Long-Lived Solid-State Circuits

Earth-bound research instruments are benefiting from electronic components designed for space travel.

Consumption of electric power per capita used to be taken as a rough index of the state of a nation's technology. A new index is available: the extent to which transistors have replaced vacuum tubes in electronic equipment. And a more sophisticated yardstick may soon be useful: how far have integrated circuits built into microsize semiconductor chips replaced transistorized circuits?

Texas Instruments, which reached top rank in the $16-billion U.S. electronics industry by producing the first silicon transistor, is now making microcircuits 1/100 the size of transistorized circuits. Texas recently built microcircuitry that reduced a telemetry encoder to 1 percent of its previous size. Westinghouse, a pioneer in molecular electronics, is supplying 3000 microcircuits for each airborne Univac 1830 computer, built by Sperry Rand under Navy contract.

A number of other producers are in this field, which has high capital requirements, and Commerce figures for the first three quarters of 1964 show sales for integrated microcircuits of $35 million, a 50-percent increase over the same period in the year before. According to an industry source, the sales increase was accompanied by a price cut of 50 percent below an average unit price of $33 in early 1964.

Both this shift in the nation's fourth largest industry and the fact that man-made instruments are orbiting the earth and invading other parts of the solar system are the result of work in solid-state physics.

The laser is the most recent and spectacular development in the rapid progress made since Shockley, Bardeen, and Brattain showed how quantum theories of atomic structure could be used to develop a microarchitecture of electromagnetic energy. Without their discovery of the transistor effect in the course of basic study of the solid state, neither high-speed computers nor the instruments that control spacecraft in flight would be possible.

The new work in microcircuitry goes farther. Integrated circuits are not unit-by-unit translations of transistor circuits: in their most promising form, they are redesigns of certain physical properties of a solid to produce a circuit function more complicated than that performed by individual components (*1*). While most integrated circuits now being produced are used in missile and rocket controls, work at the research level suggests that molecular electronics, coupled with the search for organic semiconductors, is bringing researchers close to understanding and emulation of the electromagnetic energies of the human nervous system and of such examples of organic semiconduction as photosynthesis.

Each year the Instrument Society meeting gives a chance for rapid assessment of how far the advancing front of electronic research has affected instruments on the market. At the last meeting (12–15 October 1964) the program and accompanying exhibits at the New York Coliseum indicated that integrated microcircuits and

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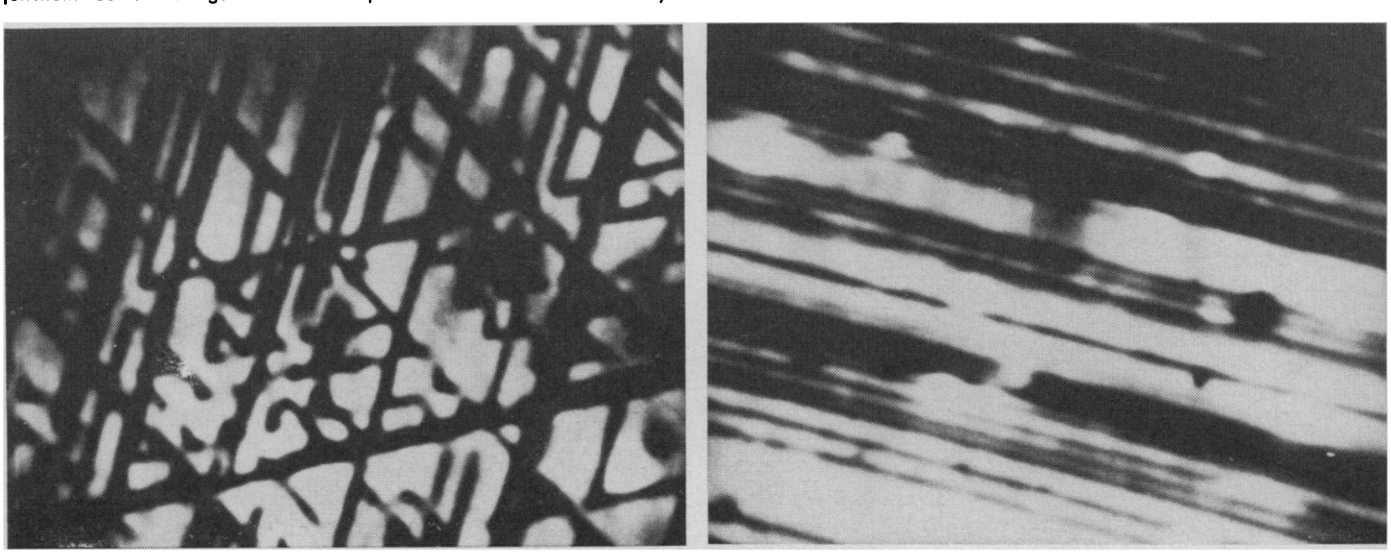
Electron beam probes semiconductor interiors by technique developed at Bell Laboratories. When beam scans for lattice defects in semiconductor diode, hole electron pairs are produced in field of p-n junction. Current so generated is amplified and fed to cathode-ray tube which displays map-like internal view (left below, magnification × 620; right × 710). Where lattice structure is defective, electron pairs recombine and reduced current appears as dark areas in micrograph. Lander, Mathews, Schreiber, and Buck developed technique.



laser beams, while subjects of first interest in private conversations of the 20,000 registrants, are not yet applied in research instruments except for experimental units.

While not bestrewn with integrated microcircuits, the exhibits were evidence of the extent to which the transistor, regarded only a decade ago as little more than a miniaturization device for hearing aids and pocket radios, has invaded instrument technology. "Second-generation" transistor and transducer circuits are showing significantly reduced power and weight requirements and longer operating life than did such packages only a few years ago.

For example, in a paper on a solid-state rate-of-turn sensor intended for attitude control in aircraft and spacecraft, Edward H. Ernst and Stephen W. Tehon of the General Electric Co. said, "With proper design, the life of the solid-state sensor can be made infinite." Theoretical sensitivity of this piezoelectric device, these designers said, is four orders of magnitude better than that of the conventional rate gyro using a high-speed rotating wheel, while it can be made at a quarter of the cost. The sensor occupies about 1 cubic inch, weighs 1 ounce, and operates on 0.1 watt as compared with the 2 to 6 watts required by conventional devices. In installation, integrated microcircuits would be used in the driver or oscillator part of the device as well as in the output portion, Ernst said.

Progress in Semiconductor Technology

The current advance in solid-state devices is also the result of great progress in crystallography, which has made it possible to grow and cut semiconductor crystals in smaller sizes and in orientations precisely calculated for desired properties, and of comparable progress in techniques for adding the impurities that convert the basic crystal lattice to both active and passive circuit elements. All this is the fruit of a high degree of interdisciplinary effort by physicists, chemists, and electronics engineers.

While much of the advance has been stimulated by a plentiful supply of federal funds allotted for the development of shock-resistant instruments light enough to go to the moon, the greatly widened range of earth-bound instruments making use of long-lived solid-state devices was well illustrated at the Instrument Society show. These ranged from a recording electrolytic titrator in which a solid-state circuit controls the titration current (Barton Instrument Corp., Monterey, Calif.) to a strip-chart pen recorder equipped with an infinite-resolution slide-wire and solid-state amplifiers and chopper (Texas Instruments' apparatus division, Houston).

Here are some other examples, all described in papers read during the scheduled program and, in many cases, shown among the accompanying exhibits:

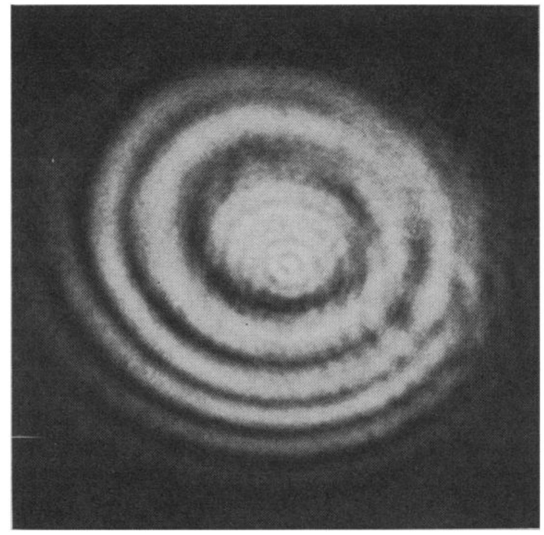
Measuring Moonquakes

Moonquakes may be measured by a 10-pound seismometer based on an electronic design by Wayne F. Miller of the California Institute of Technology seismological laboratory. U.S. ability to detect underground explosions elsewhere in the world may be improved by a transistorized, ultralow-frequency band-pass filter designed by William Gile of the same laboratory.

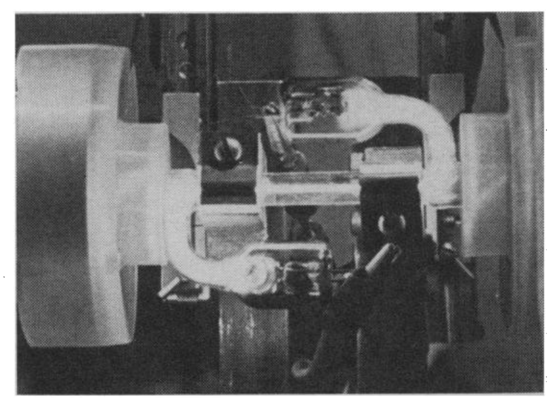
The Caltech seismometer is a part of work done under NASA contract at the seismological laboratory, one of the world's foremost centers of research in this field. Caltech has produced such major instruments as Hugo Benioff's strain seismograph; mounted deep in an old gold mine at the Lake Isabella observation station, it is capable of measuring vibrations of the earth as a whole, excited by the largest earthquakes.

Seismic waves roll around the earth at frequencies ranging from 100 cycles per second to 1 cycle per 53 minutes. Much of the work on instruments to measure them has been concerned with efforts to lengthen the natural period of the pendulum by devising a very loose mounting. A long natural period means that the pendulum can move in resonance with the slowest seismic waves, surface waves that travel along the earth's periphery.

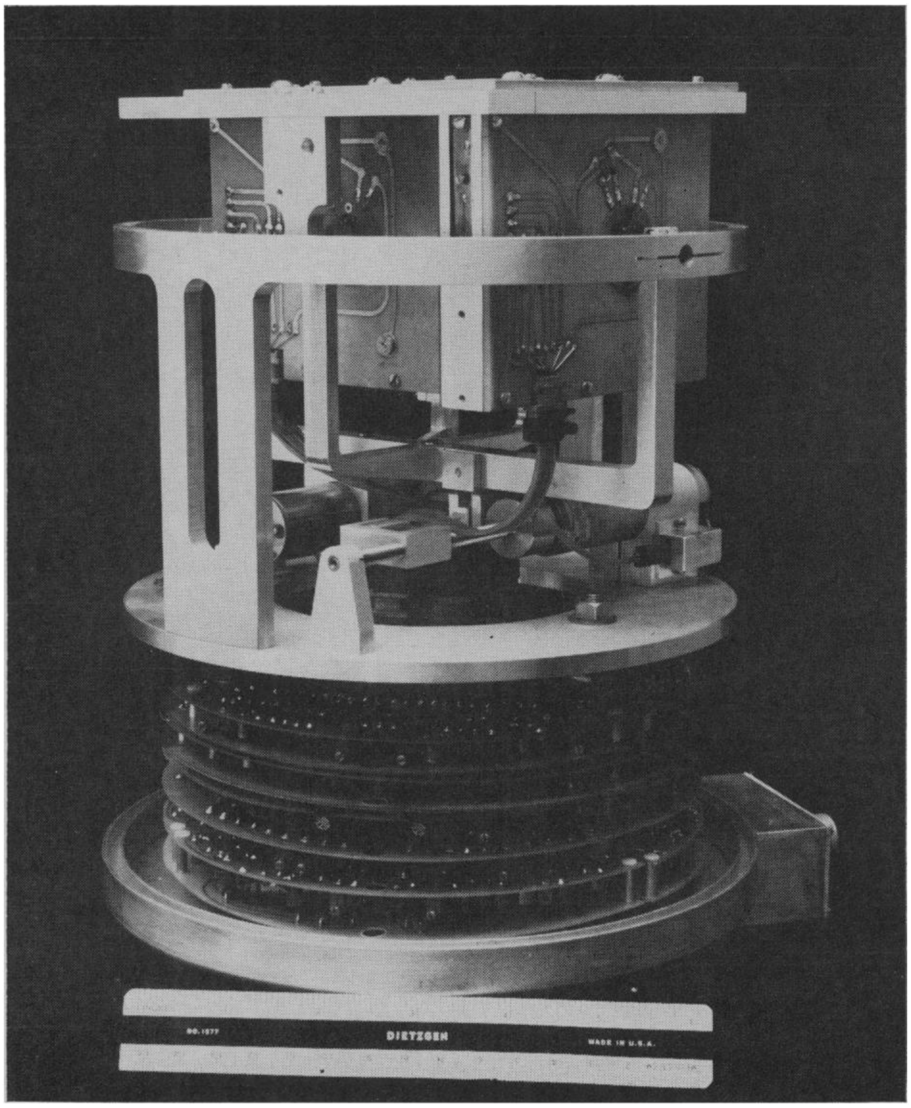
Short-period instruments, built to detect local earthquakes, are better for measuring the artificial earthquakes produced by underground nuclear explosions (*2*). Luckily the analytic area is limited by the fact that nuclear experimenters cannot yet drill below the earth's crust, while the majority of the earthquakes detected in an average year originate in the earth's mantle. But the task of distinguishing seismic



Interference rings are made by light waves from two helium-neon lasers locked at the same frequency: 5 $\times 10^{14}$ cy/sec. First phase-lock for beams from two lasers was devised by Louis Enloe and John Rodda of Bell Laboratories. Constructive interference of combined beams increases output from a photomultiplier; destructive interference decreases output. Output is fed back to piezoelectric transducer supporting one of the mirrors for the resonator of the receiving laser. Variations in voltage change resonator length and thus laser frequency. The device will be applied to lock the receiving laser to frequency of the transmitting laser in a communications system, thus permitting homodyne detection. The phase-lock will also make it possible for researchers to study interactions of light waves from separate sources.



Miniature helium-neon laser emits light at a single frequency that can be swept continuously over a 1500 megacycle range centered on 4.73×10^{14} cy/sec. While narrow optically, this is a wide range in terms of communication potential. Two-inch laser tube is set between mirrors 4 inches apart. The mirror at left is attached to a piezoelectric crystal. An applied voltage will change the crystal's length and so move the mirror, giving the precise control of the length of the resonator cavity that permits the frequency sweep. By means of a feedback circuit, the piezoelectric element is also used to correct variations in cavity length resulting from vibration or thermal change; thus laser frequency is held constant within one part per billion. System gives an excellent light source for the Michelson interferometer and has made it possible to measure distances of 10 feet with an accuracy within half a wavelength. This tuneable laser was developed by Eugene I. Gordon and Alan D. White of Bell Laboratories.



Seismometer will measure moonquakes after drop to lunar surface.

waves produced by nuclear explosions from several thousand natural earthquakes of comparable size occurring in an average year is a difficult one.

New methods of analysis have been devised based on arrays of instruments, set for different operating periods, at a given observation station. Such arrays make it possible to compare arrival times for waves of different frequencies. For example, there are 47 seismometers in an array at the Payson, Arizona, observatory, one of the five special observation stations built under the Vela Uniform program, a $100-million research effort launched in 1959 to establish a basis for detecting underground nuclear explosions and operated by the Advanced Research Projects Agency of the Department of Defense.

While a few 19th-century-built observatories are still turning in good measurements made by 50-pound pendulums driving pen recorders, modern observatories like the Vela stations use seismographs in which transducers and amplifiers are applied to yield signal magnifications as high as 6 million. Until recently such electronic equipment used vacuum tubes with high power requirements.

Now, faced with the task of lifting a seismograph to the moon or, perhaps, sealing it in a capsule in an unattended station capable of monitoring underground nuclear explosions occurring in another country, designers have turned to solid-state devices. Transistorized components are the basis of both Miller's and Gile's designs.

The Caltech three-axis seismometer designed for operation on the surface of the moon consumes only 1 watt of power per axis. Miller designed a servo-mechanism that feeds back a fraction of transducer output to a damping coil placed between the mass of the pendulum and its frame-mounting. The electronic effect of this negative feedback is in part like the mechanical effect of using a stiffer spring to suspend the pendulum mass: it minimizes the effect of the tilt that the instrument is almost certain to encounter when dropped to a lunar location. A stiff spring would give this protection but also prevent the pendulum from moving in resonance with long-period seismic waves. The ingenuity of Miller's electronic design lies in the addition of a filter that limits the "stiffening" effect of the feedback to resistance to tilt. The net result is a looser suspension than would be possible with a wholely mechanical system. This lunar instrument detects seismic waves with periods up to 20 seconds, although its size and weight are much below those of comparable conventional instruments. The mechanics of the seismometer were designed by E. E. Lehner and E. O. Witt.

Ultralow Frequency Band Pass

While band-pass filters for higher frequencies are routine equipment, it has not been easy to design them for reliable operation at ultralow frequencies. Not patented (it was designed under a Vela contract), Gile's transistorized band-pass filter aroused considerable interest at the Instrument Society meeting and is now being examined for uses ranging from devices for monitoring nuclear reactors to gas chromatographs (according to the designer, the circuit design is applicable for frequencies up to 1000 cycles/second).

Gile said that his band-pass, which can select frequencies of a single octave, achieves a 50-percent reduction in noise level compared with a vacuum-tube filter. This may make the device of particular interest for use in seismometers detecting underground explosions. While high amplification permits detection of seismic signals from such explosions over great distances, noise is similarly amplified; thus signal-to-noise ratio becomes the critical factor in detection. Noise often masks the beginning of a seismic signal—a period critical for one of the best ways to distinguish nuclear explosions from earthquakes.

Power consumption by the unit averages 25 milliwatts. While the operating life of the vacuum tube is limited by its filament, Gile said the semiconductive band-pass filter has indefinitely long life expectancy. Diodes matched to the structure of the transistor (for example, planar, alloy) compensate for drift caused by temperature change.

Help from Peltier

In Apollo spacecraft, fast measurement of moisture content of gases may be made by means of a rugged, long-lived, dew-point sensor weighing only 50 grams. This last word in hygrometry is based on an observation made in 1834 by the French physicist, Jean Peltier. Peltier's demonstration that heat is generated by passage of an electric current through the junction of two metals and absorbed if the current is reversed found little application in technology for more than a century. When the advent of semiconductor crystals greatly reduced the current needed for Peltier-effect cooling, devices began to appear ranging from a baby-bottle cooler-and-warmer to a miniature beer cooler that delighted boat owners.

About 6 years ago a student at Massachusetts Institute of Technology designed a hygrometer using a crystal of bismuth telluride as a thermoelectric pump to cool the rhodium-plated mirror of a dew-point sensor. Dew-point sensors had long been preferred to devices based on changes in chemical equilibrium which give only indirect moisture measurements. But dew-point instruments were bulky and expensive, requiring mechanical or chemical units to cool the mirror surface of the sensor to condensation temperature.

Recognizing that the semiconductor thermoelectric pump promised great reduction in hygrometer size and cost, David J. Beaubien, also an M.I.T. student, bought the device and in 1960 formed Cambridge Systems, Inc. (Newton, Massachusetts) to produce it. Cambridge Systems' annual sales, which include a variety of instruments for meteorological and geophysical use, will amount to about $300,000 in 1964, according to Charles C. Francisco, treasurer.

With $350,000 in development funds, much of which came from NASA contracts, Cambridge Systems succeeded in reducing the size of this solid-state hygrometer from a 5 by 5 by 10 inch cell plus a 10 by 9 by 4 inch control unit to only 1.6 cubic inches; it is mounted inside a tube of 15/16-inch inside diameter. This instrument was shown for the first time at the New York meeting and was described in a paper read by Arthur Bisberg, chief engineer, Cambridge Systems, Inc.

Bisberg said that the thermoelectric module that makes the miniature hygrometer possible has interesting applications in biomedical research. For example, the unit, 1 by 1 by 2 mm in size, is being used to cool or heat specimens during microscopic examination. It also forms the tip of an insulated probe being used by P. P. Lele at Massachusetts General Hospital for neurological examinations. The thermoelectric probe is set at a temperature just below that of the body; the patient's inability to detect the temperature difference in certain surface areas indicates a possible neural deficit.

The size reduction of the thermoelectric unit is one of the many dividends of recent progress in crystallography, which has made it possible to grow and slice crystals to greatly reduced sizes, with corresponding reduction in current requirements. Similar size-reduction has been made in the cadmium sulfide photoresistor, which detects the change in reflectivity when the illuminated mirror surface is covered by condensed moisture, and in the silicon and germanium transistors of the amplifiers that pick up the photoresistor signal. The new hygrometer operates on a power supply of only 3 watts.

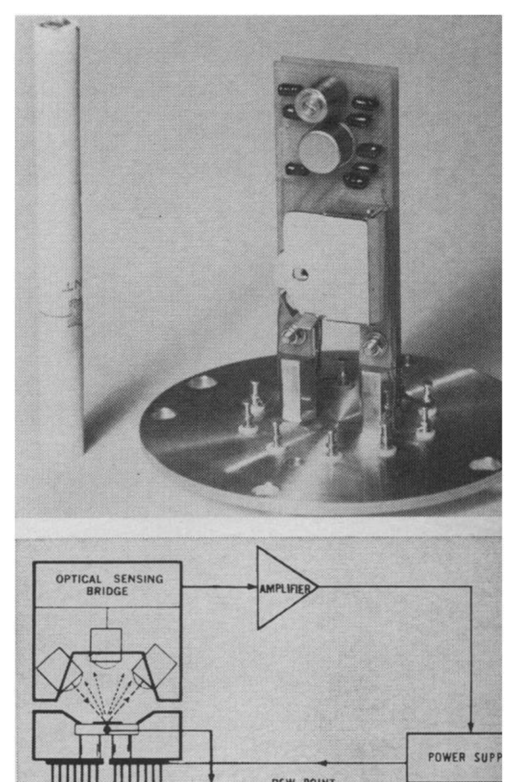
Bisberg told how a reduction in transistor size to 0.1 cubic inch has made it possible to place two silicon transistors in a single package; one balances the other for ambient-temperature changes. Amplifiers used in earlier hygrometers were subject to considerable output drift due to ambient-temperature changes, since the minimum distance that could be achieved between differential sections of the larger transistors was 0.5 inch.

The basic design scheme is to feed back amplifier output to control the direct current supplied to the thermoelectric cooling module. By this means, mirror temperature is lowered when condensation decreases; thus the system stabilizes at a particular dew thickness. So stabilized, mirror temperature, sensed by a thermistor, thermocouple, or platinum resistance thermometer, is taken as a direct measure of dew point.

Semiconductor Strain Gages

Strain gages that orbited with the first U.S. manned satellite and help to monitor operating safety in the newest 306-ton pressure reactor recently installed at Oak Ridge National Laboratory were shown by BLH Electronics (a division of Baldwin-Lima-Hamilton Corporation), Waltham, Mass. Strain-gage design, which accounted for a major part of the Instrument Society program, rests upon the observation by Kelvin in 1865 that stretching a wire increases its resistance to electrical current. Not until the big-dam construction of depression years was Kelvin's observation put to use in measuring strain. When the piezoresistivity of certain semiconductor crystals was discovered, silicon elements were introduced to produce strain gages with a 100-fold increase in gage factor as compared with foil or wire devices. The rapid response and sensitivity of semiconductor gages to small changes in strain make them valuable for uses ranging from monitoring the Boeing-707 structure to testing a parachute buckle. BLH recently supplied some to an orthopedic researcher working on skeletal strain in the human body.

Miniature hygrometer is designed for use in manned spacecraft.



James Dorsey of BLH described a semiconductor gage design which, he said, yields a high degree of linearity in the relation of degree of strain to change in electrical resistance. He said that this is based on three main elements: choice of transducer elements, proper use of the bridge circuit, and bonding of the silicon elements to metal transducer components in a way that balances the differing response of each to temperature changes.

A strain-gage installation stable enough for use in nuclear reactors was described in a paper by Leon J. Weymouth, also of BLH. Strain gages made of fine platinum-alloy wire are bonded by means of an aluminum oxide coating developed originally by the Norton Co. for rocket nozzles; the coating was made more acceptable for gage work by reduction of impurities. Applied by flame-spray, this bonding material produces an all-inorganic gage installation resisting temperatures up to 1500°F. The adhesive technique is now being studied for application to semiconductor strain gages.

Quartz Temperature Sensor

Since the earliest electronic uses of quartz crystals, designers have fought with the high temperature sensitivity of this crystal lattice. With increased understanding of the anisotropic character of the crystal structure, producers found they could make quartz virtually insensitive to temperature by precise orientation of the crystal slice cut relative to the crystalline lattice. Now, in a turnabout, they are exploiting the fact that, in most orientations of quartz-crystal lattice, frequency of natural vibration increases as temperature rises.

Hewlett-Packard Co. (Palo Alto, Calif.) showed a quartz-crystal temperature sensor useful over a range of −40° to 230°C; it permits a resolution of 0.001°, C or F. Mounted in a steel tube ⅜ inch in diameter, the quartz sensor is linked to an oscillator-counter by 12 feet of cable, while the instrument, with visual digital display or recorder connections, can be hundreds or thousands of feet away. A variety of probes are available ranging from low-mass units for laboratory use to long probes for insertion in tanks or pipes; a series of probes could be linked by amplifiers for oceanographic use.

A decade of study of quartz-crystal orientations has made it possible to cut the slice for this sensor in a way that makes the frequency-temperature relation a highly linear one. This means that temperature can be measured directly.

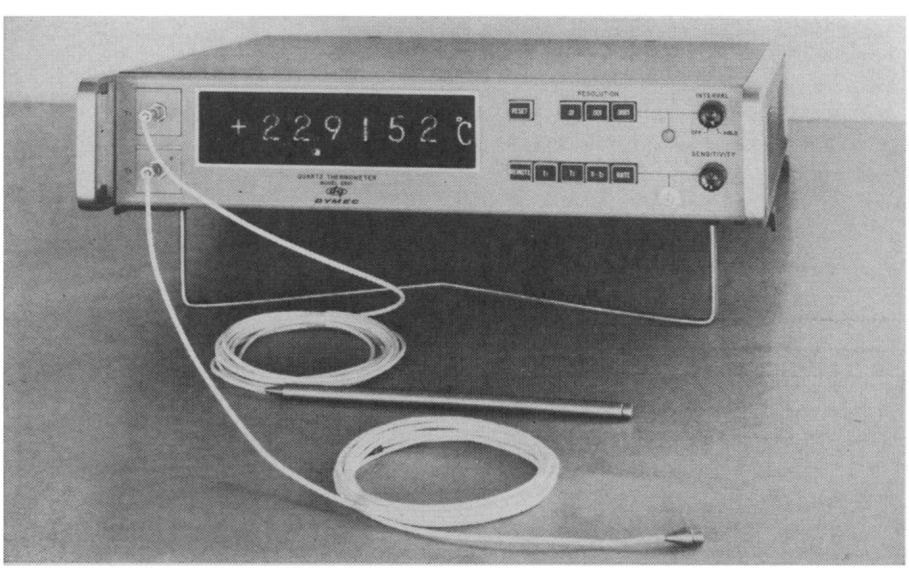
"It avoids the problems of other types of temperature-sensing methods, by eliminating the need for bridge balancing, reference temperatures, and conversion tables," Herschel C. Stansch of Hewlett-Packard said in a paper on the new instrument.

The linearity of temperature frequency also makes possible digital readout in degrees Centigrade, Fahrenheit, or other units, as desired; at 0°C the frequency of crystal vibrations in the orientation chosen is 28,208,000 cycles per second.

"In this orientation, the temperature coefficient of frequency is $35.4 \times 10^{-6}/°C$," according to a paper by Donald L. Hammond, Charles A. Adams, and Paul Schmidt, all of Hewlett-Packard. "This large coefficient makes it possible to apply to the measurement of temperature the high precision which has been obtained with frequency-standard crystal units."

These researchers said that mathematical analysis of the lattice orientation chosen indicated a departure from linearity of not more than 0.002 percent over the range of 0° to 200°C. Analysis of experimental tests of the frequency-temperature relationship in the unit as cut showed a departure of 0.06 percent over this range. "Most of this will be corrected by a slight change in orientation," the authors of this paper said.

Temperature sensitivity of quartz-crystal lattice is exploited in thermometer.



What's Ahead in Computers

Computers with improved logic and memory can soon be expected. These advances will result from solid-state electronic devices that have only recently become practical, Lawrence W. Langley, research supervisor, digital systems, Corning Glass Works (Raleigh, North Carolina), said. Among the new developments Langley described are:

► Electroluminescence produced by injection of direct current in thin layers of cadmium sulfide and gallium phosphide; such light emission does not deteriorate as does electroluminescense produced by alternating-current capacitor devices. Further development of materials will probably make it possible to combine electroluminescent and photoconductive effects in optically coupled amplifiers and logic elements.

► Very high-speed transducers in which an ultrasonic input is converted to an electron flow in an extremely thin region of high-resistance material in a piezoelectric semiconductor.

► The discovery that ultrasonic waves (phonons) can be amplified by interaction with electron currents in certain semiconductors. Not enough experimental knowledge is yet available in this field to predict application, Langley said, "but the possibilities of using electron-phonon interaction amplifiers in digital memories are certainly outstanding."

► A newly reported magnetostrictive effect permitting permanent information-storage in a delay line. In certain magnetic materials, an acoustic impulse interacts with a magnetic field to store residual induction; a subsequent acoustic impulse reversibly changes induction at storage points. This technique, Langley said, "will have far-reaching effects . . . making computers easier to apply and capable of handling bigger jobs."

► New organic and organometallic semiconductors. Such materials will not as hoped reduce the cost of semiconductors, but may yield compounds that could function as artificial neurons. This would make it possible "to produce associative or adaptive computers with the power to learn. . . . It is entirely possible that organic semiconductors will provide a memory density greater than any achieved so far."

► Extremely high-speed diodes and other devices using electronic tunneling: the passage of electrons through a potential barrier at a voltage lower than that of the barrier itself. Tunnel diodes have converted an analog signal into a six-figure digital indication in 200 nanoseconds.

► Thin film tunneling, which combines the high-frequency response made possible by electron tunneling with the high density of superconductive thin films. Such a superconductive tunneling strip has been proposed as a microminiature transmission line for computers. "This type of element is called a neuristor, and is similar in behavior to a neuron, although several orders of magnitude faster."

Recognition tasks and many other simple-decision functions could be readily handled by such computers, Langley said. "With appropriate transducers, computers can recognize voices, markings, and combinations of effects or 'situations.' The adaptation of computers to operate industrial vehicles, particularly equipment operating in hazardous areas, is something that can be foreseen."

T. L. CAMPBELL
American Association for the Advancement of Science, Washington, D.C.

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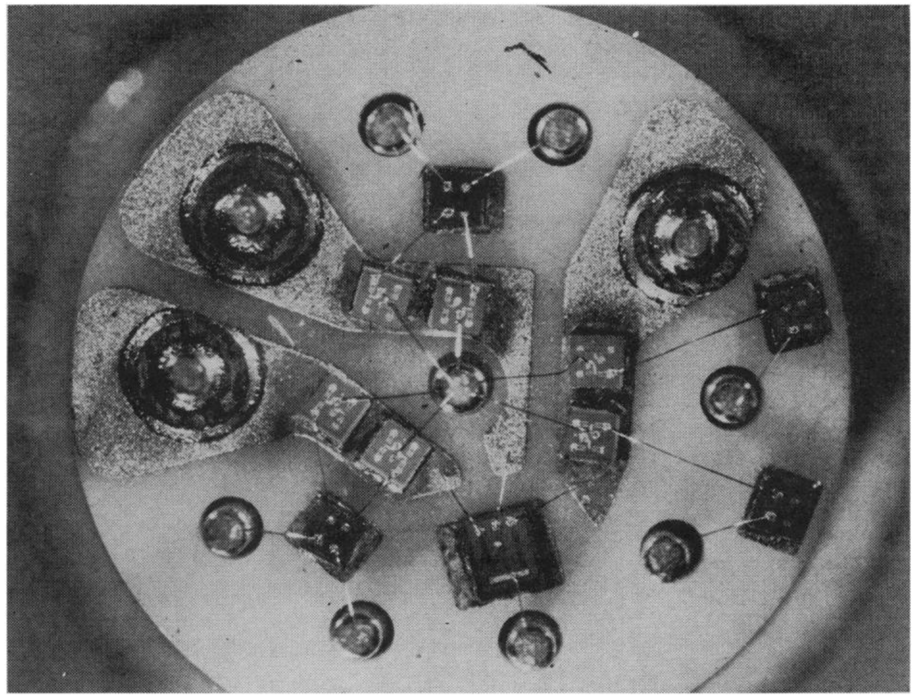
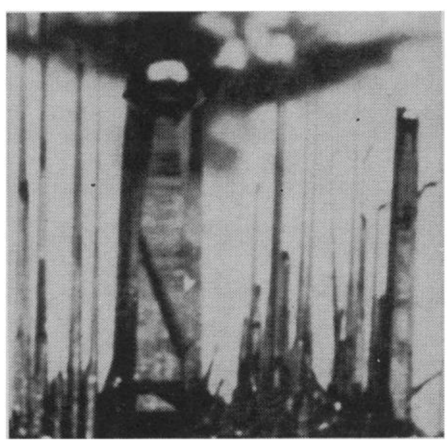
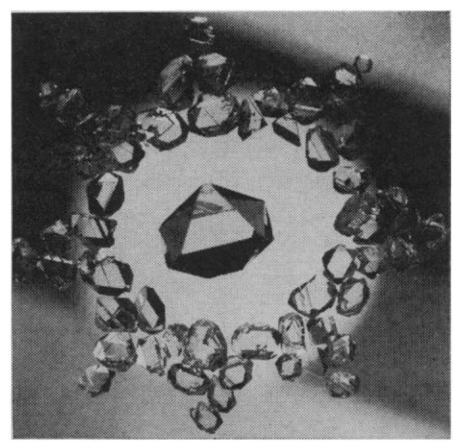
1. S. W. Herwald and S. J. Angello, *Science* **132**, 1127 (1960).
2. J. P. Ruina, *Hearings before the Joint Committee on Atomic Energy*, Congress of the United States.



Multiple-chip microcircuit was recently designed in Bell Laboratories for use in logic circuit of a computer used to guide missiles. Eleven silicon wafers are connected with gold leads and enclosed in a 0.35-inch diameter can. Wafers provide 5 resistors and 24 transistors.



Study of how "whisker" crystals grow led to development of new vapor-liquid-solid method. This process is being used to produce crystals of near-perfect structure at temperatures much lower than those required for widely used vapor-phase process. When small particles of gold are placed on a silicon crystal and heat is applied, droplets of gold-silicon alloy form. A vapor of silicon tetrachloride and hydrogen adds silicon atoms when passed over droplets, supersaturating them. Some silicon and gold atoms then come out of solution and add to crystal lattice. Liquid droplet is displaced from crystal substrate and continues to ride on top of whisker until growth is stopped. Method was developed by R. S. Wagner and W. C. Ellis of Bell Telephone Laboratories.



New flux-growth method yields ruby crystal with almost no strain and highly uniform structure. Method also gives very flat and parallel crystal faces, providing excellent surfaces for reflecting the light produced by laser action. Best previous method (Verneuil flame-fusion) gives crystals with some non-uniformity as a result of strain; this causes scattering of light and loss of output. Flame-fusion-grown crystals also must be cut and polished to provide faces suitable for laser use. Crystals above were grown by slow cooling of $PbO(B_2O_3)$ flux containing Al_2O_3 and doped with Cr_2O_3. Method was devised by J. P. Remeika and crystal was used in laser experiments by D. F. Nelson, both of Bell Laboratories.