 to 99	100 to 999	1000 to 4999
HP 5082–2800	0.99	0.75	0.55
5082–2804	2.20	1.90	
5082–2805	4.40	3.75	
5082–2810	2.50	2.10	
5082–2811	1.25	1.00	
5082–2813	12.00	10.20	
5082–2814	12.00	10.20	
5082–2815	6.00	5.10	

ABSOLUTE MAXIMUM RATINGS

P_{DISS}	Power Dissipation @ $T_A = 25°C$	250 mW (Note 2)
T_A	Operating Temperature Range	−65°C to +200°C
T_{STG}	Storage Temperature Range	−65°C to +200°C

Note 2: As measured using an infinite heat sink.

MANUFACTURING DIVISION: HP ASSOCIATES
620 Page Mill Road
Palo Alto, California 94304

HEWLETT-PACKARD JOURNAL **FEBRUARY 1969** *Volume 20 • Number 6*

TECHNICAL INFORMATION FROM THE LABORATORIES OF THE HEWLETT-PACKARD COMPANY PUBLISHED AT 1501 PAGE MILL ROAD, PALO ALTO, CALIFORNIA 94304
Editorial Staff: F. J. BURKHARD, R. P. DOLAN, L. D. SHERGALIS, R. H. SNYDER Art Director: R. A. ERICKSON