8. R. Payne, R. Scavuzzo, K. Olson, J. Nacci, and R. Moline, "Fully Ion-Implanted Bipolar Transistors," *IEEE Trans. Electr. Dev.* **ED-21**, 273–278 (1974).
9. A. H. Agajanian, "A Bibliography on Semiconductor Device Isolation Techniques," *Solid State Technol.* **18**, 61–65 (1975).
10. E. F. Koshinz, "Semiconductor: Wire Bond and Face Bonding Considerations and Comparisons," *Proc. SAE Microelectronic Packaging Conference*, November 20-22, 1968, Palo Alto, Calif., pp. 94–100.
11. Special Issue on Beam-Leads, *Western Electric: The Engineer*, December 1967.
12. "Tape-Carrier Packaging Boasts Almost Unlimited Potential," *EDN*, October 20, pp. 30–37 (1974).
13. P. A. Totta, "Flip Chip Solder Terminals," *Proc. Electronics Components Conference*, May 10-12, 1971, Washington, D.C., pp. 275–284.
14. "IC's to Pass Discretes in 1976 Shipments," *Electronics* **49**, 35 (May 27, 1976).
15. I. E. Sutherland, C. A. Mead, and T. E. Everhart, "Basic Limitations in Microcircuit Fabrication Technology," February 1976, Rand Corporation, Santa Monica, California, #WN-9409-ARPA.

Clocks, Atomic and Molecular

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Almost any clock can be thought of as being composed of three main parts: (1) a pendulum or other nearly periodic phenomenon, which determines the rate of the clock; (2) a counting mechanism, which accumulates the number of cycles of the periodic phenomenon; and (3) a display mechanism to indicate the accumulated count (i. e., time).

An atomic (or molecular) clock makes use of an atomic (or molecular) resonance to control the periodic phenomenon. The atomic (or molecular) clock is a very good clock because these resonances are determined by the atom's properties rather than by the man-made dimensions of an artifact; they are among the most stable and accurately measured phenomena known to man. Since all clocks are just devices that count and display the total of a series of periodic events (such as swings of a pendulum, passages of the sun overhead, or oscillations of an atom), the accuracy of the clock depends directly on the stability and accuracy of the periodic phenomenon used to establish the rate of the clock.

The most accurate clocks (in rate) today make use of a cesium resonance (Fig. 1). In fact, the present definition of the unit of time, the second, is in terms of a microwave resonance of cesium, and the national standards of time and frequency for the United States and other countries are cesium clocks. Expressed as a fractional error, time (and frequency) can be measured with the smallest uncertainty of any physical quantity. Current estimates of possible errors in various national standards laboratories are of the order of one part in 10^{13} for clock rates; or, expressed differently, independent cesium clocks can maintain synchronism with one another to within a few millionths of a second after a year's operation. This is more than 100 000 times more predictable than the earth's spin on its axis.

Cesium atomic clock operation depends on the observation of a particular resonance in cesium atoms. The atoms are *not* radioactive, and radioactive decay processes play no part in the scheme. Neutral atoms boiled off from a quantity

FIG. 1. Commercial cesium-beam atomic clock. (Photograph courtesy of Hewlett-Packard Co.)

of liquid cesium are allowed to escape through narrow holes in a small oven and form a beam, which traverses an evacuated chamber. To prevent the cesium atoms from colliding with air molecules and being scattered out of the beam, a good vacuum must be maintained in the chamber.

By passage through the strong, inhomogeneous magnetic field of a Stern–Gerlach magnet, the beam of atoms is separated into two beams with opposite magnetic polarizations. In many cesium-beam devices one of the polarized beams is absorbed in graphite and is of no further interest, while the other continues down the chamber.

Further down the chamber is another strong, inhomogeneous magnetic field nearly identical to the first. At the end of the chamber there is a detector (which is sensitive to cesium atoms) placed in just such a position as to detect only those atoms that somehow *change* their polarization while traveling between the two magnetic field regions. Thus, the detector would *not* detect cesium atoms unless something happens to the atoms between the two strong magnetic field regions to change their polarity.

What happens is that the atoms are exposed to microwave radiation at a frequency of about 9 GHz (actually 9 192 631 770 Hz). If this frequency is adjusted rather precisely to the proper resonance frequency of cesium, the magnetic polarization of the atoms reverses, causing the beam to be deflected by the second magnetic field toward the detector. The detector indicates the presence of cesium atoms by means of an electric current. In actual operation the frequency of the microwave signal is automatically controlled by a servomechanism to maximize the detector current, thus ensuring the resonance condition of the microwave signal with the cesium atoms.

At this point it should be mentioned that other atomic and molecular clocks use entirely different principles to extract frequency information from the atoms or molecules. The first atomic or molecular clock ever developed (completed in 1949 by Dr. Harold Lyons of the U.S. National Bureau of Standards) used the absorption of a microwave signal in ammonia to control the frequency, while hydrogen maser clocks use the stimulated emission of microwave radiation, and rubidium gas cell clocks use an optical pumping technique.

Because the most usable resonant frequencies of atoms and molecules are very high (in the microwave region or

higher), the counting mechanisms tend to be elaborate. Present-day computing technology allows direct counting at rates approaching one billion counts per second, but this is lower in frequency than most interesting resonances. Typically, a link between the atomic or molecular resonance and the actual counting mechanism is a very stable oscillator operating in the range of several megahertz (several million cycles per second). The signal from this oscillator simultaneously drives the counter and is multiplied in frequency by an exact integer to the resonance of interest. The frequency of the oscillator is then adjusted to maintain resonance with the atoms or molecules. The counter accumulates the passing seconds and provides a display of time.

Frequency multiplication by an exact integer is accomplished by first distorting the signal in a nonlinear element (e. g., a diode) and then filtering and amplifying the appropriate harmonic of the signal in a tuned circuit. For frequency multiplication into the infrared and visible region, it is very difficult to find efficient nonlinear devices, and this is currently a major technological limitation on the use of atomic and molecular resonances for clock applications.

The requirements of modern society and technology for accurate time and frequency standards are so demanding that mechanical timing mechanisms are no longer adequate for many purposes. Precise electronic air and sea navigation, television and other telecommunication systems, electric power networks, and a multitude of scientific investigations are but a few of the fields that depend on extremely accurate time and frequency references. We have passed the time when astronomical observations were sufficient for these purposes; achieving the accuracy needed today would require months or years of observation, and even then a stable frequency would not be provided by the stars and sun.

Several manufacturers produce atomic clocks commercially (Fig. 1). The most accurate commerical devices are based on a resonance technique using a beam of cesium atoms similar to the various national standards. Somewhat less expensive atomic clocks are based on rubidium vapor. There is a trade-off between cost and stability or accuracy. At present there are several thousand atomic clocks in routine use in many areas. Specifically, atomic clocks are used to control the Loran C and Omega navigational systems, to control network television signals, and to define an internationally accepted time-of-day system that is the time reference for most of the world.

See also BEAMS, ATOMIC AND MOLECULAR; MASERS; OPTICAL PUMPING; TIME.

BIBLIOGRAPHY

B. E. Blair, ed. *Time and Frequency: Theory and Fundamentals*, NBS Monograph 140. U. S. Gov't. Printing Office, Washington, D. C., May 1974. (I–A)

B. Decaux, and B. Guinot, *La Mesure du Temps*, Presses Univ. de France, 1969. (E)

"Fundamentals of Time and Frequency Standards," Application Note 52-1, Hewlett-Packard Co. (E–I)

"Timekeeping and Frequency Calibration," Application Note 52-2, Hewlett-Packard Co. (E–I)

Time and Frequency, *Proc. IEEE*, **60**, (5), 473–648 (1972). (I)

Cloud and Bubble Chambers

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In order to detect nuclear interactions, for instance in radioactivity, cosmic radiation, or at high-energy accelerators, we can use the trails of ions and of more energetic "knock-on" electrons produced by charged particles colliding with atoms when passing through matter. In cloud chambers, first built by C. T. R. Wilson in 1912, tracks consisting of drops of liquid are formed along these trails, whereas in bubble chambers, invented by D. A. Glaser in 1952, the tracks consist of bubbles in a liquid. Both techniques have many important discoveries to their credit. However, cloud chambers are now used rather infrequently, and in the case of bubble chambers, arrays of various kinds of wire chambers compete. These electronic detectors are now able to distinguish between passages of two particles in space almost as well as the older techniques, in addition to their always superior ability to distinguish in time between successively passing particles. Presently, bubble chambers are still important for studies of neutrino interactions. Neutrinos do not leave ion trails and have very small nuclear interaction cross sections, so that intense, partially collimated neutrino beams can be passed through large bubble chambers without producing much background radiation, but producing weak-interaction events in the dense liquid, which acts as a target as well as a particle-detector medium.

In cloud chambers a gas containing a saturated vapor is expanded adiabatically, lowering the temperature, so that the vapor becomes supersaturated. The liquid surface tension prevents spontaneous drop formation without the presence of some kind of condensation nuclei. The electrostatic field of ions opposes the effect of the surface tension and permits drops to form and grow beyond a critical radius if the vapor is sufficiently supersaturated. Surface tension also prevents spontaneous bubble formation in a liquid in a superheated state, which in a bubble chamber is accomplished by letting the liquid expand elastically. But here the ionization energy due to a passing particle is very quickly converted to molecular kinetic energy, thus producing "heat spikes," locally raising the vapor pressure, which now can overcome the contracting effect of the surface tension, enabling bubbles to grow beyond a critical radius. In gases ions diffuse, but do so sufficiently slowly that cloud chamber expansions can be triggered for interaction events of special interest by means of electronic detectors. This is not possible for bubble chambers because the heat spikes responsible for bubble formation diffuse in about 10^{-12} s.

Chamber vessels usually must withstand pressure differences of less than 1 atm for most cloud chambers, up to 25 atm for bubble chambers. Excellent temperature control must be provided to obtain uniform drop or bubble size and to minimize convection currents, which produce track distortions. Expansions are provided by adequately sealed diaphragms, bellows, or pistons, or by valves letting gas pass through heat regenerators. Volume expansions range from $<1\%$ for liquid hydrogen to 30% for air saturated with water vapor and must take only 10–20 ms to reduce convective distortions and to allow cloud chamber expansions to be triggered. Recompression must be equally fast in order to restore temperature equilibrium as soon as possible, so that