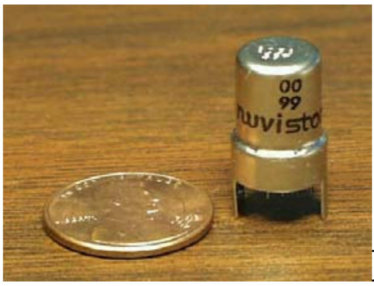



# Electronics Museum---Review of 20th century progress in electronics devices(1900~1999)

## Prelude: Progress of electric-magnetic devices in the second half of 19th century (1850~1899), splendid era in electrical engineering

19th century is power century, steam engine is invented in late 18th century and is very popular in various applications of transportation and manufacturer since early 19th century. During the mid-19th century, the internal combustion engines are invented and widen the applications in transportation, such as automobile invented in late 19th century and airplane invented in early 20th century.

For the high-power applications steam turbine engine is invented in mid-19th century and now widely used in power stations and ship engines either conventional fossil-fuel boilers or nuclear reactor/heat exchangers, gas turbine engine is invented in late 19th century and now used in jet planes or smaller power plants and ship engines. The solid-propellant rocket is invented by Chinese around one thousand years ago, then learned and improved by European scientists and engineers. The liquid-propellant rocket is invented by Goddard in mid-1920s, but the first practical liquid-propellant rocket---V2 is built by Braun in early 1940s.

Static electricity, static magnetism and direct current generated by battery are discovered long time ago, even can be traced to pre-history era. Archaeologist find some evidences that ancient Greek, Chinese and Egyptian know these phenomenon several thousands years ago. But not until Coulomb, Ampere, Faraday and Maxwell formulating relationships with electricity and magnetism experimented and discovered by the many contemporary physicists in the first half of 19th century, the electrical engineering won't be truly emerged, which largely change the "power" era and then open more important "information" era.

In 1784 Coulomb carried out Coulomb law relating force and charges. In 1820 Ampere formulate the Ampere law of magnetism building related with current, then in 1831 Faraday formulate the Faraday law of current building relating changing magnetism. Since then motor, generator, telegraph(1838) and telephone(1876) based on electricity and magnetism principles are invented, improved and commercially practical.

The first telegraph line was established in 1844 from Baltimore to Washington by Morse, inventor of telegraph---historically it is the first time message send and receive immediately except very limiting smoke blocking or light blanking/reflecting methods; for several thousand years all races used same method to send message---by horse in land and ship at sea, takes several days, weeks, months, or even years---if unlucky.

In 1849 the first telegraph printer is invented, the high-speed telegraph printer is invented in 1860.

The Western Union Telegraph Company was renamed from New York, Mississippi Valley Printing Telegraph Co. and several small companies in 1856. The first transcontinental telegraph is established in 1861. The first transatlantic cable was carrying on telegraph signal in 1858 but working only 4 weeks, the first successful transatlantic cable is laid in 1866. Between the first transatlantic cable failed and the successful second cable Western Union actually tried to connect America and Europe through Russia. Sibley, president of Western Union, visit and negotiate Russian government in St. Petersberg. The idea of transamerica-europe cable through Russia was given up forever since the success of second tranatlantic cable in 1866.

In 1878 Bell founded his Bell Telephone Company, since then telephone service started to grow. In 1881 Bell Telephone Company acquired Western Electric(founded in 1869) as manufacturer of Bell and then AT&T. In 1885 Bell Telephone Company changed to AT&T. In 1887 US has 150,000 telephone subscribers, the Europe has 97,000 subscribers. After the expiration of Bell's patent in 1893, the telephone service grew tremendously in US, 20 times within 20 years. By the way the carbon microphone used in telephone for almost 100 years is invented by Edison in 1877.

Although Volta invented the volta cell---the first practical battery in 1800, the first "dry battery"---using electrolyte paste instead of liquid electrolyte appeared in 1888. All early telegraph and telephone used primitive batteries---two electrodes immersed in a glass bottle of electrolyte solution. No wonder Alexander Graham Bell's the frist telephone conversation "Mr. Watson! Come here, I want you." when he carelessly spilled the solution of his battery outside. He repeated his famous talk 40 years later at New York when he was invited speaking to the celebration meeting of trancontinental telephone by AT&T at San Francisco in the transcontinental telephone. Mr Watson was in the meeting, he replied "It will take me five days to get there now!".

The electric power industry started in US around 1880. Edison Electric Light Company---forerunner of GE(General Electric) is established in 1878, initially generated DC power in 1882 at Pearl St. of New York City, in 1887 they have 121 power stations serving 325,000 lamps. All early Edison power used DC power, not AC power which can use transformer stepping up and down voltage and easily transmit power to remote users. But at that time there is no practical AC motor and no AC power meter, therefore Edison initially used DC power. In 1892 it renamed as GE, long time it has been a dreamland of many electrical engineering talents. It is #1 electrical company before the end of $19^{th}$ century and also #1 electrical company worldwide sales in the end of $20^{th}$ century.

Westinghouse Electric formed in 1884, in 1885 decided to use AC power by using European patents on AC generators and operate in 1886. In 1888 Shallenberger invented the AC watt-hour meter, and Tesla invented the practical AC motor, and Nigara fall's hydro-electric power plant(it is the first remote power plant, the line loss is very important since then) was established, since then AC power vs. DC power war is over. Westinghouse is also dreamland of many electrical engineering talents and strong competitor with GE over 100 years, but several years ago Westinghouse changed the business direction only limited to television, multimedia and entertainment business totally withdrawn from electrical and electronics industry business.

In 1864 Maxwell building the famous electromagnetic field law structuring from previous related works

$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$ from Faraday law and Lenz Law

$\nabla \cdot \mathbf{D} = \rho$ from Coulomb Law and Gauss Law

$\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D}/\partial t$ from Oersted Law and Ampere Law

$\nabla \cdot \mathbf{B} = 0$

In 1886~1891 Hertz verified the electromagnetic wave transmission of Maxwell theory by using spark-gap generator with resonant plate or sphere and spark detector with resonant loop, measuring wavelength by standing-wave concept to determine approximate electromagnetic wave velocity, showing the reflection and refraction phenomena. Later Lodge and Marconi improved the spark detector by using coherer detector(glass tube with metal fillings, first invented by Branly in 1890, it needed to tap manually or using automatic mechanism after received signal) and invented first wireless telegraph in 1894 and 1896.

Marconi then improved antenna and increased power in the twilight of $20^{th}$ century, dramatically decreasing the resonant frequency to LW or MW different from VHF or UHF in the experiments of Hertz. That is one lucky of Marconi, by Fourier analysis (developed in early $19^{th}$ century) the spectrum of spark is very broad from very low frequency(less than LW) to very high frequency(more than UHF) and roughly the higher frequency the lower energy density. If he used VHF or UHF there is impossible beyond the horizon, even if he used HF there is no enough energy transmitted and no sensitive receiver(no any radio frequency amplifier at that time, audio frequency amplifiers are bulky, low efficiency and low gain, such as magnetic amplifier or carbonmicrophone-headset coupler, Marconi never used them in his equipments).

In 1897 Marconi Company is formed, their experiment station successful transmitted wireless telegraph from England to France in 1898. In 1900 Marconi International Marine Communication Company was established, the experiment station in Poldhu, Wales using 25 kw and then 75 kw ac generator with stepped-up transformer, spark-gap, resonant circuits(before then there is only battery-operated induction coil wireless telegraph and without resonant circuits) and huge antenna tried to across the Atlantic to Cape Cod in Massachusetts, he claimed successfully in December 12 1901 by receiving letter S(probably due to very good ionosphere situation and he did not know at that time, sombody said it was only atmospheric noise---avoid debating with these people, he should use more complex signal and/or changing with some pattern, that is the basic probability issue used in the modern radar/communication system).

In later years the systematic tests of S.S. Philadelphia showed its reliable communication from Poldhu only several hundred miles at daytime and much larger distance at night, the transatlantic radio service not established in these years. During 1900s the primitive spark generator gradually improved as rotary, impulse or quenched gap. In October 1907 the Clifden station in west coast of Ireland, which used 300 kw 20Kv dc generator and resonant circuits at 45KHz with one mile inverted-L antenna and is state of the art of spark radio transmission, commercially operated. In 1901only a few ocean-going ships installed wireless telegraph. But by the end of 1902 over 70% transaltantic liners installed wireless telegraph, and in 1907 virtually all transatlantic liners loaded with wireless telegraph.

**Spark transmitter circa 1905 (Courtesy of HSC)**

In 1903 Poulsen(he also invented the steel coil recorder in 1900---ancestor of practical tape recorder 30 years later) invented the electric arc transmitter(remember electric arc as high-intensity light source is very popular in late 19th century even earlier than the incandescent light invented by Edison in 1879, but he is the first one combined resonant circuit to electric arc forming high frequency generator, even Lodge and Marconi did not use resonant circuits until around 1900) which is first continuous wave(CW) generator, the spark generator is damped sine wave device which can not used in the wireless phone. But the drawback sometimes is also advantage, in the early days there is only way hearing dits or dahs without local beat oscillator, that is another lucky of Marconi. Federal Telegraph Company purchased patent from Poulsen in late 1900s and then developed high-power transmitter. Federal Telegraph sold two 1MW stations to US Navy installed in France during World War I period.

In December 1906 Fessenden of Harvard Univ. made the first radio broadcast by inserting a carbon microphone between output of high-frequency alternator(invented by Alexanderson of GE in 1906) and antenna, it surprised shipmen on north Atlantic while music and voice from their earphone after a series dits and dahs. Others used arc transmitter instead, for example the voice station of Herrold in San Jose---Capital of Silicon Valley and Headquarter of XCV Corp., Inc. later near the end of this century, he established this voice station in 1909 and it is the first known broadcasting with regular schedule. They are actually the earliest AM station, almost 14 and 11 years earlier than famous KDKA station---the first licensed radio broadcast station.

The spark transmitter, arc transmitter and high frequency alternator transmitter(50 kw at 50KHz in 1915) are dominated wireless telegraph area during the first twenty years in $20^{th}$ century until vacuum tube transmitter is practical in late 1910s. Marconi received jointly with Braun the Nobel Prize of physics in 1909, the first Nobel Prize of physics in practical electrical engineering field; the first Nobel Prize of physice is granted to Roentgen in 1901 due to discovery of X-ray in 1895.

Finally we will mention some electric-magnetic devices which have analogue electronic devices either electronic tubes or solid state devices later during $20^{th}$ century. There are **amplifier**, **rectifier**, **converter/inverter**. Magnetic amplifier has two different kinds, static and rotating. Rectifier divides into two categories, one is synchronous vibrator for small power immediately replaced by vacuum tube rectifier in mid-1910s; the other is AC motor-DC generator set for high power applications, some mid-current version replaced by mercury-vapor tube rectifier in mid-1910s also, high-current version still existed until high-current silicon rectifier available after early 1960s. Converter/inverter is popular after early 1930s when mobile radio equipment are gradually emerged. Ironically, radio receiver before late 1920s all are battery-operation based, by using A-battery for filament, B-battery for plate, or even C-battery for grid, essentially they are mobile radio. They also subdivide into two kinds: one is vibrator usually for small power DC-AC inverter, the other is dynamotor(usually for low DC voltage to high DC voltage) or motor-generator set. Both are available in all electronic-tube era during the first half of $20^{th}$ century until gradually replaced by transistorized version during late 1950s since the tube essentially is high-voltage low-current electronic devices.

**Dynamotor and vibrators**

Relay is the most important electric-magnetic device except transformer and rotating machine---motor and generator. Actually electric-magnetic rectifier and converter/inverter we mention in the previous paragraph were all made by relay. The early telegraph is actually a relay combined with an electric key. The telephone switching systems(step or crossbar) before electronic switching system---ESS(the first commercial ESS is ESS4 putting in service at 1976) use a lot of relay and early computer(Zuse Z2~Z4 and Bell Mark I ~ VI in 1940s) also made from relay also, AT&T and later Bell Lab had done a lot of works in these area since early1910s till early 1970s. All high-voltage induction coils widely used in the $2^{nd}$ half of $19^{th}$century virtually are composed from some form of relay and high-turn ratio transformer.

**Relay, both old and modern**

Imagine people in the December 31, 1899---New Year Eve of $20^{th}$ Century, they thought "Tomorrow will be better", but can they imagine all the details of new inventions, discoveries and events in the $20^{th}$ century?

## A. Electronic tube era(1900~1949)

In 1856 Geissler found a glass tube enclosed two electrodes with high voltage DC attached, while largely decrease the vacuum degree inside by lowering the inside mercury, the tube will glow and conduct current a little---ancestor of all electronic tubes, especially on cold-cathode tubes. Since then physicists of all Europe put a lot of efforts in research this issue include Faraday, Hittorf(discovery of magnetic field deflecting the cathode ray, evidence of cathode ray is charged particle, the name "electron" is given by Thomson after his famous measurement of charge/mass value of this "charged particle"), Crookes(discovery of cathode ray with kinetic energy and it can be shaded in 1879), Roentgen(discovery of X-ray in 1895), Thomson(from electric and magnetic fields derived the charge/mass value of electron---cathode ray in 1895, combined with mass value of electron from Millikan's oil-drop experiment in 1909, the electron charge value can be calculated), and Braun (invented CRT in 1897). Braun put phosphorescent coating inside gas discharge tube facing cathode which can display the voltage waveform on the deflection plates or coils---later name as cathode ray tube.

In 1883 Edison discovered Edison effect---actually diode vacuum tube later discovered by Fleming in 1904. Possibly he is too busy for his power station business and other inventions to continue this important discovery. Fleming invented diode vacuum tube in 1904 based on Edison effect on 1883, then opening the electronic tube era. De Forest invented triode vacuum tube in 1906, he named as audion. Both are not popular until early 1910s, since the vacuum and filament technologies are not matured, life of these tubes are very short so not commercially practical in that time.

In October 1912 scientists and engineers of Western Electric Company---manufacturer of AT&T invited de Forest to demonstrate his audion for telephone repeater application. This demo shows the amplifier ability in low voltage but on high voltage there are blue haze in tube, amplifier choking then died. Arnold, research director of AT&T, later worked on vacuum technology, oxide-coated filament and more precise of grid geometry substantially improved output of triode tube. One year later AT&T use vacuum tube repeater in telephone lines from New York to Baltimore, then soon vacuum tube telephone repeaters used everywhere in US.

**Early '10 rectifier tube** **Early '20 S tube**

Davisson in AT&T, the major contributor of discovering the wave nature of electron in late 1920s---one important milestone in quantum mechanics of modern physics, continued working vacuum tube and related circuits for wireless communication. In late 1915 AT&T transmitted the first transoceanic telephone conversation between Navy station(but the transmitter is not vacuum tube transmitter, it is still Alexanderson's alternator operating on 100 kw at 113KHz, the high power vacuum tube transmitter is not available until early 1920s) of Arlington, Virginia to Eiffel Tower in Paris. The first licensed broadcast radio station KDKA is established in November 1920 by Westinghouse at Pittsburgh shortly after the wireless ban from World War I removed, since then radio for every field is proliferated very fast. The transmitting tube of 50 kw output power is very popular in mid-1920s and it is maximum legal power for AM station from late 1930s till now. In 1934 one broadcast station even has achieved 500 kw output power at 700KHz, the transmitter was designed and manufactured by RCA.


**Transmitter Power tubes circa 1925, the largest glass RF power tubes still using forced air cooling system**


**Transmitter Power tubes circa 1925, the improved-design second largest glass RF power tubes with large anode(plate) contact outside for water cooling system which can dissipate more power**

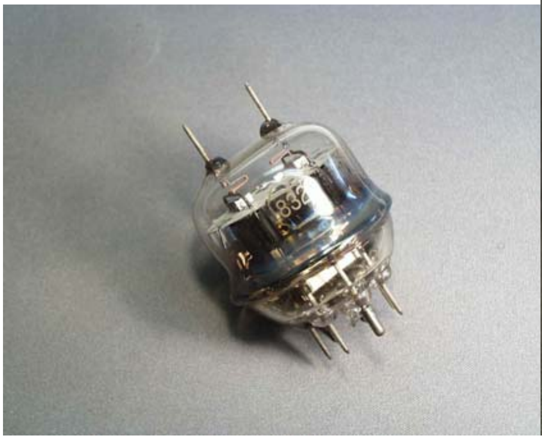
In 1919 RCA(Radio Corporation of America) is founded and invested by GE, and managed by David Sarnoff who transferred from American Marconi Company and famous for the wireless operator in Titanic tragedy. RCA has very deeply influenced the development of radio, television, electronic tube and semiconductor since then.

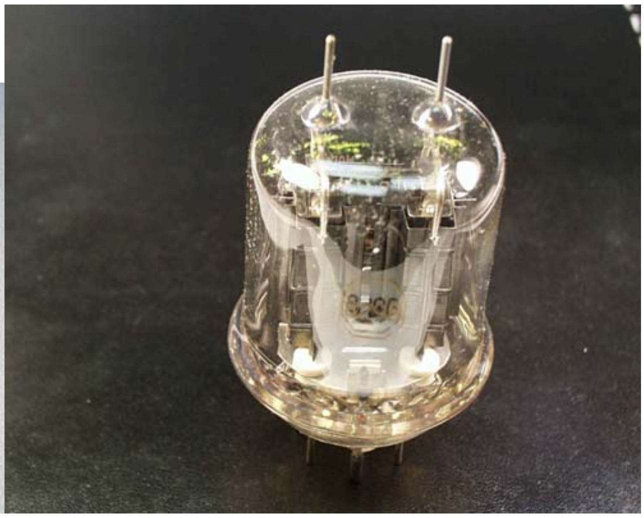
**Late '20 ST tube**

In January 1,1925 AT&T incorporate a separate entity called the Bell Telephone Laboratories performed all R&D works of AT&T. Bell Lab discovered and invented a lot of electronics principles and devices, included the most important device in this century---transistor, and then microwave communication(system), solar cell, non-volatile memory, CCD, cellular phone(system) and heterostructure transistor and also important progress in microwave tubes, radar(system), missile guidance(system), superconductor, semiconductor lasers & sensors, digital signal processing---especially on sonar signal processing(system) and fiber optic communication(system).

During early 1920s radio amateurs discovered that DX(long distance) communication can be obtained by HF with only 1 kw legal transmitter power by amateur and do not need very high power (up to 1MW) on LW as used in past 20 years. Since then the trend of vacuum tube technology was not only toward high-power, but also shrinked the dimension for higher frequency. In mid-1930s transmitting tubes around 100MHz can be obtained several kw continuously, mainly for radio amateurs and radar. Resonant line for VHF operation is already popular and then resonant cavity is starting to be popular at that time.


**Transmitter tube in '30 era**





**Transmitter tube in '40 era**


**Transmitter tube popular in '50 era**

In 1937 Varian brothers invented Klystron---first UHF and microwave tube, which uses two or more resonant cavities **inside** an electron tube letting accelerated electron beam passing through it, the RF energy in the first cavity will modulate the velocity of electron beam and these velocity-modulating electron beam releases their magnifying energy in last cavity and transfer it into magnifying RF of same frequency. In the early 1940s Pierce and Shepherd of Bell Lab invented the reflex Klystron, which is low-power device and used in the heterodyne oscillator of radar receiver.

**Reflex Klystron**

In 1921 Hull of GE proposed magnetron first, in 1935 Ponte and Gotten of CSF invented the magnetron and later in 1940 Randall and Boot of Univ. of Birmingham(most known as inventors of magnetron because they closely connected to government in war time and immediate used in radar application) independantly also invented Magnetron---first microwave power oscillator, which uses multiple resonant cavities in a electron tube exerting a strong orthogonal magnetic field and can generate microwave energy at 3GHz around 1 kw at that time and at least 10 times frequency ability than triode or tetrode transmitting tubes at that time. Soon the magnetron developed very fast due to high demand of war radar. For example Western Electric manufactured 10,000 units per month of X-band magnetron in early 1944 for bomber.

In1944 Kompfner invented TWT(Travelling Wave Tube)---similar principle to Klystron but using slow-wave structure instead of resonant cavity, which has much wider bandwidth but a little lower efficiency. Pierce(also inventor of reflex Klystron) of Bell Lab improved the original design with better gain and much wider bandwidth. For a long term TWT widely used in microwave and millimeter wave from signal level to medium-power range till now, but gradually replaced by various kinds of solid state devices.

The first pulse radar is practical in 1936 by US Naval Research Lab using VHF frequency, the first microwave radar is invented by British Military Research in 1940 using magnetron, then widely used by US and British military forces like bombers and fire control of anti-aircrafts made in World War II period.

In the period from 1944 till 1948 Bell experimented the microwave TDM system, they use 96 PCM channel on 4GHz link. In 1950 the first TDM microwave system was built. Till 1983 about 72% of long distance net work of Bell system are through TDM microwave system.

In 1897 Braun invented the cathode ray tube. In 1906 Dieckman proposed cathode ray tube as television display, in 1907 Rosing also tried to develop the mechanical scanning and CRT display TV system. In 1920~1930 period of early TV development era cathode ray tube was already popular display device even image transmitting still used mechanical scanning. In 1929 Zworykin invented Kinescope with focusing anode, graphite anode and magnetic deflecting coil as TV display tube similar to modern TV display tube.

After the first CRT invented by Braun, the first commercial oscilloscope(called as cathode ray oscillograph at that time)is produced by Du Mont in 1932 although rudimentary oscilloscopes were used in the laboaratory for a long time. RCA then also introduced his oscilloscope in 1935, in these day the oscilloscope only used in the audio frequency(not full audio spectrum only 5KHz, Tektronix founded in January 1946, one and half year later the first product---511 released, the bandwidth is 10MHz with auto-triggered, in 1969 7000 series with 150MHz bandwidth, using sampling technique measuring repetitive 1 GHz signal oscilliscopr appeared in 1962.). Hewlett-Packard(HP) was founded in January 1939, the first product is RC-bridged audio oscillator. VTVM, tube tester, analog computer and electron microscope are emerged in this period also.

In 1880 Hallwaches and then Righi noticed that metal illuminated by ultraviolet will acquire charge---ancestor of photocell. In 1889 Elster and Geitel discovered the photoelectric effect of alkaline metal such as sodium or potassium in vacuum tube at visible light spectrum. This effect is then explained by Einstein in 1905 using quantum mechanics, which open the era of modern physics. The photoelectric effect is the basis of all electronic image tubes.

Television can be traced back to Nipkow's spinning disk concept in 1884 but technology difficulty never successful until 1923 by Baird and Jenkins separately. In 1926 Alexanderson of GE demonstrated the first commercial television systems still based on mechanical scanning. But Farnsworth, later working in controlled thermonuclear fusion program and missile guided systems in 1960s, and Zworykin, originally working in Westinghouse then hired by RCA in 1930, both started to develop all electronics television seperately since early 1920. In 1928 Farnsworth finished the first all electronics television system with his Dissector image tube---the first photo image tube of all. During the late 1920 Federal Radio Commission(former organization of FCC before 1934) has granted 28 experimental television stations license to early TV developers.

In 1931 Iconoscope---the first television image tube with storage is invented by Zworykin of RCA. In 1939 RCA invented Orthicon, much more sensitive than Iconoscope and did not need trapezoidal correction. In 1941 NTSC recommends standard of 525 line with 30 frames to FCC, NBC started the commercial television broadcasting in July and then ABC, CBS demonstrated color television experiment, but both stopped at wartime. In 1951 RCA invented the vidicon, which is more compact and rugged. In 1954 RCA marketed the first color TV set, in 1960 RCA profited from color TV set, after 1970 the sell of Color TV set was starting more than that of black-and-white TV set. In 1959 both Philco and SONY introduced their transistorized portable black-and-white TV. Starting from 1952 UHF TV emerged, all UHF TV transmitter used Klystron amplifier.


**Vidicon and Photomultiplier**

In December of 1933 Armstrong---inventor of regenerative(1912), heterodyne(1912), super-heterodyne(1920) and super-regenerative(1922) circuits patented frequency modulation(FM) after almost 10-year research. In 1936 FCC granted experiment FM station license to Armstrong. In 1939 FM radio are starting to be manufactured by GE. In March of 1940 NTSC decided FM as audio portion of television signal. In 1945 FCC moved FM band from old 42~50 MHz to current standard 88~108 MHz  releasing old FM band for emerging mobile communications, since then AM-FM radio grows very fast just like AM radio after 1920.

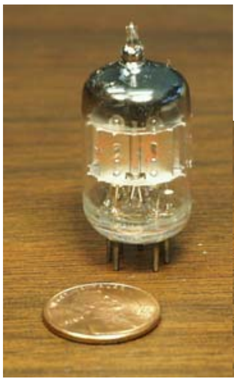
Geiger invented the Geiger counter tube in 1908. Mercury-vapor rectifier is invented in 1912 by Langmuir of GE, it  used for high-current rectifier until partially replaced by selenium rectifier in 1940s and totally replaced by high-current silicon rectifier in early 1960s. Thyratron also invented by Langmuir in 1914 but practical phase control of thyratron was invented by Toulon in 1922. The RF induction heating was invented by Northrup in 1918 using arc transmitter(60 kw at 10KHz). Multivibrator circuit was invented by Abraham and Bloch in 1918. Flip-flop circuit was invented by Eccles and Jordan in 1919. Ignitron was invented by Westinghouse in 1933. Both the thytron and ignitron greatly increase industry power control and converter/inverter ability until1958 GE invented SCR. Gas voltage regulator is invented in mid-1930s also and used in voltage-regulating circuits. Nixie digital display tube was appeared in early 1950s based on same gas-discharge principle.

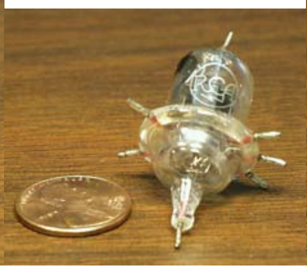


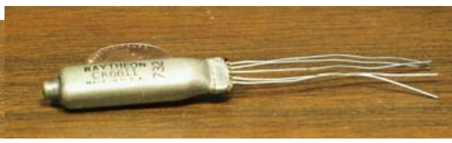
**Thyratron and Ignitron**

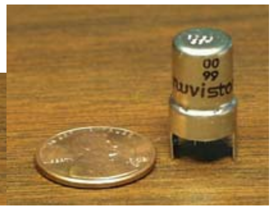
Electronic navigation(1942 LORAN by MIT Radiation Lab), NMR, microwave oven(1947 by GE), fine-grooved LP and stereo phonograph(1941 in studio then 1948 to consumer, but the old 78rpm record still sell as late as in 1954), 45 rpm record and changer(1949 by RCA), tape recorder(1944) are invented in 1940s period.

During mid-1920s till mid-1930s era tetrode, pentode, beam power tube, metal tube are gradually invented. Then during mid-1930s till mid-1940s era vacuum tube continue shrinking their size, miniature tube, acorn tube and lighthouse tube are invented at this time frame. And then during mid-1940s till late 1950s era vacuum tube still continue shrinking their size such as sub-miniature tube (originally used in proximity fuse---ingenious idea never become old) and nuvistor. Ceramic-metal transmitting tube is invented in mid-1950s and still use very popular today. In 1959 RCA invented the smallest vacuum tube---Nuvistor, the size is similar to that of transistor at that time and it is ceramic tube although with metal case.





**Metal tubes, miniature tube, Acorn tube Lighthouse tube, two different sub-miniature tubes, and Nuvistor---The smallest vacuum tube(invented by RCA in 1959)**


**Tube tester circa 1950**

Although transistors are invented in 1947 and practical since 1951, early transistor can only work at low frequency and low power until silicon planar technology emerged in late 1950s. During late 1950s germanium transistors already entered into medium high-frequency(100~300MHz) or medium high-power(10~30W) fields(not both) even better than silicon transistors before planar technology at that time(especially frequency ability), but both the performance and manufacturing cost of germanium transistors can not compete with silicon transistors from planar manufacturing technology(germanium transistor can not benefit from planar manufacturing technology since no easy oxidation or other similar passivated materials of germanium can be generated, the passivated surface protection by oxide or other passivated material is mandatory for reliable transistor or IC.). And the maximum operating temperature of germanium is much lower than that of silicon, which will severely limits the power capability of germanium transistor.

Most of important the leakage current of germanium transistor is thousand to million times(because germanium is low energy-band gap semiconductor) higher than that of silicon transistors and very sensitive to temperature, although there is bias-stabilized circuits which will help to stabilize the current of simple direct-coupled circuit(Of course the complex circuits of germanium transistors still can be built if every stage is ac-coupled---blocked by capacitor or transformer, applicable for radio, audio and television consumer products and some instruments[analog narrow-band products], but not applicable for computer, calculator and most of instruments[digital or analog wide-band products].). Therefore, it virtually decides the fate that germanium can not be built as integrated circuits except very simple one. Because all analog or digital ICs need direct-coupled(since capacitor in IC needs much much more space than transistor) which means the leakage current in the front stage will impair the latter stage and accumulate to stages thereafter, finally collapse this circuits. Therefore, germanium transistors are obsolete very soon in early 1960s. After then silicon transistors, IC and other solid-state devices replaced almost all the area of electronics tube applications and even open new applications since compact, low power and easy to use except high power RF field.

For current state of the art below HF band all the practical power level can use solid state devices (very high power use SCR), for HF or VHF bands both bipolar and DMOS transistors can obtain up to 200 watts for single device and easily be combined to a couple kw levels, for whole UHF band the new LDMOS transistor can obtain a couple hundred watts, for more than 3GHz GaAs MESFET can obtain similar power as LDMOS transistor and derate to about 10 watts at Ku band(12~18GHz), and GaAs or InP HBT(Heterojunction Bipolar Transistor) or HEMT(High Electron Mobility Transistor) can obtain watt level till upper millimeter-wave range(30~300GHz). Beyond these level you should use either ceramic-metal tube(HF or VHF) or microwave tube. But expecting GaN, SiC or Diamond high frequency and high power transistors will gradually replace all ceramic-metal tube and microwave tube in the first 50 years of 21$^{st}$ Century.

**Ceramic-metal transmitter tubes**

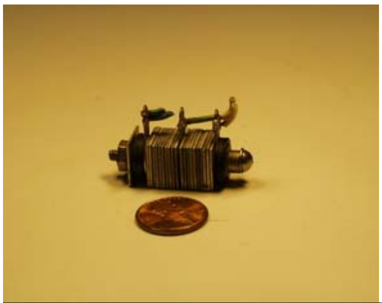
## B. Solid-state device era(1950~1999)

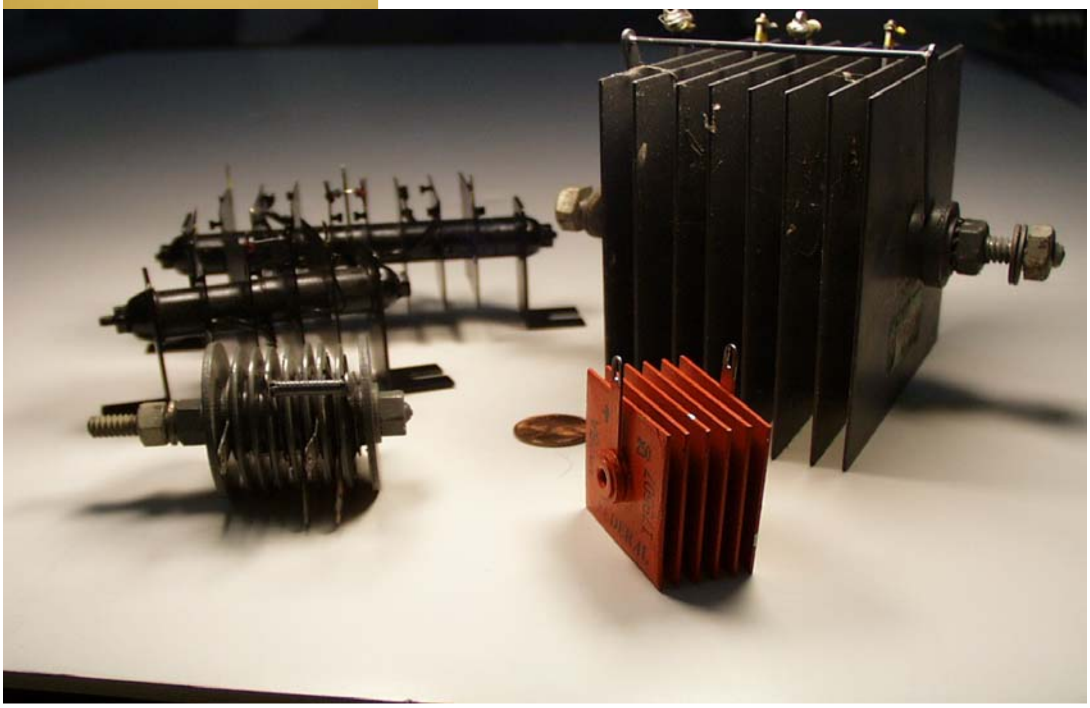
In 1876 Braun found galena(lead sulfide) has puzzling property of "rectification" effect by using catwhisker on some point of this mineral, it is totally violated Ohm Law established in 1826 and not directly related to Faraday's discovery of negative temperature coefficient of resistance of silver sulphide in 1833 and Smith's discovery of photo conductance of selenium in 1873, although both are phenomena of semiconductor which are explored almost 100 years later.

He only lectured in physics society and published in physics journal for his discovery but never file the patent for this discovery, the patent law has existed in Europe for several hundred years. That is unusually compared to other inventers, some inventors file patents frequently even very trivial improvement or discovery. In 1898 he set up the Telebraun Company after his invention of cathode ray tube, then suggest galena with catwhisker as detector of wireless telegraph before 1899. He and Siemens established Braun-Siemens Company in 1900. He shared the Nobel Prize of physics in 1909 with Marconi.

The first practical crystal(or mineral) detector was patented to associate with telephone headset around 1901 by Bose, since then the insensitive coherer detectors soon phased out. Obviously his patent did not have legal power since Braun and Marconi already invented and used crystal detector with telephone headset before him. During 1902 to 1906 period Pickard of AT&T systematically found silicon and about 250 different minerals also associated with rectified function, it is said he tested at least 30,000 different materials. Remember the story of Edison's invention of incandescent lamp that he used everything in the world at that time to form the filament, finally the carbon filament from cotton thread, the most easily found item, is the best selection. Galena and new discovered iron pyrite(iron sulfide), carbourundum(silicon carbide, SiC) are made as mineral(or crystal) detector of wireless telegraph and later broadcast radio receiver until late 1920s.

In the early 1920s Becker and Brattain of Bell Lab found copper oxide has similar rectification effect without catwhisker. Later selenium has similar effect also without catwhisker. Since these two materials do not need unreliable catwhisker, both copper oxide and selenium has been manufactured as commercial rectifier at 1930s even the operating principle was unknown at that time. In 1938 Schottky explained it by potential barrier of metal-semiconductor based on energy band theory of solid of Wilson in 1931.





**Copper oxide rectifier and selenium rectifiers**

After late 1920s crystal detectors obsolete from the popularity of AC-powered vacuum tube radio receivers, but the silicon detector was reinvented in Bell Lab after mid-1930s since the development of VHF to microwave tubes. Due to erratic behavior of silicon detectors with catwhisker they gradually found that the problem is derived from the impurity of silicon, at that time silicon is only agent in steelmaking(silicon steel is material of all transformer and motor) with several percent impurity, most of Aluminum. In 1937 the purity of best silicon is 99%, the Bell Lab start to purify by themselves similar to current melting and pulling up method.

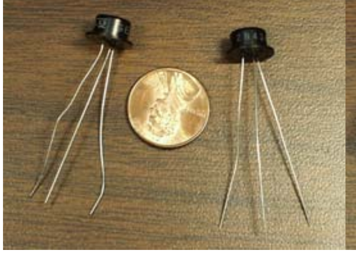
In February 1940 they found PN rectifying junction from some wrong cutting silicon rod with purified silicon end and the other non-purified silicon end, they also found this junction with photoelectric effect like oxide copper and selenium. Soon these silicon detectors are widely used in radar receiver because no any other device can detect microwave at that time. Since the requirement of reliability is extremely high, the purity of silicon has improved to 99.999% in 1942. In 1951 the purity of germanium even has reached to incredible 99.99999999% by zone-refined method.

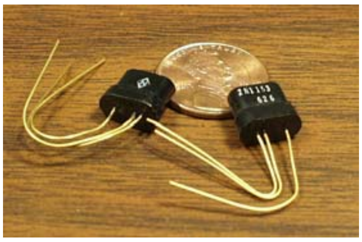
In 1941 GE and Purdue Univ. started to research germanium crystal, since it is the same IV element in periodic table as silicon with similar electrical property, Bell Lab later also involved the research work of germanium. Since the much lower melting point of germanium than that of silicon and easily processing, all early transistor are made from germanium.

After semiconductor diode had been perfected, Bardeen, Shockley, Brattain and other staff of Bell Lab gradually thought of amplifying devices by putting a thin layer of other material between two semiconductors(ancestor of junction transistor) in 1945 or applying a transverse electric field on semiconductor(ancestor of FET) in 1945 or pressing two point contacts(point contact transistor, the first invented transistor) on semiconductor. Finally they found the first point contact transistor using single germanium crystal with two point contacts really amplified signal on December 23 1947, but naming as the "transistor"(by one author, Pierce, of #5 reference) and announcing almost half year later.

In 1949 the first junction transistor is invented and within several years replaced all low-reliable and high-noise point contact transistors. The principle of point contact transistor is totally different from that of junction and all later-version transistors, for example the current gain of point contact transistor at ground-base configuration is always greater than unity, the current gain of all other transistors at ground-base configuration is always lower than unity although very close to. The junction transistor is announced on July 1951, three years after announcement of point contact transistor.

In 1951 TI(Texas Instruments) renamed from GSI(Geophysical Service Inc., founded in 1930)---military electronics instrument company, and decided to start transistor business and very successfully. At that time only Raytheon point contact transistor, not reliable and high-noise, and GE alloy junction transistor, operating frequency under several MHz or even much lower, they are both germanium. TI decided to develop grown junction and then diffused junction transistor both germanium and silicon.





**GE 2N43A alloy junction germanium transistors, germanium power diodes and two different germanium transistors---popular in '50 era**

After Korea war TI decided to develop transistor radio before then transistors are only for military, experimental computer, experimental telephone switching system and hearing aids(that is the first commercial transistorized product) applications. The first transistor radio Regency's TR1, list price of $49.95, is emerged in October 1954, consists of four grown junction germanium transistors made from TI. Guess who is the second transistor radio manufacturer? SONY!

In 1952 RCA invented the unique transistor audio amplifier---Complementary symmetry configuration, totally new concept no electronic tube analogy. Complementary and later quasi-complementary symmetry, some called SEPP(single-ended push pull) OTL(output transformerless) or OCL(output capacitorless) are foundation of all solid state amplifiers till now. The transformer-coupled transistor amplifier of high-powered version is obsolete soon after emerged in late 1950s, but the low-power version in portable radio still used in 1970s.

Thick-film technique from early 1940s, etched printed circuit from 1951(solder mask from 1955, multilayer board concept in 1960), miniature packaging(Tinkertoy from 1951 and micromodule from 1957), thin film hybrid technique from 1959, wirewrapping technique for high-density wiring from 1953 and automatic insertion of leaded components from 1955 all are emerged in 1950s period.

Computer aided design for IC emerged in mid-1960s, there is significant progress that Conway and Mead of Caltech cooperated with Xerox and MIT to develop IC layout methodology with their students during 1970s. IC schematic design use hardware design language because of the complexity since early 1980s. Board-level schematics and layout CAD also started from 1980s, now they are well-developed.

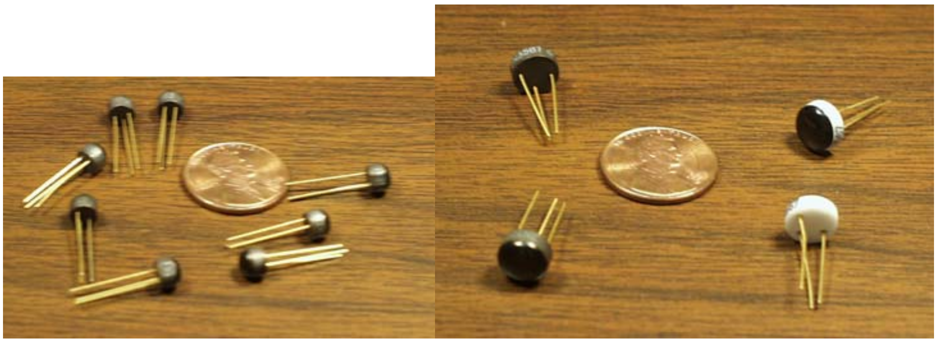
The solar cell is invented by Chapin, Fuller and Pearson of Bell Lab in 1954, although the primitive and low efficiency(~1%) of selenium solar cell was invented 30 years earlier. Since then the efficiency of silicon solar cell is gradually improved from original 7%, to 14% in mid 1960s, 20% in early 1980s till recently 28%. Most of III-V or II-VI compound photoelectric semiconductors also reveals the photovoltaics---that means it can be manufactured as solar cell. But almost all of practical solar cells are fabricated from silicon, since the material cost of large-area semiconductor is most dominated.

In late 1954 the diffused junction transistors of germanium and then silicon are invented in Bell Lab and pushed the operating frequency 10 times---170MHz compared to old alloy or grown junction transistor. In 1954 Shockley resigned from Bell Lab and formed Shockley Semiconductor Lab in Palo Alto, the first semiconductor company in silicon valley, developed both diffusion transistor and Shockley diode(PNPN device). But in September 12, 1957 after resigned from not-successful Shockley Semiconductor Lab, R&D staff of Shockley formed Fairchild Semiconductor financed by Fairchild Camera and Instruments Company and dedicated to silicon diffusion transistors, foundation of all modern solid state technology.

**Silicon rectifiers**

In 1957 the production quantity of US transistor has reached 30 millions, compared to 0.6 million at 1952, similar to tube production quantity at 1952. Actually the semiconductor progress of first 10 years is more than the tube progress of first 25 years, said by Kelly of Bell Lab. Transistor has been used everywhere, and the growth of complex electronics system, such as computer, telephone switching system and space/military applications pushing transistor to more integrating form---solid circuits(later name as integrated circuit) prototype in 1958 by Kilby of TI, but it is germanium. All the practical integrated circuits are manufactured by silicon planar technology, which is after Noyce of Fairchild in 1959. This story is just like true transistor(junction type) invented in 1949 not point-contact transistor invented on December 1947.

In 1958 Fairchild marketed their first silicon diffusion mesa transistors to RCA, and then planar transistor in 1959. In early 1960s the epitaxial growth technology is invented. The planar silicon dioxide passivated and epitaxial growth manufacturing processes are the same as silicon diffusion technology as the foundations of modern solid state device. The other important semiconductor manufacturing process---ion implantation(can give the most precise control of impurity profile) is practical in 1970s.



**Epoxy planar silicon transistors---most popular silicon transistors in '60 era**

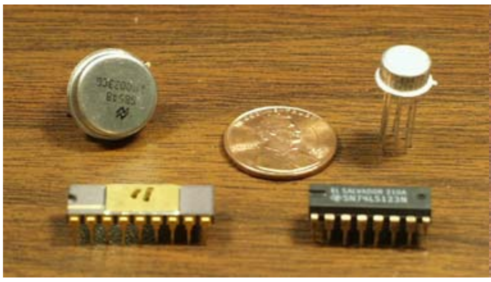

**Silicon power transistors**

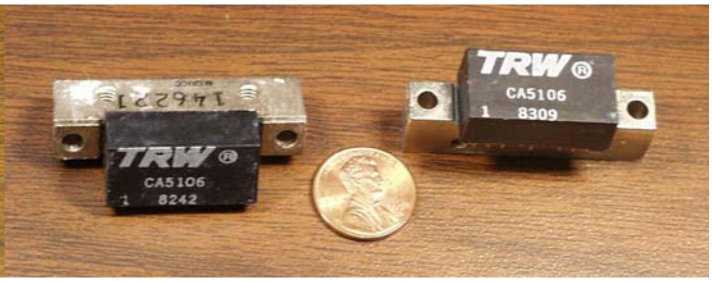
With excellent semiconductor manufacturing technology the old(1945) idea of FET successful fabricated in 1961 at Fairchild, and it is MOSFET used in any large scale IC. But MOS IC was not really took off until late 1960s, all 1960s are still bipolar IC territory. The DIP apckage is introduced by Fairchild in 1965, soon adopted by other semicondcutor companies, the plastic package for all other semiconductors also.

In 1967 Sporck, general manager of Fairchild resigned and take four key man to reorganize National Semicondcutor(founded at Connecticut in 1959 and moved to silicon valley in 1968)---famous for complete pheripheral IC line. In 1968 Noyce, R&D manager of Fairchild, Moore and Grove founded Intel---now it is the world's largest chip manufacturer, famous for complete processor lines(actually also famous for memory in the 1970s, but can not compete with asian semiconductor companies after 1980s, and also famous for network chipset.). In 1969 Sanders, market director of Fairchild and transferred from Motorola one year ago, took seven colleagues to form AMD, also famous for processor, memory and network chipset---strong competitor of Intel. In 1966 and 1967 there are three chip companies formed each, in 1968 there are 13 companies, in 1969 another 8 companies formed in Santa Clara Valley---that is the name of Silicon Valley come from.

In March 1961 Fairchild sold several kinds of IC to NASA. At the same time TI showed off midget computer made from 587 IC for computer of Air Force, which is only 1/150 volume and 1/50 weight of the same function transistor computer, which use 8,500 discrete solid state components. In this

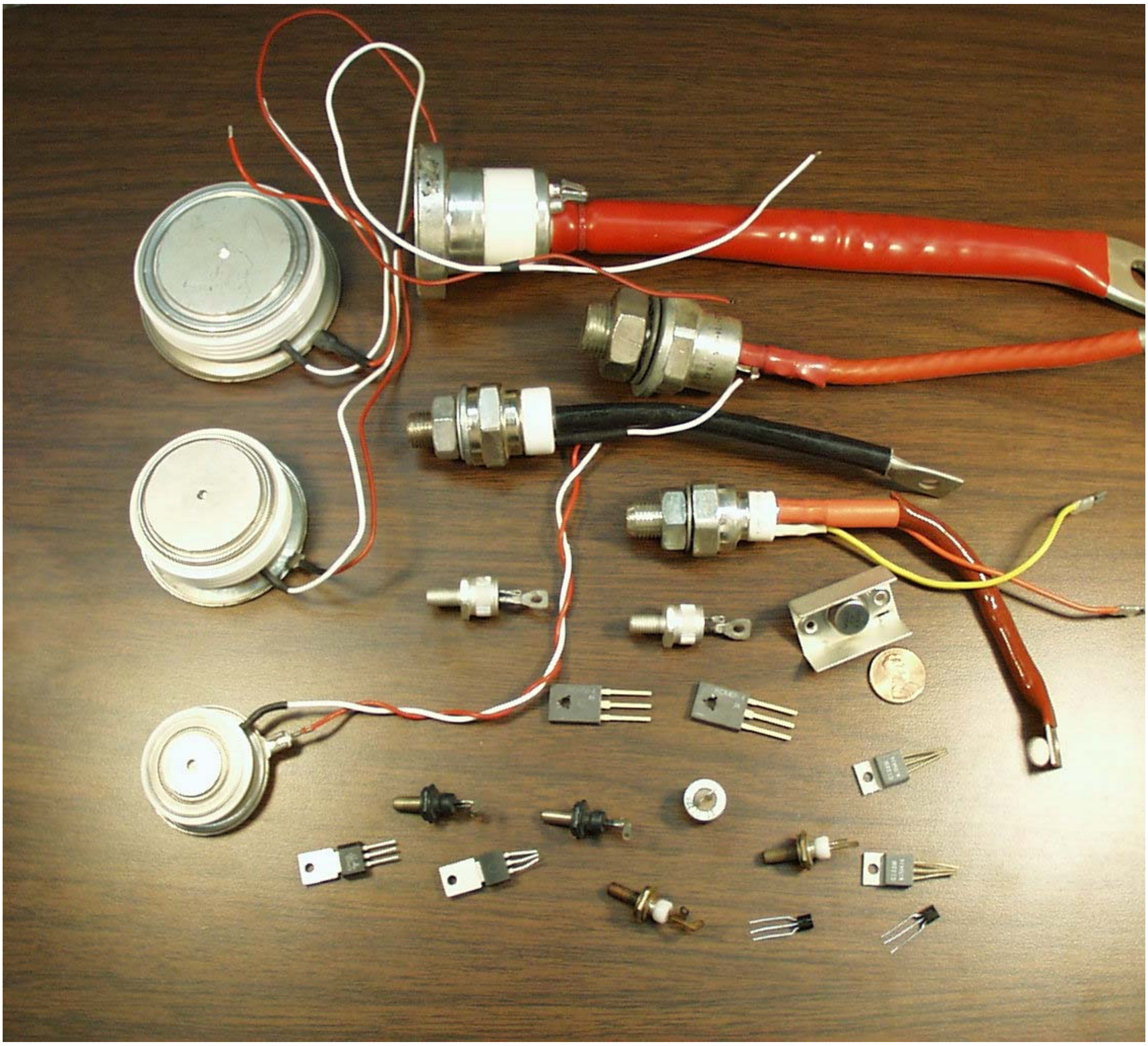
May President J. F. Kennedy announced that US will send a man to moon by the end of this decade, this aim has been fulfiled successfully but he can not see it by himself. This is only possible by IC which save a lot of space, weight and power. In 1962 the first communication satellite---Telstar, it's also impossible without IC, opening the satellite communication era. In 1964 Fairchild made the first linear IC---µA702, and then popular µA709 in 1965 and more popular µA741 in 1968, all are from Fairchild Semiconductor and all OP AMP IC---basic of all analog circuits.





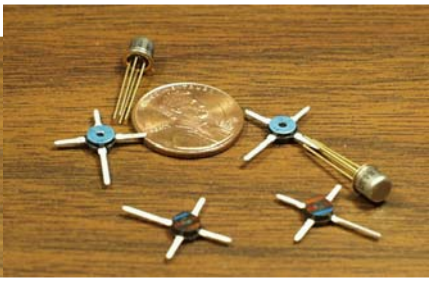

**Integrated Circuits in '60 and '70 era**

In 1956 Shockley invented the PNPN diode---the antecedent of all thyristors. In 1953 GE invented UJT in their Advanced Semiconductor Laboratory at Syracuse, in 1957 GE invented the first SCR---the most important thyristor, which based on PNPN diode. In early 1960s GE also invented TRIAC---bi-direction SCR and light-triggered SCR LASCR. All thyristors totally replaced previous thyratron and also open new applications since compact and easy to use.



**SCR and TRIAC**

The first microwave solid state device is tunnel diode, explained by Esaki  in 1954, then transferred electron devices, like Gunn diode in 1963, and avalanche transit-time diode, such as IMPATT in 1965. All these diode both have negative resistance as the basis of oscillator or amplifier in 1960s to 1970s era, now almost replaced by silicon, GaAs or InP transistors except high-pulsed power needs.



**"Pancake" and other silicon VHF~Microwave transistors**


**RF power transisotrs**

Although micromachine technology and MEMS(Microelectromechanical systems) are passive devices, they are growing exponentially in recent years and actually they are derived from the planar technology---the radical source of all semiconductor devices after '60. They use photomask/eteching technology on planar semiconductor or non-semiconductor surface just like any other semiconductor devices. Right now there are switch, relay, pressure sensor, gyroscope, mirror, motor, pump and etc, all are micro forms and implementated in suitable chip either with active devices or without.

SAW(Surface Acoustic Wave) devices are not active devices, but they are very important and very popular in all kinds of communication system like TV, RADAR, two-way radio, cellular phone and satellite communication. They are basically like ideal bandpass filter implemented by using fine inter-digital metal structure on the surface of some piezoelectric substrate like lithium niobate, lithium tantalate or lithium borate. The principle of SAW is discovered by Rayleigh in 1885, but the practical SAW device is not available until invented by White and Voltmer in 1965. Due to progress of microfabrication technology the SAW devices already replace LC filter even bulk piezoelectric filter in many communication applications. Recently research trend is putting signal processing functions in this tiny device.

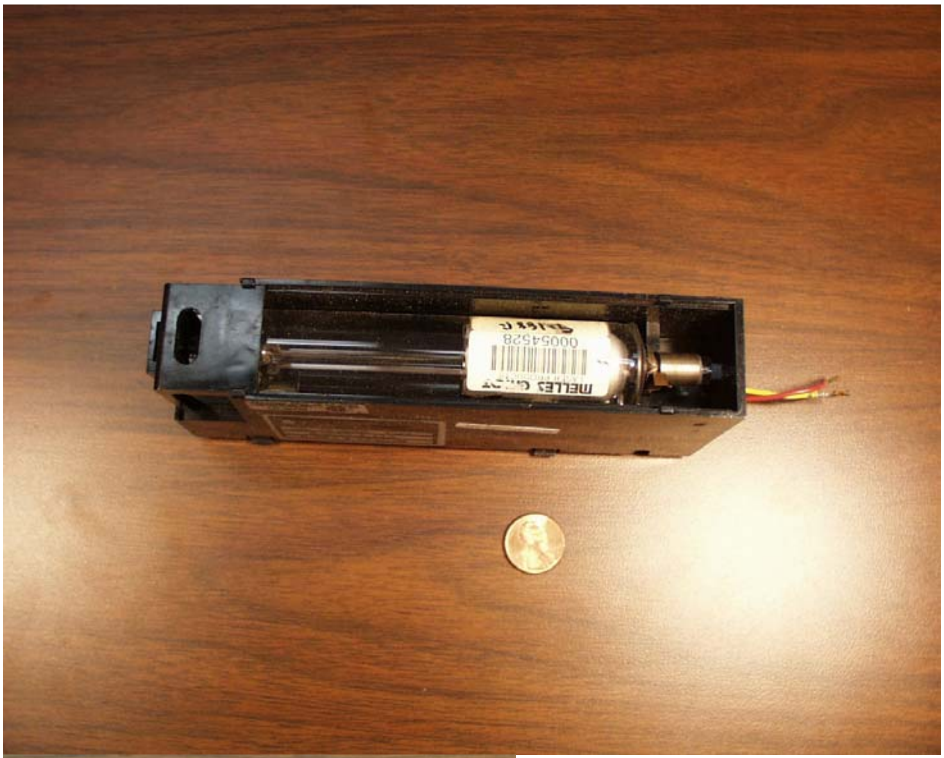
Sensors and actuators(or called as transducers in general) are the most technology-diversified electronic devices. Since it is belong to passive devices we don't mention too much here(but never under-estimate its importance). Transducers of different category have totally different technology associated. Some sensors are actually complete system, for example GPS as coordinate sensor(one form of position and velocity sensor) and missile seeker as another kind of position and velocity sensor. Recently biosensors grow very fast, it is the first example of electronic technology and biology technology combined together.

Most of sensors are open loop for measuring, display and storage purpose, but some sensors are used in the closed loop---feedback control system. Feedback control systems are used for position and velocity(or called as motion in general) control over one century even before invention of any active electronic devices. Original control systems use analog method, now digital control wholy dominates since the proliferation of DSP-enhanced microprocessors. Deep space probe and UAV(Unmanned Airborne Vehicles) are some examples of most outstanding sensor and actuator controlled unmanned  systems.

Let's see quantum electronic devices---maser and laser. In 1957 Scovial, Feher and Seidel invented maser with the paramagnetic $Gd^{3+}$ ion at 9GHz. In 1960 Maimen invented the first laser by ruby crystal. In 1961 Javan invented He-Ne laser. In 1962 Dumke invented the first semiconductor laser--

-GaAs junction laser in liquid nitrogen by pulsed mode, which is also the first important compound semiconductor(III-V) device openning compound semiconductor devices era. Since then many new laser materials are invented.

The first practical semiconductor laser is produced in 1970 by using heterojunction---it can be operated under room temperature continuously since much lower threshold current. LED(incoherent light source, first produced in 1960 but the phenomena of light-emitting in some compound semiconductor junction is discovered in 1950s.) and semiconductor laser(coherent light source) have innumerous applications. For example the optical fiber communication can not work without them, and there will be no CD or DVD if no practical semiconductor laser diodes available.



**He-Ne Laser module and Semiconductor Laser module**

The most interested and practical high-energy physics apparatus(actually high-energy electronics devices) is controlled thermonuclear fusion devices, either magnetic-confined deuterium(D) and tritium(T)(There are several other thermonuclear reactions by using other similar light elements, but D-T reaction is most easy---only needs about one hundred million Celsius or Kelvin degrees! Others need several times to several ten times of this temperature, but some reaction won't cause radioactivity and maybe the good choice in the second generation of controlled thermonuclear fusion reactors.) plasma fusion or inertial-confined laser induced deuterium and tritium pellet fusion. controlled thermonuclear fusion program was started from Project Sherwood in 1950s, seeking energy and power forever.

Magnetic-confined plasma fusion uses strong magnetic field confining plasma, also resistively heated by strong changing magnetic field, and inject high-energy neutron beam, ultra-short laser or microwave pulse, then induced nuclear fusion. The structure can be either linear ended by magnetic mirrors(invented by Princeton Univ. in late 1960s) or toroid(Tokamak, invented by Russian scientists in mid-1960s). During late 1960s to early 1970s period the design of Tokamak is proved to be better than that of linear one. Then Princeton Univ. also build two bigger Tokamaks, PLT (Princeton Large Torus) in early 1970s to early 1980s period and TFTR(Tokamak Fusion Test Reactor) in late 1970s to early 1990s period.

In 1991 JET(Joint European Torus) in England first in history produced the controlled fusion energy in a brief experiment generating 1MW peak thermonuclear fusion power by using 10% tritium (reduce the quantity of tritium since its strong radioactivity) in deuterium and tritium mixtures, and then in December 9, 1993 TFTR first by using 1:1 deuterium and tritium generate 3MW peak thermonuclear fusion power, 6MW on next day and 10.7MW one year later achieving the design goal of 10MW at 1976 in the beginning of this project, finally success after four decades of many people efforts. Now ITER(International Thermonuclear Experimental Reactor, joint venture of US, European Union, Japan and Russia) is now planning, the rated power is 1,500MW. If success, we can expect that there will be almost forever energy source, cheap and clean, starting from early 21$^{st}$ century.

Deuterium and tritium plasma heating(TFTR still uses resistive plasma heating of original Tokamak design and injecting high-energy neutron beam) or laser pumping(very high power and short wavelength lasers, most are noble gas halide family laser first developed in mid-1970s, often used in laser induced fusion) needs high-energy ultra-short microwave(include millimeter-wave) pulse, these high-power microwave source include traditional magnetron, klystron and BWO(similar to TWT) with very high power and voltage(mega-volt range so that the speed of electron is near light speed involving relativistic effect), and free electron laser(first developed in early 1970s, somewhat more like microwave tube than laser since it is not a quantum device).

Inertial-confinement laser induced deuterium and tritium pellet fusion needs very high power laser, current research use neodymium:glass laser or noble gas halide family laser such as KrF. The peak power needs more than 100 terawatts, the total energy may needs several megajoules or more. The current development of laser-induced fusion is near the ignition phase, the production of fusion energy will be expected around the beginning of 21$^{st}$ century. These high-power lasers, like high-power microwave pulse or high-energy charged particle beam, are also used in high-energy weapons just like weapons of movie "Star Wars"; no war starts so soon and ends so soon.

The cryogenics is using either liquid helium at 3 degree Kelvin or liquid nitrogen at 77 degree Kelvin ---liquid nitrogen is very cheap, only about 1/500 price of liquid helium and also low cost apparatus. That is the reason why we need "high temperature" superconductor for any practical applications especially large-scale applications. The cryogenics is often used in the research of physics, material and devices, seldom used in the industrial products and never used in the comsumer products due to obvious reasons. The cryogenics is derived from the discovery of superconductor property of mercury in liquid helium by Omnes in 1911, the resistance of mercury is dropped to only one-thousandth of original at 4.2 degree Kelvin. Since then a lot of effort to find superconductor materials with higher critical temperature, from 1911 to 1986 the best superconductor with the highest critical temperature is alloy of niobium and germanium with 23 degree Kelvin only.

But during 1986 to 1988 the golden age of superconductor there are at least three different kinds of "high-temperature" superconductor materials discovered, they are barium, lanthanum, copper and oxygen compound at 30 degree Kelvin in 1986, the yttrium, barium, copper and oxygen compound at 90 degree Kelvin in 1987 by Chu, the bismuth, strontium, calcium, copper and oxygen compound at 110 degree Kelvin in 1988 and the thallium, barium, calcium, copper and oxygen compound at 125 degree Kelvin in 1988 also. Now the powerful superconductor electromagnets already used in the high-energy physics apparatus---gigantic particle accelerators used in the basic research of subatomic particles, also will be used in the future magnetic-confined controlled thermonuclear fusion reactors. Other important superconductor-related devices are Josephson junction---ultrafast switching device(invented in mid-1960s, but IBM already gave up in 1980s just like bubble memory since not competitive with other technology of similar functions), and SQUID(Superconducting QuantUm Interference Device)---a very sensitive magnetometer.

The first optical fiber is invented by Kao and Hockham of ITT in 1966, but the loss is almost 1000db/km. In 1970 loss of the optical fiber has dropped to 20db/km, after mid-1970 the loss dropped to less than 0.2db/km(occurred at 1.55μm for all pratical glass fiber, plastic fiber still has very large attenuation only used for short rang or non-communication purposes.) near current value. The optical communication is proliferated since then. The first optical fiber phone system was installed in Chicago in 1977. The first transatlantic optic fiber cable---TAT-8(What about TAT-1~TAT-7? They are all coaxial cables, operated from 1956 for TAT-1 to 1983 for TAT-7; they all need repeaters for every several kilometers.) started to operate in 1988. TAT-8 uses 1.3μm and the data rate is 0.28Gbps. Recently TAT12/13 emerged in 1996 uses 1.55 μm and optical amplifier technology, the data rate is 10Gbps.

The first silicon transistor entered the microwave region is emerged in the mid-1960s, it can obtain several watts output on L or S band and small signal extends to 10GHz(but high-noise which can not compete with Si-Ge HBT or GaAs MESFET, HEMT or HBT, so the practical limit of Si transistor is around 3GHz) in mid-1970s. In 1976 Siliconix invented VMOS---the first power MOSFET, in early 1980s Motorola and other semiconductor companies named it as TMOS or DMOS, it can obtain a couple hundred watts in 800MHz at late 1980s. In 1992 Motorola introduced LDMOS for UHF power applications(a couple hundred watts for single device till 2~3GHz in 1999) with better efficiency and lower manufacturing cost.

The electron mobility of Gallium Arsenide(GaAs) is about 5 times that of silicon under low electric field, so it is suitable for very high-frequency applications long time ago. But the peak electron drift velocity of GaAs is only twice of that of silicon and it is occurred under much lower electric field than that of silicon, that means either increasing operating voltage of silicon transistor(if not breakdown) or scaling down gate or base width of silicon transistor(that is the current trend) can obtain half of frequency capability of GaAs homostructure transistor(only MESFET). That is the reason why recently low cost Si LDMOS power transistor or Si MMIC occupy the low GHz(L or S band) market originally dominated by GaAs MESFET power transistor or MMIC only.

The fist practical **GaAs** MESFET is manufactured in 1971 by Turner with 1 μm gate width, usable frequency up to 18GHz and the fmax is 50GHz. Now for top speed applications either analog or digital we first consider GaAs transistor or IC, but the current density of GaAs VLSI still can not compete with BiCMOS---that means super computer(clock rate may be up to 10GHz, in past it can be made only by ECL---high-power and low-density, so it will be huge machine) made by GaAs IC still needs tens or even hundreds chips. And if it uses heterostructure GaAs or InP IC, the operating clock frequency can be up to 1000GHz. Ironically, all IBM super computers from Deep Blue till recently Blue Gene all use silicon chips not GaAs chips. Because IBM uses parallel processors of gigantic numbers, from several thousands parallel processors in Deep Blue till one million parallel processors in Blue Gene, they can only implement in very high density silicon chips not on medium-density GaAs chips.

Since the first important compound semiconductor devices---GaP LED in 1960 and GaAs laser in 1962, a lot of compound semiconductor materials(III-V or II-VI) have been researched and developed---most of all are only useful in optoelectronics or sensors areas. Till now only two compound semiconductor materials, GaAs and InP, are important in transistors---foundations of all analog and digital IC.

Most of II-VI compound semiconductor are for optoelectronic devices especially infrared spectrum, for example CdS, CdSe and HgCdTe. CdS is the earliest practical II-VI semiconductor material for visual spectrum, bulk CdS photo resistor has been used as low-cost photo controller for over 40 years. $Hg_xCd_{1-x}Te$(MCT), discovered by Lawson, Nielsen, Putley and Young in 1958, is the most important far-infrared detector material, it can extend to 20µm depending on the mole fraction of Hg and Cd. The optimal operating range of the best III-V infrared detector InSb is about 3~5µm. The peak wavelength of thermal image of creature is about 9µm, the visual spectrum is 0.39~0.78µm.

Most of scientists and engineers still think that the optical image frequency is much, much, much higher than the frequency used for communications, Wrong! Under the cryogenic temperature(for example 77 degree Kelvin at liquid nitrogen) some semiconductors can be operated to detect infrared ray up to 1000µm, same frequency of top millimeter-wave(300GHz). And the communication frequency soon will extend to the tera hertz range(1000GHz) for the next generation precision and smart(dual-mode missile seeker of special signal/coding and frequency-hopping ability for millimeter wave and multiple wavelength-window IR image sensor which will have strong anti-jamming and anti-decoy capability; simple dual-mode missile seeker emerged in 1950s shortly after passive radar or simple IR missile seekers in early 1950s.) active missile radar, wireless broadband communications and optic fiber communications(right now use DWDM[Dense Wavelength Division Multiplexing] technology, which already achieved 1000Gbps bandwidth by multiplexing 100 channels of 10Gbps in single optic fiber) before 2010 by using heterostructure GaAs or InP family semiconductor devices.

After exhausting research of III-V or II-VI compound semiconductors and progress of semiconductor technology, the old idea of other IV semiconductor interest arise again. The most outstanding devices are Si-Ge, SiC and Diamond(pure and highly-structured C). The practical Si-Ge chip technology has developed by several companies such as IBM during past ten years, now already used in low-noise front-end of L, S and C band.

SiC and Diamond technologies are totally different direction, they are both high-energy gap, high-breakdown voltage, high-electron saturation velocity and high-thermal conductivities materials. Therefore, they are expected to fabricate as high-frequency(from UHF to millimeter wave) and high-power transistors(100 watt to upper kilowatts or even more) and can replace virtually all currently-used ceramic-metal tubes and microwave tubes in the first half of $21^{st}$ century. Right now SiC transistor technology is not matured, Cree is the only pioneer semiconductor company as we know. Practical SiC transistor with all the potential advantage of SiC may appear in 2000~2010(?) period (although SiC MESFET has already been commercialized recently).

Diamond transistor should have all the best capabilities of all high-frequency and high-power transistor, "Diamond is forever". Unfortunately even the semiconductor diamond material technology is not yet matured, don't mention the diamond transistor manufacturing technology is not yet really started. However, we probably see that the first diamond transistor with all the potential of diamond will emerge in 2010~2020(?) period(although rudimentary diamond MESFET has been reported)

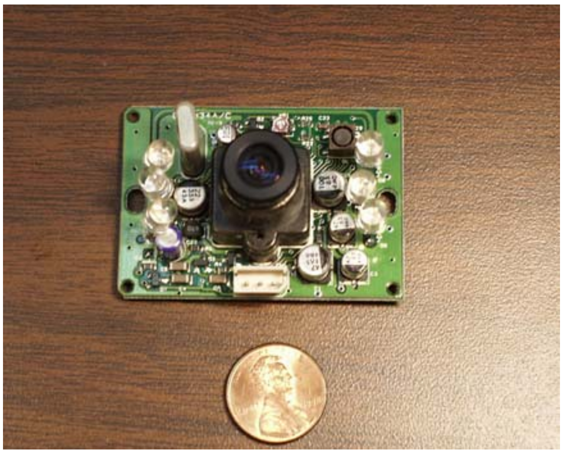
The heterostructure(or heterojunction if bipolar devices) is proposed by Shockley in 1951, there is a lot of research works in silicon devices---but no important devices until used in GaAs laser in 1970. Heterostructure compound semiconductor often represents by different mole fraction of composition, like $Al_xGa_{1-x}As$. After the successful implementation of double heterojunction in practical GaAs laser due to new manufacturing technology--- MBE(Molecular Beam Epitaxy) and MOCVD(Metal Organic Chemical Vapor Deposition), semiconductor researchers used the heterojunction in LED, solar cell and obtained much better efficiency in 1970s.

In 1980 Dingle, Stormer, Gossard, Wiegmann of Bell Lab first proposed heterojunction in GaAs transistor and then realized by Mimura, Yoshin and Hiyamizu of Fujitsu Group in 1981. In late 1980s several pioneer semiconductor companies such as TRW used heterostructure in GaAs or InP compound semiconductor transistors and achieved very high frequency ability. Heterostructure in microwave transistor is just like modulating velocity in microwave electronic tube, quantumly jumping the frequency ability up to 100 times.

Both HBT(Heterojunction Bipolar Transistor) and HEMT(High Electron Mobility Transistor ---Heterostructure FET) demonstrate the superior high frequency ability(some even in high millimeter-wave range, 30~300GHz) than all silicon devices or even GaAs MESFET. GaAs or InP HBT also have the advantage of high power density under low operating voltage, high-linearity, easily power-down and are already popular in RF power amplifier of cellular phone handset---expecting to dominate this market before 2003 and it emerged in 1994 only, some new companies are famous for this area such as EiC. Besides the high-volume cellular handset market, HBT also dominates the emerging LMDS(very broadband multimedia or internet wireless network at Ka band), 10~40Gbps high speed optic fiber communication(OC192 & OC768) and precision active missile radar(94GHz or higher band[140GHz?, 220GHz??]) markets.

GaN(and other III-Nitride) has been recognized as optoelectronic semiconductor for a long time. But recently due to wide bandgap property similar to SiC, several years ago GaN has been considered as perspective high-frequency and high-power device. Cornell Univ and Lockheed-Martin has developed GaN HEMT for demo in 1999. Newly formed Nitres(founded in 1997) and RF Nitro Communications(founded in 2000, and acquired by RF Micro Devices by the end of 2001) is GaN devices company with strong potential. Both Cree(major SiC device company) and RF Nitro Communications are the most active commercial developers in this field. Lockheed-Martin, Hughes and TRW are the most active military developers in this field.  Cornell Univ and Univ. of Michigan are the most active academic developers in this field. Practical GaN high-power microwave transistor with all the potential of GaN may be available before 2005(?).

In 1969 Boyle and Smith of Bell Lab invented CCD(Charge Coupled Device), it used as shifting register and solid-state image chip. The first black-and-white CCD camera appeared in 1971 and color one introduced in 1973, both made by Bell Lab. The CCD shift register is obsolete for a long time and totally replaced by higher density DRAM and SRAM. But the solid state image chip grows very fast and replaced of all applications of previous image tubes and open many new applications since the size can be very compact---all camera unit can be small as match box. Now the density of CCD image chip can be higher than 60 million pixels, the spectrum can extend to soft X-ray or far-infrared(thermal image), some even integrated with image intensifier. On the other hand the new CMOS camera technology gradually replaces the low-end market segment(<1Meg pixel) of CCD since the intrinsic low cost property.



**CCD camera module with near-infrared LED**

There is no other commercial electronics technology like LCD(liquid crystal display) virtually dominated by only one country---Japan. People will think that  liquid crystal or LCD are invented by Japanese, Wrong! In 1888 Renitzer discovered the liquid crystal, but the adequate liquid crystal material and the practical use of liquid crystal is not available until eighty years later. The first practical liquid crystal material---cyanobiphenyl was invented by Gray in late 1960s, Merck and Hoffmann-LaRoche companies in Europe hold this patent, now already expired, and manufacture since 1970s. The TN and later STN LCD display are both passive display---they don't have transistors inside, the characteristic of passive display is cheap but slow response. Therefore, they are already used anywhere, like watch, calculator, cellular phone, pocket game machine; except no on high-end computer---they only use TFT LCD.

TFT LCD was invented by Weimer in 1966, but like passive LCD all R&D and manufacturing of TFT LCD are done by Japanese companies. Manufacturing TFT(Thin Film Transistor) is just like very large area IC with liquid crystal, so it is very expensive. The current price of TFT LCD is almost five times that of CRT display with same size. But TFT LCD has advantages of light weight/compact size and virtually no electromagnetic emission, in the high-end market TFT LCD will share a significant market in the near future. All TFT LCD are brilliant color, in contrast most of passive LCD are monochrome only, even color passive LCD still has limitation in the range of brightness and contrast.

In 1964 TI invented 5400 series TTL(the original idea TCTL is from Pacific Semiconductor in 1961 then acquired by TRW later in the same year, in 1963 Sylvania introduced another TTL---named as SUHL) and soon obsolete previous RTL(invented by Fairchild in 1963, the idea of RTL was from mid-1950s) and DTL. **CMOS** are invented by RCA and other semiconductor companies in 1968, and in mid-1980s obsolete previous NMOS. All modern **VLSI** are actually CMOS device with bipolar input/output. Since CMOS device is just like ideal switch(needs energy only when switching) with very high-density advantage combined high-current driving ability of bipolar device makes a perfect combination of VLSI devices---BiCMOS. *n*vidia.GeForce256 graphics chip, which is BiCMOS, has 23 million transistors and designed by Avanti(Acquired by Synopsys on December 2001) IC design software tools. The processor die of Intel Pentium IV CPU, one of the largest BiCMOS chip, has over 42 million transistors inside---also one of the most complex chip ever except memory chip--- and the operating speed is as high as 2.4GHz(using 0.13 μm manufacturing technology).

CMOS is the first(and probably also the last one) perfect logic device since it looks like the ideal switch(need energy only switching---power consumption proportional to clock speed and symmetrical high switching threshold---high noise immunity). In 1978 CMOS is only novice device in digital field, the maximum operating frequency is no more than 2MHz for most of CMOS devices and no any CPU uses CMOS technology at that time. Today CMOS devices can operate over 2GHz (e.g. 2.4GHz Pentium IV CPU). Virtually all VLSI devices("Chips" are their popular name) are CMOS(include BiCMOS) and no any CPU will not use CMOS technology since early '90. Recently CMOS technology even extends to analog and RF fields in which no any digital device did before. It is just like the silicon device in '60 era proliferated and penetrated every field in electronics, which did not only replace electronic tube but also generate new applications.

In 1964 Moore(later he is the president of Intel) of Fairchild Semiconductor indicates that transistor number in one chip increases double for every year after invention of the planar transistor technology, it is often called as Moore's law even right after 35 years later. The index of VLSI technology progress can be expressed by gate length in mass production of the highest density chip (for small experimental chip usually can obtain very fine line much beyond the production standard), in early 1960s era the standard gate length is 50 μm, in 1969 is 10 μm, in 1979 is 6 μm, in 1989 is 1 μm, in 1999 is 0.18 μm. In 2002 the commercial minimum feature size is 0.09 μm, it is expected to reach quantum mechanics limit(~0.03μm) before 2010.

Does it mean that there is no way more dense, lower power and hgiher frequency? No, at least there are two ways. One is SOI(silicon on insulator, silicon dioxide is the most popular one) CMOS device, the other is nano technology. Actually SOI is very old idea that the CMOS device just emerged in '70 is a very slow device and creating CMOS silicon on sapphire(one kind of insulator) can reduce parasitic capacitance largely and increase frequency ability greatly at that time. Nano technology(used in diversified technologies fields, in electronics field it is called as molecular, nano or atomic electronics) is the most promising trend in the near future, will it look like transistor---the greatest electronics invention in the 20th century or like later trying to invent active liquid state electronic device(because transistor is solid state device and gaseous electronic tube[special electronic tube] is gas state device) in '50(totally fail, but probably created a new important field---liquid crystal and then TFT)? Maybe it will not go to either extreme ends, but just looks like exciting at some time then go nothing(bubble memory, cold fusion, etc.) or limited success in niche fields (tunnel diode, Gunn diode, etc.).

SOC(System on chip) is a loosely-defined and broadly meaning terminology, it is neither new technology/device nor new methodology. Long time ago silicon chip aleady can integrate sophiscated and complex digital system in a die, currently it is integrated even more than 100 million transistors in a single chip. Recentl trend is integrating all related analog/mixed signal function and even RF function in a complex digital chip. There is some issues regarding manufacturing but major concern is CAD tool. Digital design already uses standard HDL(Hardware Description Language) but analog and RF still use proprietary design and simulation tools. We will expect that there is some development in these areas.

In 1967 Kahng and Sze of Bell Lab proposed the first non-volatile memory device---ancestor of all programmable logic and memory. In 1972 the first 2kb EPROM---1702 was developed by Intel, erasing operation needs ultraviolet(UV) light exposure. The UV and then OTP(one-time programmable) versions EPROM are very popular until several years ago gradually replaced by flash memory. In late 1970s the byte-erasable EEPROM was produced, but it is very expensive even now and never popular. In mid-1980s the bulk-erasable flash memory was produced and soon replaced all previous EPROM.

The programmable logic started from bipolar-fuse technology in late 1970s, in early 1980s the CMOS erasable version was emerged. The logic density of programmable logic devices is from less than 100 gates(PAL, PLA or PLD) in early 1980s through mid-1980s FPGA(Field Programmable Gate Array) of several thousands gates, then early 1990s CPLD(Complex Programmable Logic Device) of several thousand gates also, now over ten thousand gates of CPLD and for FPGA even near 10 Mega gates. CPLD/FPGA technology is not limited by erasable technology and also include the SRAM-based technology invented by Xilinix in 1985 and antifuse technology by Actel in 1988.

Here we also mention digital signal processing(**DSP**) because it is very important, although it is only methodology not device. The major units of DSP are only digital filter and fast Fourier transform (FFT), that is all what we need to manipulate in digital signal domain. DSP in early stage(whole 1970s era till early 1980s) can only be implemented by software or dedicated hardware. Since TI introduced the first DSP controller TMS32010 in 1983, there is a lot of DSP controller in the market, such as TI TMS32Cx0 series, Motorola DSP56K & 96K series and Analog Device ADI21xx and ADI21xxx series and several Japanese and European companies. Basically DSP controller is a micro-controller with enhanced DSP instructions, now it is mandatory component in digital communication, digital control and high-end multimedia applications.

Although mechanical 4 function arithmetic calculator started from mid $17^{th}$ century and massively produced in $19^{th}$ century, the computer concept can be traced from famous Babbage's differential and analytical engines since 1823. The modern computer started from Zuse relay computers Z2~Z4 (1938 ~ 1944) followed by his mechanical computer Z1, and Bell Lab relay computers Mark I ~VI (1937~1950), and then ENIAC of Pennsylvania Univ. from 1943 till 1946 using 18,000 tubes---the first vacuum tube computer running at 100KHz, much faster than the relay computer but with much lower reliability.

The first Von Neumann structure(program and data stored in the same memory) computer is EDVAC running at 1MHz in 1947~1949. The first commercial computer is UNIVAC in 1951 running on 2MHz, also made from vacuum tubes. The first experimental transistor computer is TX-0 at Lincoln Lab of MIT in 1953. The second generation computer such as IBM 7090/7094 by using transistor is available from 1959, the third generation computer such as IBM 360 is available from 1965 by using IC. In 1970 IBM announced 370 using semiconductor memory instead of magnetic-core memory, which used for past twenty years. After 1970 virtually all computers use VLSI(IC with over 1000 gates, some person preferred over 10,000 gates, then year will be around 1975 or so).

The first transistor calculator is emerged in 1963, more popular 2 or 3 chip pocket calculator are entered the market around 1967 by TI, HP and other companies. Since then calculators are proliferated, the first microprocessor---Intel 4004 originally customized design for a Japanese calculator company. The first digital watch is introduced in 1971 by Pulsar, the retail price is around $2000 using power-hungray LED even without date display. In 1976 TI introduced five-function LED watch only $19.95, the price of digital watch drops dramatically to one-huindredth only five years. At same year TI also introduced LCD watch, but the price is from $275 to $325. Electronic game was also emerged in 1970s both commercial coin-operated and handheld consumer one, early microcomputers were influenced greatly by electronic games. Both are benefited from the popularity of higher density and lower cost MOS integrated circuits starting from late 1960s.

Intel introduced the first microprocessor 4004---contains 2,300 transistors in 1971 opening the era of microcomputer, in the next year 8008---the first 8 bit microprocessor, in 1974 the famous 8080 emerged. During mid-1970s and mid-1980s era there are a lot of mcirocomputer and microprocessor in the market. In 1981 IBM used Intel 8088 CPU to build the famous IBM PC, the ancestor of all IBM PC-compatible system. Since then we have elapsed the 80286(PC AT based CPU), 80386, 80486, Pentium, Pentium Pro, Pentium II and Pentium III CPU based computer. The speed of **XCV** P2BXA mainboard loaded with dual Pentium III 1GHz CPU has at least three thousand times(not only high clock speed, but also much better CPU structure) speed of the original 4.77MHz 8088 IBM PC, and the features you never though even a couple years ago.

Guess how many CPU in your home? Let's see I have high-performance full-featured computer system loaded with **XCV** P2BXA mainboard associated two 1GHz Pentium III CPU running under Windows 2000 professional edition and on-board Crystal Semiconductor audio PCI DSP(and I know DSP is enhanced CPU, is it smart?)---That means THREE CPU.

WRONG! The number of CPU is much more than what you imagine. Even in your PC there are at least three more DSP inside for precision motor control of floppy drive, CD-ROM drive and hard drive. And in modern electronics devices there is usually at least one micro-controller(or named as embedded controller), also CPU, inside. TV, VCR, Video Disc player, Audio CD player, DVD, IR remote controls of previous devices, phone(either featured or cordless), cellular phone, microwave oven, even large appliance such as refrigerator, washer, dryer, disk washer, air conditioner, etc both have embedded controller, some are even DSP; you may count up to more than a dozen CPU inside your home. What an amazing number!

Micro-controller or embedded controller started from Intel 8748 in 1976, it consists of microprocessor, program PROM or EPROM, data RAM, timer, interrupt controller and I/O ports in single chip. In 1979 Intel introduced 8051---enhanced 8048 chip, since then there is a lot of derivatives from here and formed the industry standard---80C51 series, now manufactured by more than a dozen semiconductor companies. Motorola introduced 68HC05/11 series later, also industry standard embedded controller. There is fast-growing micro-controller of low-pin count(serial data input/output) introduced by MicroChip, which extends and dominates new micro-controller fields not occupied by standard micro-controllers before.

There are also 16 bit and 32 bit embedded controller for complex and intensive works, such as data communication, laser printer and also palm computers---PDA and pocket computer. Most are derived from RISC(Reduced Instruction Set Computer), originally designed for workstation. One of the most famous RISC company is MIPS, 32 and 64 bit RISC IP provider. They license to many company such as NEC and Toshiba. NEC generates VRxxxx and Toshiba generates TXxxxx series

RISC CPU for PDA and pocket PC by merging their properitary design. They are both famous CPU of palm computer, shared the market with Motorola Dragon Ball(derivative of 68HC000), the first and the largest market share of palm computer CPU. The other famous RISC IP provider is ARM, the major 16 and 32 bit embedded microcontroller IP provider. Recently Intel introduced StrongARM(ARM based embedded controller) and XScale(also ARM based embedded controller) targets on high-end palm computer, it will have competitive performance with x86 structure but much less power consumption.

Cellular phone is a very great idea since the experiment in 1977 at Chicago by Bell Lab. In past the car dialed radiophone has existed for a long time, but there is always with range limitation and impossible to shrink into handheld or even portable set since high-power operation. By using a cellular concept which uses different frequencies associated all adjacent region cells and smoothly the frequency switching(handover) while crossing the boundary of cells, the subscribers never feel the range limitation even using very low RF power.

Analog cellular phone(1G) grows very fast since mid-1980s, the digital cellular phone(2G) emerged in early 1990s and soon dominated all cellular market since superior quality and rich features. The third generation(3G) of cellular phone soon emerged will combine voice communication, data communication(up to 2Mbps, the accent of current 2.5G, implemented by GPRS, with much faster data communication speed; a couple hundred kbps for 2.5G versus 9.6 or 14.4kbps for 2G data communication) and multimedia(especially video) applications together. And it is the first commercial electronic product(current newly-designed 2G cellular phone already used) which uses three different semiconductor materials---GaAs or InP, Si-Ge and Si for transistor or IC, virtually all commercial electronic products only use Si-technology.

Cellular phone has many standards since analog era, 2G has GSM(most popular standard used for almost all European and Asian countries, currently 847 million* subscribers and 70% market share of among all cellular phone[either digital only or whole include analog since analog phone subscribers are only 26 million right now and still decreasing]), IS-95A(CDMA standard, 158 million[include both IS-95B and CDMA2000, but CDMA2000 increases much faster and shares more than 25% of all CDMA subscribers compared with 10% on June 2002 and 0.5% on June 2001] * subscribers worldwide), IS-136(US TDMA standard, 110 million* subscribers worldwide), PDC (Japanese TDMA standard, 62 million* subscribers worldwide). 2G to 2.5G migration path will have GPRS/EDGE for GSM, IS-95B for IS-95A and IS-136+(already given up) for IS-136. But it is very possible that the migration path for GSM will be through GPRS to W-CDMA bypassing EDGE. Recent trend of 2/2.5/3G cellular phone system will be two major standards worldwide in order to be globe roaming interoperability. For example AT&T Wireless recently gave up their IS-136 migration path to 2.5/3G and will gradually transition to GSM/GPRS standard. Guess who is the largest cellular phone market? Before 2000 it is US, after 2001 it is China. It is obvious that the trend of this market size will keep till mid of this century, but India may replace the second rank position anytime as they are willing to do. *Data till April 2003 from GSM World and CDMA Development Group

Guess who is the first launching 3G cellular system country? It is based on how 3G standard is defined. If it is loosely defined(>144kbps data rate), then guess who is the first launching 3G cellular system country? Surprised! Not US(not even before the beginning of next year for W-CDMA, since no spectrum available ), not Germany(one of most expensive 3G license fee country worldwide), not British(also one of most expensive 3G license fee country worldwide), not even Japan(although she is the second launching 3G [FOMA, W-CDMA technology] cellular system country on October 2001). Korea launched her CDMA2000 1x system in June 2001 massively and solidly, it is actually the first 3G cellular system worldwide. US is the most intensive using wireless spectrum country in world so that all international assigned 3G spectrum for W-CDMA was already used for other purposes long time ago. Now FCC is negotiating with Department of Defense and Department of Commerce and hopes to get final spectrum assignment. Who is the third launching 3G cellular system country? US, Verizon Wireless(the largest cellular network operator in the US) launched her

CDMA2000 1x network at limited area in late January 2002. If based on a little stringent standard, Japan is the first launching 3G cellular system country(FOMA, 384kbps, is faster than CDMA2000 1x). Who will the first launching true 3G peak rate country? Still Korea---launching CDMA2000 1x EV-DO in April 2002---2.4Mbps peak data rate!

How about 4G? Although 4G is still an initial concept and there is no any standard, it will expect to emerge before 2010 and the transmission data rate will be up to 100Mbps. Most of 1G cellular systems use 0.8GHz or 0.9GHz band, most of 2G sytems use 1.8GHz or 1.9GHz band, and 3G systems will use 2GHz band. Guess what frequency will use for 4G systems? It will be very possibly much higher than 2GHz band used by 3G system. High data rate needs high bandwidth, improving modulation method will help a little but not too much(although it will very possibly use high spectral efficiency OFDM just like Digital Audio Broadcast[DAB], Digital Video Broadcast[DVB]. high-speed wireless LAN[802.11a, 802.11g{2.4GHz band same as 802.11b but using high spectral efficiency OFDM, approved by IEEE on November 2001}, and HiperLAN/2] and also ADSL).

Thinking of LMDS---fixed wireless cellular system for high data rate which uses Ka or K band(it depends upon which country, 28GHz band used in US), the terminal is desktop one and base station is a big cabinet one using microwave electronic tubes. Fortunately recent proliferation of high speed InP HEMT(and also InP HBT) and soon-will-be-practical GaN HEMT power transistor(all 3G and newly designed 2G base station use Si LDMOS power transistors, which approach the silicon high-frequency limit) will shrink the size of both mobile terminal and base station dramatically. And they will even be smaller than current cellular phone system either terminal or base station by scaling-down technology. The wrist-watch radio of movie "Dick Tracy" will be a true gadget in reality.

The data communication emerged since SAGE system---air-defense system in 1950s era, then ARPANET---goverment sponsored internetwork between research centers and major universities since 1960s period. Internet is actually derived from ARPANET, now e-mail, web and e-commerce already have been everyday life of everybody if he or she uses computer. The most popular of local area network(LAN)---Ethernet emerged in early 1980s and now use at business of everyday, speed from early 10Mbps till 100Mbps and 1Gbps, and now even considering 10 Gbps. Recently the trend of network is to be merged together between high-speed LAN and high-speed telecommunication (WAN) and also extend to wireless/mobile networks in order to obtain seamless communication service.

We start this review from power, now we conclude with power. Since the recent success of controlled thermonuclear fusion experiment, the commercial fusion reactors should be emerged within 20 years and preserving the precious fast-exhausting petrolem(should be happened before the end of 21$^{st}$ century if the consumption still grows) for raw materials of fiber and plastics will be more and more important, the most impact energy-consuming apparatus will be vehicles. Both the technologies of fuel cell and rechargeable battery(actually both concepts are very very old because power/energy density and cost dominates everything) are near practical for vehicles, we will see that the mass production of hydrogen-fueled fuel-cell powered cars(especially hydrogen storage issue probably will be solved by nanotechnology material in the near future) will be started in 2003~2005 by Benz, Toyota(both already announced on November 2002), Nissan, GM and almost all major vehicle manufacturers, then Li-ion or Li-polymer rechargeable battery powered car later(Macro fuel efficiency is not good if power is generated by natural gas or petrolem products. Large-scale use of recharge battery vehicle will be waited after major portion of electric power generated by non-petrolem products.). It will grow and dominate the car market before the end of 21$^{st}$ century, also cheap and clean like thermonuclear fusion power plants.

Finally we need to emphasis the progress in device level is much less than that of subsystem and system levels recently. New function, structure and protocol have largely changed the every aspects of electronics systems of any applications, but the principles and devices used still same as long time ago, only scaled down more and more complex, integrated and compact. Si-based technology has matured for a long time and become the mainstream technology of solid state devices expecting to last at least 50 years more(maybe forever). Although there are a lot of semiconductor material such as GaAs or InP with heterostructure for very high frequency applications, GaN, SiC or Diamond, should be heterostructure also, expecting for very high frequency **and** very high power applications in the near future, and numerous compound semiconductors for optoelectronic source/detector and sensor devices, none will replace silicon. Is the trend continued in future?

## C. Epilog in Future(After 2000~)

Now we are already in the 21st century, what will we expect in this century? In previous century many experts and academicians thought that both electronic technology and biology technology are most complex and sophisticated technologies and should be benefit the contributions each other. Unfortunately, none is successful(We only count the principle directly applied, the practical instrumentations are not considered.) Although there are some ambiguous terms such as "neural networks", "digital DNA"; none is the real benefit from the biology technology. But it does not mean that electronic technolgy and biology technology may not be contributeable each other in the future, especially both technologies progress more delicately and sophisticatedly and make consideration from physics grounds.

What about nanotechnology? Will it be the "star" technology in 21st century like power technology in 19th century and electronic technology in 20th century? Biotechnolgy has developed for several hundred years or even thousand years dependant upon your definition, in any era it is a important technology but not a "star" technology. Nanotechnology belongs to material technology(is it somewhat old technology?) entering nano-meter scale domain, the principle is based on Quantum Mechanics--- one of the most important discovery of physics field in 20th century(actually developing in the beginning thirty years of 20th century). Nanotechnology in electronics field is generally called as molecular electronics, carbon nanotube($C_{60}$) FET is the first molecular electronic device, then ART, SMART, MOSES and many more devices will be invented. But will these nano electronic devices be really practical enough and can be competitive with existing electronic devices?

It is expected that Si technology will continue scaling down till around 2010 reaching quantum mechanics limit. During the past decade one of the hottest research area in the solid state devices is quantum heterostructure solid state device, which succeeds from the gigantic success of heterostructure transistor research in the 1980s and practically implementation in the 1990s. Qunatum electronic devices especially heterostructure will be the front-line electronic devices in the first 50 years of 21st century, but it won't replace the current silicon technology(already low-cost, high-density, practical high-performance and tremendous technology progress since early 1960s) which replace almost all previous electronic device(The major practical product of germanium transistors in 1950s is only portable transistor radio since low power and low frequency properties of germanium transistors, although there are a lot of diversified development works in every electronics system fileds at that time, which became practical products after adopting silicon transistors in early 1960s.)---electronics tubes and open many new applications, which are impossible implemented by electronics tubes, in the second half of 20th century. Finally, remember that the eras of two important halves in 20th century---electronic tube era and solid-state device era actually can be traced back to invention or discovery of 19th century. Will it happen again, or totally new invention or discoveries in 21st century?

**References of early history:**

1. Joseph W. Duffy, "Power---Prime mover of technology", McKnight & McKnight Publishing Company, 1964
2. John Day, "Engines---The search for power", Hamlyn Publishing Group, 1980
3. ASA Briggs. "The Power of Steam---An illustrated history of world's steam age", Bison Books, 1982
4. Lyle Cummins, "Internal Fire---The internal combustion engine, 1673-1900", Society of Automotive Engineering, 1976
5. John R. Pierce and A. Michael Noll, "Signal---The science of telecommunication", Scientific American, 1990
6. Lewis Coe, "The Telegraph---A history of Morse's invention and its predecessors in the United States", McFarland & Company, 1993
7. Aitken, Hugh G. J., "Syntony and Spark---The origins of radio", John-Wiley & Sons, 1976
8. Tom Lewis, "Empire of the Air---The men who made radio", Edward Burlingame Books, 1991
9. David Fisher and Marshall Jon Fisher, "Tube---The invention of television", Counterpoint, 1996.
10. Albert Abramson, "The History of Television---1880 to 1941", McFarland & Company, 1987
11. Editors of Electronics, "An Age of Innovation---The world of electronics 1930~2000", McGraw-Hill Publications Co., 1981
12. Robert Morris Page," The Origin of Radar", Anchor Books, 1962
13. Robert Buderi, "The Invention that Changed the World---How a small group of radar pioneers won the second world war II and launched a technological revolution", Simon & Schuster, 1996
14. Frederick Seitz & Norman G. Finspruch. "Electronic Genie---The tangled history of silicon", Univ. of Illinois Press, 1998
15. Riordan, Michael & Hoddeson, Lillian, "Crystal Fire---The birth of the information age", W.W. Norton & Company, 1997
16. S. Millman, editor, AT&T Bell Laboratories, "A History of Engineering & Science in the Bell Systems---Communications sciences 1925-1980", AT&T Bell Laboratories, 1984
17. A.R. Burks and A.W. Burks, "The First Electronic Computer---The Atanasoff Story", The University of Michigan Press, 1988
18. Stan Augarten, "Bit by Bit---An illustrated history of computers", Ticknor & Fields, 1984
19. Stan Augarten, "State of the Art---A photographic history of the integrated circuits", Ticknor & Fields, 1983
20. John G. Truxal, "The Age of Electronic Messages", The MIT press, 1990
21. Elizabeth Antebi, "The Electronic Epoch", Van Nostrand Reinhold Company, 1982
22. G.W.A. Dummer, "Electronic Inventions and Discoveries", Pergamon Press, 1978
23. F. Clifton Berry, Jr. "Inventing the Future---How sciences and technology transform our world", Hughes Aircraft Company, 1993

**References of latest development:**

24. Parker, "McGraw-Hill Encyclopedia of Physics", McGraw-Hill, 1993
25. Jerry C. Whitaker, "Power Vacuum Tubes Handbook", Multiscience Press 1999
26. Lindsay W. MacDonald and Anthony C. Lowe, "Display Systems: Design and Applications", John Wiley & Sons, 1997
27. Larry D. Partain, "Solar Cells and their Applications", John Wiley & Sons, 1995
28. Muhammad H. Rashid, "Power Electronics---Circuits, Devices, and Applications", Prentice Hall, 1993
29. Ronald Waynant and Marwood Ediger, "Electro-Optics Handbook", McGraw-Hill, 2000
30. John F. Ready, "Industrial Applications of Laser", Academic Press, 1997
31. A. A. Harms, K. F. Schoeph and D. R. Kingdon, "Principles of Fusion Energy: An introduction to fusion energy for students of science and engineer", World Scientific, 2001
32. Kyoji Nishikawa and M. Wakatani, "Plasma Physics: Basic theory with fusion applications", Springer-Verlag, 1999

33. W. James Sarjeant and R.E. Dollinger, "High-Power Electronics", TAB Books, 1989
34. Robert J. Barker, "High-Power Microwave Sources and Technologies", John Wiley & Sons, 2001
35. Andrei V. Gaponov-Grekhov and Victor L. Granatstein, "Applications of High-power Microwave", Artech House, 1994
36. Jeff Hecht, "Beam Weapons: The next arms race", iUniverse, 2000
37. William J. Broad, "Teller's War---The top secret story behind the star war deception", Simon & Schuster, 1992
38. Robert W. Duffner, "Airborne Laser---Bullets of light", Plenum Press, 1997
39. Charles P. Poole, Jr., "Handbook of Superconductivity", Academic Press, 2000
40. Peter J. Lee, "Engineering Superconductivity", John Wiley & Sons, 2001
41. Jeff Hecht, "Understanding Fiber Optics", Prentice Hall, 2001
42. S.M. Sze, "Modern Semiconductor Devices Physics ", John Wiley & Sons, 1997
43. Charles A. Harper and Ronald M. Sampson, "Electronic Materials and Process Handbook", McGraw-Hill, 1994
44. L.Z. Berger, "Semiconductor Materials", CRC Press, 1997
45. M. Shur, "Compound Semiconductor Electronics---The age of maturity, selected topics in electronics and systems Vol. 4", World Scientific, 1996
46. Peter Capper, "Properties of Narrow Gap Cadmium-based Compounds", INSPEC, the Institute of Electrical Engineers of British, 1994
47. John Lester Miller, "Principles of Infrared Technology---A practical guide to the state of the art", Von Nostrand Reinhold, 1994
48. Antoni Rogalski, "Infrared Photon Detectors", SPIE, 1995
49. Lawrence A. Klein, "Millimeter-wave and Infrared Multisensor Design and Signal Processing", Artech House, 1997
50. E.T. Yu and M.O. Manasreh, "III-V Nitrade Semiconductor: Application and Devices, Vol 16", Taylor and Francis, 2002
51. R.K. Willardson and Eicke R. Weber, "Semiconductors and Semimetals, SiC Materials and Devices", Academic Press, 1998
52. Mark A. Prelas, Galina Popovici and Louis K. Bigelow, "Handbook of Industrial Diamonds and Diamond Film", Marcel Dekker, 1999
53. F. Ali and A. Gupta, "HEMTs and HBTs: devices, fabrication and circuits", Artech House, 1991
54. C.Y. Chang and Francis Kai, "GaAs High-speed Devices", John Wiley & Sons, 1994
55. B. Jalali and S. J. Pearton, "InP HBTs: Growth, Processing, and Applications", Artech House, 1995
56. Osamu Wada and Hideki Hasegawa, "InP-Based Materials and Devices", John Wiley & Sons, 1999
57. Jiann S. Yuan, "SiGe, GaAs, and InP Heterojunction Bipolar Transistors", John Wiley & Sons, 1999
58. William Liu, "Fundamentals of III-V Devices---HBT, MESFET and HFET/HEMTS", John Wiley & Sons, 1999
59. William Liu, "Handbook of III-V Heterojunction Bipolar Transistors", John Wiley & Sons, 1998
60. Vladimir, V. Mitin, Viatcheslav, A. Kochelap and Michael A. Stroscio, "Quantum Heterostructures---Microelectronics and Optoelectronics", Cambridge Univ. Press, 1999
61. Ari Aviram and Mark Ratner, "Molecular Electronics: Science and Technology", 1998, the New York Academy of Sciences
62. C.Y. Chang and S.M. Sze, "ULSI Technology", McGraw-Hill, 1996
63. S.M. Sze, "Semiconductor Sensors", John Wiley & Sons, 1994
64. H.R. Everett, "Sensors for Mobile Robots: Theory and Applications", A K Peters, Ltd., 1995
65. Erika Kress-Rogers, "Handbook of Biosensors and Electronic Noses", CRC Press, 1996
66. James R. Janesick, "Scientific Charge-Coupled Devices", SPIE Press, 2001
67. Pochi Yeh and Claire Gu, "Optics of Liquid Crystal Display", John Wiley & Sons, 1999
68. Ashok K. Sharma, "Programmable Logic Handbook", McGraw-Hill, 1998
69. Michael John Sebastian Smith, "Application-Specific Integrated Circuits", Addison-Wesley,

1997
70. Kiat Seng Yeo, Samir Rofail and Wang Ling Goh, "CMOS/BiCMOS ULSI: low voltage, low power", Prentice Hall, 2001
71. Behzad Razavi, "Design of Analog CMOS Integrated Circuits", McGraw-Hill, 2000
72. Thomas H. Lee, "The Design of CMOS Radio Frequency Integrated Circuits", Cambridge Univ. Press, 1998
73. Vijay K. Madisetti and Douglas B. Williams, "The Digital Signal Processing Handbook", CRC Press, 1997 or 1999(CD-ROM version with same content as 1997 edition)
74. Stergios Stergiopoulos, "Advanced Signal Processing Handbook: Theory and implementation for radar, sonar and medical imaging real-time system", CRC Press, 2000
75. D. Curtis Schleher, "Electronic Warfare in the Information Age", Artech House, 1999
76. Gene F. Franklin, Michael L. Workman and Dave Powell, "Digital Control of Dynamic Systems", Addison-Wesley, 1997
77. Myron Kayton and Walter R. Fried, "Avionics Navigation Systems", John Wiley & Sons, 1997
78. Cary R. Spitzer, "The Avionics Handbook", CRC Press, 2000
79. Nicholas C. Currie and Charles E. Brown, "Principles and Applications of Millimeter-Wave Radar", Artech House, 1987
80. George W. Stimson, "Introduction to Airborne Radar", Scitech Publishing, 1998
81. R. Michael Hord, "Understanding Parallel Supercomputing", IEEE press, 1999
82. Ulrich L. Rohde and David P. Newkirk, "RF/Microwave Circuit Design for Wireless Applications", John Wiley & Sons, 2000
83. Ulrich L. Rohde, "Microwave and Wireless Synthesizers: Theory and Design", John Wiley & Sons, 1997
84. Myke Predko, "Handbook of Microcontrollers", McGraw-Hill, 1999
85. Myke Predko, "Programming and Customizing PICmicro Microcontrollers", McGraw-Hill, 2001
86. Tatsuo Itoh, George Haddad and James Harvey, "RF technologies for Low Power Wireless Communications", John Wiley & Sons, 2001
87. P. Rai-Choudhury, "MEMS and MOEMS Technology and Applications", SPIE Press, 2000
88. Colin K. Campbell, "Surface Acoustic Wave Devices for mobile and wireless communications", Academic Press, 1998
89. John Michael Golio, "The RF and Microwave Handbook", CRC Press, 2001
90. Bernard Sklar, "Digital Communications: Fundamentals and Applications", Prentice Hall, 2001
91. Robert C. Dixon, "Spread Spectrum Systems with Commercial Applications", John Wiley & Sons, 1994
92. Nathan J. Muller, "Mobile Telecommunications Factbook", McGraw-Hill, 1998
93. Jerry D. Gibson, "The Mobile Communications Handbook", CRC Press and IEEE Press, 1999
94. Vijay Kumar Garg & Theodore S. Rappaport, "Wireless Network Evolution: 2G to 3G", Prentice Hall, 2001
95. Juha Korhonen, "Introduction to 3G Mobile Communications", Artech House, 2001
96. Bruce Elbert, "The Satellite Communication Applications Handbook", Artech House, 1996
97. Michael Russell Rip & James M. Hasik, "The Precision Revolution: GPS and the Future Aerial Warfare", Naval Institute Press, 2002
98. Serge Luryi, Jimmy Xu and Alex Zaslavsky, "Future Trends in Microelectronics---The Nano Millennium", John Wiley & Sons, 2002
99. Various issues of EDN, Electronic Design, Microwave Journal and Microwave & RF magazines
100. Various issues of IEEE Spectrums, Proceedings and Journals

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