connections. Chips can be attached to packages with wire bonds, beam leads, beam tape, or solder pads.

At present, the minimum line width and line spacings used by industry are about 0.5 µ, a dimension that is taxing the capability of optical systems. Innovative approaches will be required to meet the lithographic challenges of the decade of the '90s.

Integrated circuits have revolutionized computers, television, radio, and electronic products, and have made possible lower costs, higher reliability, savings in size, weight, power, and better performance and have made a major impact on how we live.

See also SEMICONDUCTORS, CRYSTALLINE; TRANSISTORS.

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Clocks, Atomic and Molecular

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Almost any clock consists of three main parts: (1) a pendulum or other nearly periodic device, 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 clock makes use of an atomic resonance to control the periodic phenomenon. Similarly, a resonance in a molecule could be used 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 today make use of a microwave resonance in the ground state of cesium. In fact, the unit of time, the second, is defined in terms of this microwave resonance in cesium, and the national standards of time and frequency for the United States and other countries are cesium clocks. 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 a few parts in 10^{14}. This can be expressed by saying that independent cesium clocks can maintain synchronism with one another to better than one-millionth of a second after one year's operation. This is more than 100 000 times more predictable than the earth's rotation on its axis.

The operation of a cesium atomic clock 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 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.

After passing 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.

Farther 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 happened 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. If this frequency is adjusted very precisely to the proper resonance frequency of cesium (9 192 631 770 Hz), the magnetic polarization of the atoms reverses, and the beam is 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 controlled electronically to maximize the detector current, so the resonance condition of the microwave signal with the cesium atoms is ensured. A clock is obtained by counting the cycles of the microwave radiation.

Other kinds of atomic and molecular clocks use similar principles to extract frequency information from the atoms or molecules. The first atomic or molecular clock ever developed (completed in 1949 by 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 absorption of microwave radiation.

Several manufacturers produce atomic clocks commercially. The most accurate commercial devices are based on a resonance technique using a beam of cesium atoms like the various national standards. Somewhat less expensive atomic clocks are based on rubidium vapor. There is a tradeoff between cost and stability or accuracy. Most clocks in use today are based on resonances in atoms rather than molecules. At present there are a few tens of thousands of atomic clocks in routine use in many areas. For example, atomic clocks are used to control Loran-C, Omega, and GPS navigational systems, to do very long baseline interferometry and measure continental drift, 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.

Recent experimental advances and techniques are improving the accuracy of atomic clocks. The spectral width or possible frequency fluctuations of the cesium resonance used in the cesium atomic clock is approximately equal to the inverse of the transit time of a cesium atom down the beam. More narrow spectral widths have been obtained on atomic resonances with ions stored in traps. Ion traps use the force of electric and magnetic fields on ions (which have a net charge) to confine the ions to a small region in a good vaccum. Confinement times of several hours can be obtained routinely. Two types of traps have been used in the development of new atomic clocks: the rf or Paul trap, and the Penning trap. The rf or Paul trap uses spatially inhomogeneous rf fields to confine the ions, much as an rf quadrupole mass filter works in a mass spectrometer. The Penning trap uses static magnetic and electric fields to confine the ions. In general there is a trade-off between the number of trapped ions which gives good stability and the accuracy in a stored-ion clock. One of the first atomic clocks using ion storage is based on a microwave resonance in the mercury ion with about one million ions stored in an rf trap.

Lasers are starting to be incorporated into present atomic clocks with anticipated improvements in performance. The Stern–Gerlach magnets used in conventional cesium atomic clocks are being replaced with diode lasers. Through the technique of optical pumping, the polarization of the laser light is used to give the cesium atoms a magnetic polarization. The diode lasers are also used at the end of the beam line to detect the polarization state of the cesium atoms. The diode lasers enable all of the atoms in the beam to be used in measuring the atomic resonance.

Laser cooling or the use of radiation pressure from lasers to slow atoms or ions may provide further improvements for atomic clocks. According to Einstein's special theory of relativity, moving clocks tick slower than clocks at rest. Laser cooling enables both the spread in the atomic velocities and the mean atomic velocity to be reduced. This could improve the accuracy of the cesium clock. With the use of laser cooling, stored-ion frequency standards based on microwave resonances in ions are expected to have accuracies and stabilities better than one part in 10^{15}.

In general, atomic clocks are based on resonances in atoms at microwave frequencies, that is, frequencies less than 100 GHz. This is because of the technical difficulty of counting the cycles of higher frequencies. In addition, there is a lack of readily available, stable, narrow-band sources at high frequencies, especially at infrared and optical frequencies. Current research is making progress on both these problems, and in the future atomic clocks may be based on optical resonances in atoms or ions. An advantage of optical resonances is that the ratio of the optical frequency to the spectral width of the resonance can be very high. In a stored-ion clock, this means a good stability can be obtained with only a single ion in the trap. The projected accuracy of an atomic clock based on a single ion in an rf trap is on the order of one part in 10^{18}.

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

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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, one 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, but have been almost completely displaced by electronic methods. Electronic detectors are now able to distinguish between passages of two charged particles in space as well as the older techniques, in addition to their superior ability to distinguish in time between successively passing particles. Among the last major applications of bubble chambers were 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 could be passed through large bubble chambers without producing much background radiation, but producing weak-interaction events in the dense liquid, which acted 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