Photo by NASA – Johnson SFC

This photograph of the "earthrise" over the moon was made possible only by America's Apollo program. The singular beauty of our living earth stands in stark contrast to all other planets and other bodies in our solar system.

PAYNE ENGINEERING

THE SILICON REVOLUTION
And the creation of our beautiful earth

INTRODUCTION:

The Sun (a main sequence G2 star) was created to provide clean fusion energy so that the earth and the moon could be created along with the other planets and their moons. We call this The Solar System.
By inspection, from the moon and special telescopes, it is obvious that the visual beauty of Earth vastly exceeds the appearance of any other planetary body that we have seen or photographed to this day. Our world had never been able to see how beautiful the Earth is, until the Apollo 8 true-film photographs were shown to the world in 1970. (Followed by film from Apollo 11-Apollo 17). America is the only country that has been able to accomplish this.
The eight plus Pluto solar system planets orbit around the sun in the same plane, called the *ecliptic plane*, that is almost parallel to the sun's equator. The distance of these planets from the Sun is arranged so that each planet is approximately twice the distance from the Sun as the one before it. In fact, the Titius-Bode rule --from 1781-- is an equation where: AU = .4 + .3k mathematically predicts the AU --astronomical unit-- for each planet's orbit distance from the Sun, where k = 0, 1, 2, 4, 8, 16, 32, 64, 128 for the 9 planets. An AU is the average distance of the earth from the Sun, approx. 150 million km. There is no scientific explanation for this rule, "falling in the region of uncomfortable science."

Another singular characteristic of our planet earth is the presence of the earth's magnetic field. There are iron cores in three of the four inner planets, but the earth's molten iron core is larger and hotter than any of the others by a large magnitude. It is so hot --over 1043^{O}K-- that this magnetic field is not caused by magnetized iron deposits as is a conventional bar magnet. It is thought to be caused by large electric currents in the liquid outer core. (ref. Univ. of Tennessee Astronomy 161).

This field interacts with the electric currents in the ionosphere creating the earth's magnetosphere, which is unique from all the other planets. *"In his hand are the deep places of the earth:"* Psalm 95:4. This strong magnetosphere shields the earth from the charged particles of a plasma, known as the solar wind. This plasma of charged protons and electrons is ejected outwards from the Sun's corona at velocities over 1 million miles per hour. The solar wind is so powerful that it has scoured the other inner plants for millions of years, removing anything that could ever be described as an atmosphere or a living organism. If we were to lose this magnetic shield, the earth would soon be no different from the other "dead planets". One man who was very familiar with protons and electrons, Dr. Albert Einstein wrote in 1926, after he received the Nobel Prize in Physics, " *God does not play dice with the world* ".

The Sun's fusion energy created over 117 chemical elements to enable life, as we know it. (There is some evidence that a few of the heavy elements may have come from non-solar sources). If one studies this piece of creation carefully, an early question might be:

What would Earth be like if it were only 100 miles closer to the Sun?
or
What would Earth be like if it were only 100 miles further from the Sun?

Meanwhile, of all these 117 elements, the element Silicon (Si, atomic nr.14 - atomic weight 28) makes up over 24% of the earth' crust ---sand(silica)--- and is easy to extract from silica's plentiful availability.

Silicon has semiconducting electrical characteristics, which differ from the electrical characteristics of insulators and conductors in that current can be induced to flow in the presence of an applied electrical bias and impurity doping to define a junction. This unique material characteristic allows it to handle micro-power switching today. Less well known is silicon's ability to control large amounts of electric power --thousands of megawatts--.

Once again, the free people of America started the silicon revolution in 1947, and continue to lead the world's economy with powerful, low-cost computers available to anyone. In turn, they drive thousands of industrial silicon Power Controls that make Kellogg's frozen waffles, seal diaper moisture covers, cool the Space Shuttle's hydraulic lines, and control damper valves for the world's largest electric power plants. ---among other things--- Silicon's ability to control microprocessor logic or to modulate 1-3 megawatts of electricity has been driving the world's energy demands ever higher since the middle of the 20th century. Today, it is the single most significant of the earth's elements to create new opportunities for all free people to better their lives as we enter the 21st century.

CHAPTER 1: BASIC SILICON TECNOLOGY

A: By weight, silicon makes up 25.7% of the earth's crust and is the second most abundant element on earth, after oxygen. As a very light metal, slightly heavier than aluminum, it is normally found in minerals containing silicon dioxide (or silica) with crystalline forms such as quartz, granite, feldspar, amethyst, and sand.

Unusual for metals, which are normally good conductors of electrical current, the silicon semiconductor is a very poor electrical conductor, almost having insulating properties. But it has the astonishing ability, if "doped" with small traces of impurities, to switch very small nano-currents --as in microprocessors-- or very large kilo-amps in one megawatt solid-state power controls.

B: Metallurgical grade silicon, for alloying aluminum and steel, is about 55% of the world's production of this magnificent metal. Another 40% of pure silicon is used in the manufacture of silicones. The remaining 5% is used as the raw material for making ultra-pure electronic silicon where the purity requirements are a minimum of one part per million of impurities.

Metallurgical silicon is chemically treated by the reaction of high purity silicon dioxide (or silica) in a carbon electric arc furnace. At temperatures over 1900^{O}C, the reduction of silicon dioxide with carbon produces silicon and carbon dioxide. This product is at least 99% pure and sells for about 60 cents/lb..

C: The invention in 1947 of the first point contact transistor (using germanium)[(1)] by John Bardeen, William Shockley, and Walter Brattain, at Bell Labs in Murray Hill, N.J. was the first milestone. Shockley went further and published a paper in 1950 on the silicon junction transistor, and the theory of diffusion with electrons and holes in solid-state crystals. For this achievement, all three received the Nobel Prize in 1956.

Thus was born the "Silicon Revolution".

D: For further purification to semiconductor standards, zone melting, or zone refining, had been used for many years after the discovery of the transistor and its many other derivatives. Even then the demand for more purity was continuing into the 1980's. The basic stock of met silicon rods were then chemically treated using a Siemens or Sumitomo trichlorosilane process to further purify the silicon rods creating polycrystalline silicon. The Czochralski process is then used to grow single-crystal ultra-pure rods up to 10 inches in diameter which will then be sliced and polished to provide the basic silicon discs for all low power applications including silicon photo-cells for the solar cell industry. For high power applications from 10kw to 2-3 megawatts, Czochralski silicon is not pure enough, and the more expensive float-zone procedure is normally used today. By applying neutron-transmutation-doping (NTD) to float-zone silicon, higher quality thyristors and diodes can be produced without changing the processing in any way. NTD treatment improves the uniformity of the resistivity across the whole diameter of the silicon pellet. For megawatt silicon diameters from 30mm to 100mm, this increases their reverse block-voltage by 15-20%.

CHAPTER 2: LOGIC AND LOW POWER SILICON

A: The bipolar transistor

With one of the first licenses from Bell Labs, Raytheon became the world's largest transistor manufacturer in 1953, using the point-contact germanium transistor aimed at the hearing aid industry. Only a year later Texas Instruments--another early licensee--created the first high-production silicon-junction transistor for the very small transistor radios. The transistor was very expensive in those early days, and the military was the primary customer. When Transitron started up in 1952 in Wakefield, Mass. and began making silicon diodes(since they could not afford the Bell labs $25,000 license fee)for the Navy, they developed a low cost manufacturing method. They made millions of diodes while Raytheon, Texas Instruments, General Electric, Motorola, General Transistor, Fairchild Semiconductor, and the other original licensees emphasized transistor development and more efficient manufacturing. William Shockley was the driving force behind all the silicon-junction transistor advances, forming Shockley Semiconductor Labs in Palo Alto, CA in 1955. Also he was the only one of the three transistor inventors to push on to the silicon-junction transistor, the Standard of the industry to this day. Bell Labs, once again displayed their innovation skills by producing the first planar semiconductors. Using silicon dioxide, a precursor of silicon, they showed its excellent insulation properties so that one could build a semiconductor up in layers. The conducting layers could be separated by a thin film of silicon dioxide which could then be selectively etched away allowing specific connections between the conducting layers. Fairchild's first planar transistor was made in this manner in 1959.

NOTE:
1964: Bellcom did systems research for Apollo program.
1965: Sony 6 transistor radio with IBM rejects.
IBM was the next large user in their new Model 305 business computer.

B: The silicon diode was the next high production product.

As noted above, Transitron began high production of silicon rectifier diodes for the military, millions of them but they were small, less than 1 amp and low voltage. But it was a start. There was a large demand to replace existing rectifiers, such as mercury tubes, large plate selenium diodes, and ignitrons which were used for rectifying AC electricity to DC electricity in the manufacturing of aluminum, chlorine, and other metals and chemicals that required electrolytic processes using thousands of DC amps to separate them from other elements. Therefore, in the late 1950's silicon diodes using the same diffused(or diffused/alloy) process as the transistor with silicon pellet diameters growing up to 30mm--power semiconductors--quickly replaced 600 and 1000 amp tube rectifiers in the mines, electric drive locomotives, and all electrolytic processes. The simple diffused pn junction now became a workhorse of heavy industry. They also helped make tiny low-cost power supplies come about for the small radios and calculator industry. Unfortunately, many electronic designers forgot about the .7 to 1.3v drop that is a characteristic of any pn junction which will generate 1.3 watts of heat per amp. 1-2 amps was nothing, but 600 amps and 1000 amps would generate enough heat to destroy the device in only 1-2 hours. Silicon was a "breakthrough" but even so its current rating would go to zero amps at 120^{O}C. Normal rated current is usually a case temperature of 100^{O}C. This problem plagues the power-silicon industry to this day.

C: The silicon Schottky diode:

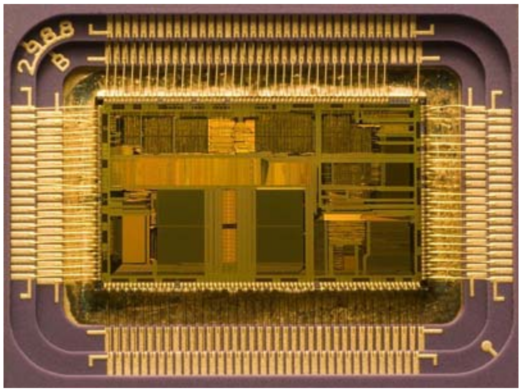
Working in the Siemens & Halske research laboratory in Pretzfeld, Germany, Walter Schottky developed in 1938 a theory explaining the rectifying ability of two metal semiconductors in contact as dependent on the barrier layer between them. This was a revolutionary discovery that undoubtedly assisted the Bell Labs people only 9 years later. The Schottky diode also reduced the voltage drop by 100% to .33-.35vdc which allowed it to be used in small power supplies with much less heat loss. In addition, its switching speed was almost zero since its reverse recovery time was essentially zero. Unfortunately, it has a limited reverse voltage of about 200 volts.

D: The integrated circuit:

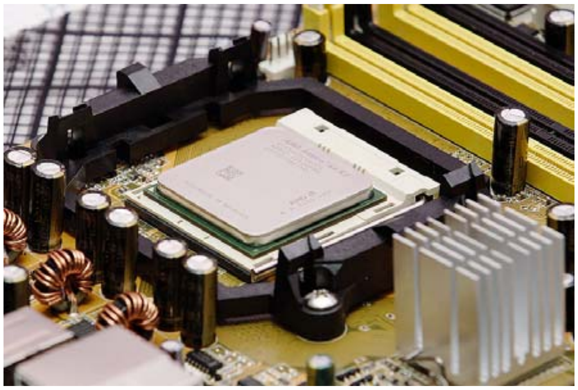
Invented by Jack Kilby(Texas Instruments) in 1958, with two circuits on a single piece of germanium to create the world's first IC. Only a few months later Robert Noyce at Fairchild did the same thing independently, using silicon which was more rugged and more suitable for their new planar transistor process. This procedure then allowed hundreds and then thousands of transistors and other components to be fabricated on small slices of silicon. (These slices have grown to over 300mm and may be even larger in the future). Kilby and Noyce are credited as the IC's independent co-inventors. However, Jack Kilby won the Nobel Physics prize in 2000. Applying the new planar process on a much larger scale was then developed into the vast industry of microprocessors that we see today.
NOTE:
1959 Fairchild first commercial IC.
1966 Fairchild first compensated op-amp, the 741.

E: Microprocessors

In 1969 Intel developed the 4-bit 4004 for a pocket calculator followed promptly by the 8-bit 8008, and the improved 8080 in 1974. The competitive pressure from Motorola, Texas Instruments, et.al, was so fierce that even after Intel announced the first 16-bit 8086 in 1978,Motorola offered their 68000 series microprocessor. They were successful in persuading Apple Computer, the first hi-volume personal computer manufacturer, to use an 8-bit version of the 68000 microprocessor in all of its computers. Apple still uses variations of the 68000 to this day. However, Intel was able to sell its 8-bit version to IBM in 1980 for use in their "Personal Computer" or PC product line. This insured the long term market success of the subsequent 286, 386, 486, Pentium, Centrino, etc. microprocessors that have over 85% of the market today, followed by AMD with 15%.
NOTE:
1972 IntelWilliam Shockley: Electrons and holes in semiconductors, with app 2006 Apple w/Corduo



Open Die of the Intel 80486DX2 microprocessor
Actual size is 12 x 6.75 mm



AMD Athlon 64 X2 3600 Dual core processor

F: Silicon photocells

a) Solar energy photovoltaic cells

Although the photovoltaic effect was first discovered by the French physicist, Alexandre Becqueral before 1840, and Dr. Albert Einstein had not provided the quantum theory until 1910 or so, the modern solar cell was patented by Russell Ohl in 1960.

Eric Lidow escaped Germany's holocaust in 1937 by immigrating to the United States where he started the Selenium Corporation of America. He intended to make probably the first selenium photocells in the country, mostly for the nearby film industry in Los Angeles. The U.S. was at war, however, and the War Dept. wanted him to make selenium rectifiers for bomb fuses. In 1947, he and his father founded the International Rectifier Company and introduced their first silicon solar cells in June of 1958. Their sunlight conversion efficiency was, perhaps, only about 9% (5).

The Sun's incoming radiation (insolation) irradiates the earth, at high-noon, with no clouds, in June and July, at the equator with an insolation of approximately 900w/m^2. In December, you might get 25%.
50 years later various improvements in the basic "large pn junction" structure of the solar cell has increased its conversion efficiency to approximately 14-15%.

Its primary market was the space power business, started by the first satellites in 1958. This business remains an essential component of all space work to this day. A new market, driven by environmentalists, is the "renewable energy" business, consisting primarily of a large number of wealthy individuals and large companies who want to show their customers how "green" they are, i.e. that they conform to the latest trends in our "politically correct" society. Unfortunately, these "wind power" and "solar power" people have seized on these 2 alternative energy sources of generating electricity as their solution to replace "dirty coal".

After they have raised the necessary capital funds---nearly all from Federal, State, and Municipal Sources---to build these "generating" plants they must apply for and wait to be sure of their Federal generating subsidy of 1.88 cents/kwhr*. The permitting process will be clogged with the usual "green Luddites", and well-known hypocrites who exhibit the normal NIMBY objections to physically large energy projects. To the author's knowledge, none of these projects has proceeded without absolute assurance that they will get this kwhr subsidy.

Since the "generating cost" of coal in 2005-2007 is approximately 2.0 to 2.2 cents/kwhr and the "generating cost" for nuclear is about 1.7 to 1.72 cents/kwhr, one wonders how these subsidy costs were originally calculated. From 2004 to 2006, the "alternative energy" subsidies for wind and solar ---3 years--- totaled over 1.2 billion dollars! That is a lot of money. This could buy a complete pollution free 600 megawatt nuclear power plant.

The resultant demand for these huge quantities---literally acres or hectares---of basic silicon that is normally used in microprocessors, etc. has caused some unusual supply and demand problems in our normal silicon market, in the same manner that huge Federal ethanol subsidies beginning in 2004 have distorted the corn, feed stock, etc. markets.

"Land Use" problems make one wonder why environmentalists, project-leaders, and hardware manufacturers have not studied the vast quantities of land required for wind mills and particularly solar farms. Dr. David Pimentel from Cornell University published an exhaustive study in the December 2002 issue of Biophysics that would prove without any doubt to anyone that utility size "alternative energy" systems will not happen. In any case, despite the steady progress in new and more efficient forms of solar cells their monstrous capital cost for any sizeable electricity generating plant remains over $10,000/mw.*

First generation solar cells ---comprising some 85% of the this booming market today--- are made using the same Czochralski process that is used to make single crystal silicon. This is the same electronic market that uses this type of silicon for microprocessors, integrated circuits, diodes, transistors, etc. Because the solar cell market is 99% subsidized by governments around the world, mono-crystalline silicon has become more expensive.

.photos by R. Harrington

120 volt Solar Cell Panel Installation

******** I should add here that in May 1972 our company installed two 12in. x 18in. Solarex panels rated 6vdc, 10watts each driving two automotive brake lights. After 25 years we can report that their output had declined by 80%. After a good cleaning of the Solarex-supplied silicone RTV covering they are producing, nominally, the same output that they were in 1972. Unfortunately, their retail cost has remained at about $1.00 per square inch.

b) CCD (charge-coupled devices)

Invented in 1969 by William Boyle and George Smith at Bell Labs in its search for sensing devices to be used on a "picture phone", they soon realized that this specialized semiconductor could receive and store photoelectric charges. It followed that electronic images could be created and stored. Today their primary usage is in digital cameras and analog camcorders.

c) Photo sensors

Photo sensors, or more precisely known as photo-transistors, switch and change their state by using Photon energy just as a normal silicon bi-polar transistor will switch by using small electric currents. Their primary usage is to act as light sensors for the home and for thousands of applications in industrial electronics.

G: The LED (light emitting diode)

The LED uses various semiconductor materials:
aluminum gallium arsenic for red light,
aluminum gallium phosphide for green light,
aluminum gallium indium phosphide for yellow light,
gallium nitride for blue light,
indium gallium nitride-gallium nitride for white light.
Silicon carbide is a more recent material that promises higher brightness and power for blue or white light.

The LED is an unusual form of diode because, unlike normal silicon or germanium diodes where holes and electrons recombine as indirect band gap materials, the materials used for a LED have a direct band gap with energies corresponding to the light frequencies of the electromagnetic spectrum.

"Junction luminescence, or junction electroluminescence, occurs as a result of the application of a direct current at a low voltage to a suitably doped crystal containing a pn junction." This is a unique form of diode that emits light when it is forward biased with DC voltage applied anode to cathode. "These semiconductor light sources can be made in a wide range of wavelengths of the electromagnetic spectrum extending from the 210nm of the near ultra-violet to the far-infrared region" up to wavelengths of 700nm or so. "Forward biased current flow in the pn junction causes holes to be injected into the N-type material and electrons to be injected into the P-type material, i.e., minority carrier injection. Some of this energy is released as light, while the remainder is released as heat. The energy contained in a photon of light is proportional to its frequency, i.e. color, and the higher the band gap energy of the semiconductor material forming the LED, the higher the frequency of the light emitted".[9]

Today, LED's are available in all basic colors and white. They produce 2-3 times more lumens of light per watt than incandescent lamps, and they are almost as efficient as the new compact fluorescent bulbs. They are very rugged with lifetimes over 100,000 hours. However, there are some problems with LED's that need to be solved:

1) For LED's that are in sockets ----Christmas tree lighting for example--- the aluminum wire leads from the LED cannot be in a socket with copper. The dissimilar metals corrode badly in contact with each other limiting their life to less than a few thousand hours, less than the old reliable multi-colored, low cost incandescent tree lights.

2) By their nature LED's are DC devices. That is fine for automobiles and other portable items that use DC batteries as their electrical heart. But for home or business use they must have "drivers" or convertors to change the standard 120vac in North America (220vac in the rest of the world) to low voltage DC.

3) Heat is the LED's worst enemy. Unlike conventional lamps which radiate their infra-red energy in their light rays, LED's photons come from a semiconductor junction where 80% of the LED's heat is generated. This requires efficient heat conduction away from the junction so that it will not be damaged due to over temperature, no more than 70-90 deg.C. (Newer Silicon Carbide LED's can operate closer to 140 deg.C)

Organic light-emitting diodes (OLED) are a more recent development where the emitting layer material is an organic compound. The polymer material is lighter and can be flexible which makes the OLED a serious competitor to conventional LCD (liquid crystal displays) as seen in digital cameras and cell-phones. Its color rendition is better than LCD's, but OLED's do not have as long a lifetime at present.

Nick Holonyak, at General Electric in 1962, invented the first visible infra-red LED (IRED). Holonyak also contributed to the GE team that developed the first SCR for which Bill Gutzwiller and his team of application engineers quickly developed the market through the publication of the GE SCR Manual. At this time he is still active in semiconductor physics and has to be considered as one of the greatest semiconductor pioneers and innovators of the 20th century. Note that through its many editions, the GE SCR Manual became the bible of power electronics in that era.

Following are examples of the use of LED’s in commercial applications:

Photos by R. Harrington

Auto Tail Light using LED’s

Cross Walk using LED’s

H: The silicon MOSFET, (smaller integrated circuits).

In 1959, Martin Atalla and Davon Kahng of Bell Labs introduced the first Field Effect Transistor (FET), and the Metal Oxide Field Effect Transistor (MOSFET). This transistor was unique in that it was very efficient, with no gate current in the OFF state and low forward voltage drop from the source to the drain. For these reasons the MOSFET is an ideal power switch to be used in integrated circuits of all types.

I: The silicon ZENER DIODE.

Invented by Clarence Zener in the early 1950's, this silicon junction diode behaves just like a normal diode in having a very high reverse cathode to anode resistance up to its critical reverse breakdown ---or zener voltage---. At this point its resistance to current flow decreases to a very low value, allowing a very high current flow.
The silicon is heavily doped to provide for this feature and to be able to make the zener diode in a variety of "zener diode" voltage levels. These clever devices, when biased in the reverse direction, can now be used as a reference voltage element or as a voltage regulator for electronic circuits.

The circuit designer must take care, however, to not exceed the wattage rating of the zener by providing a current limiting device in series. Typically, one should limit the zener current to 20% of its maximum rating. In addition, one must be aware that all zeners have a temperature coefficient of effectively zero at a 5.6 vdc zener voltage. For higher zener voltages the temp. coefficient can be as high as 0.1% for voltages higher than 24 vdc.
The "avalanche diode" uses the same process to "break-over" in the reverse direction for much larger power diodes in 50 to 300 amp sizes. This characteristic, for protection from high, short duration transient AC line voltages, was an unusually valuable asset when General Electric made their 300 amp, 3/4 in. stud-mounted, "coal mine" diode.
No one today, to the author's knowledge, makes such a device for high power. This is a typical example of irresponsible companies not having proper knowledge of how to use power silicon to build "bullet proof" power controls and power supplies.

CHAPTER 3: POWER SILICON

A: The **Silicon Diode** was the first high power semiconductor to be mass produced for all electrical industries from 1 killowatt to 2 megawatts each. Unlike transistors and other small electronic semiconductors, power diodes have a relatively simple pn junction. However, this junction requires the highest purity of construction of any semiconductor in order to minimize reverse current leakage at stress levels over 2000 volts. Excessive reverse current will destroy the device in a very short time. For this reason, 99+% pure polycrystalline silicon (made from basic "met silicon") must be further refined to 99.999999999+% single crystal silicon before attempting to create pn junctions for high-voltage power diodes.

In the late 1950's there were two then three methods of doing this.

1) Orienting properly one piece of polycrystalline silicon and one piece of single-crystal silicon --but not all of it-- and melting them together. The boundary between the solid and the liquid part must be carefully moved away from the single crystal piece throughout the region of all the material being used. As the molten liquid cools from about 1400 deg.C, it will be transformed into a single large crystal with the same pn orientation as the original small piece of single crystal silicon.

2) A second method---which is almost universally used for 99.999999% pure requirements, i.e. low voltage transistor, LED, MOSFET, is the Czochralski method, as noted in Chapter 1 Section C.

3) A third way to obtain the required purity for a power device is called the float-zone(FZ) method. This technique involves the welding of a large rod of polysilicon to a small piece of single crystal silicon. Then a small ring heater is placed right at the point where the two dissimilar silicon pieces are joined. By melting the silicon slowly towards the end of the polysilicon rod, nothing will touch the silicon—unlike the Czochralski method--and this was the highest purity silicon possible at that time (one part impurity in 10 billion parts).

Preparing the pn junction from the high purity single crystal rod also gave rise to three forming techniques:[3]

1) grown junction
2) alloyed junction
3) diffused junction

The last method is used today to ensure that the power diode will have the lowest forward voltage drop (Vf) in conduction ---typically 0.6vdc to 0.8vdc--- to minimize the thermal heat generated by currents up to 2000 amperes. 2000amps x 0.8vdc results in 1600 watts of heat that must be dissipated to keep the diode wafer from thermal runaway and destruction.

Power diodes are made in wafer sizes from 3mm diameter ---typical of the six power diodes in every automobile alternator--- to over 75mm diameter. Their cases or housings go from 1/4 inch studs (normally the cathode) to 3/4 inch studs. At this wafer size, the 800 to 1200 watts of heat generated by the forward voltage drop (Vf) becomes a serious heat transfer problem. The different thermal expansion rates of the copper mesh cable and the copper stud from that of silicon can cause cracking and/or debonding of the silicon wafer sandwiched between the copper of the anode and that of the cathode. Fortunately, the simple pn structure of the silicon structure allows junction temperatures up to 200 deg.C. This is 50-80 deg. Higher than any other silicon power device.

Production costs plus thermal problems led the industry to develop the "hockey-puck" design which sandwiches the silicon pellet, already bonded to its baseplate, between two flat copper poles. This type of package has been available since the late 1960's in diameters from 40mm to 120mm as a standard product. It is now offered by several companies as their only package for a single device. The corresponding wafer sizes are usually from 12mm (150amps) to 30mm (600amps) to 100mm (2000amps and more).

From the blocking side, the reverse leakage current (Ir), is driven by transient spikes on the main AC or DC powerlines connected to the diode. Ir must be minimized to ensure the diode does not go into the destructive reverse avalanche condition. This failure can usually be seen as a thin burn track at the beveled edge of the diode wafer. Shaping the edge of the power-diode diffused junction in order to maximize the peak reverse voltage (Vpiv) capability of the diffused wafer is a difficult job. This shaping generates a small beveled angle across the pn junction anode down to the cathode line of the approximate 0.3mm silicon wafer where it is bonded to its 1-2 mm thick molybdenum or tungsten baseplate.

The baseplate material must have a coefficient of thermal expansion as close as possible to that of the silicon wafer that is soldered and/or bonded to it. Only molybdenum or tungsten are suitable for the baseplate. Even then, silicon's thermal expansion coefficient is half that of these two baseplate materials.

Another characteristic of silicon diodes (as well as thyristors) is their "reverse recovery time", and the high voltage spike that occurs in the process. This is a result of the silicon material recombining itself to block in the reverse direction. Unfortunately, the "doping"[5] of the silicon to obtain a low Vf ---to minimize heat losses in the conduction mode of the silicon--- also increases the reverse recovery current and the resulting "turn-off" voltage spike. This is only of minor consequence for most AC electrical heating or motor control applications, but one needs to be aware of this for power-diodes used in other areas such as DC power supplies.

B: The **silicon thyristor**, originally called "SCR" (Silicon Controlled Rectifier) by its creators[4], quickly followed power silicon diode technology simply because it was a "power-diode that blocked electrical current in both directions until it was given a gate signal to turn ON in the forward pn direction". The only way it could be made to turn OFF was to bring the electrical current down to a value that was below the SCR's "holding current" ($\mathbf{I_H}$). This value is normally only 50-100 milliamps.

Figure 1a. 30mm Power Diode Pellet

Figure 2a. 30mm Power Thyristor Pellet

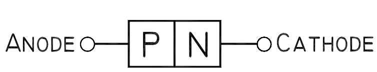


Figure 1b.

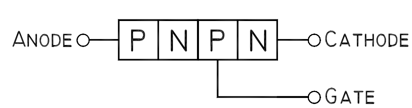


Figure 2b.

Referring to **Fig.2b**, one can see that the SCR has 3 junctions, left-to-right: J1 (P-N), J2 (N-P), J3 (P-N), and three operating modes:

1. **Reverse blocking mode**: V_{piv} can be applied exactly as with a diode, where junctions J1 and J3 are reverse biased, and only leakage current, I_{prv}, will flow. This is usually less than 1-2ma.

2. **Forward blocking mode**: V_{drm} can be applied in the direction that would cause a power diode to conduct, but the SCR retains its blocking ability.

3. **Forward conducting mode**: V_{bo} can be applied (with a properly doped pellet) to cause "2 terminal breakover" or non-destructive avalanche turn-on across junction J2. This unusual characteristic has been used for many years by Payne Engineering Co. to ensure that when two SCR's are used in an anti-parallel connection --the most common-- their V_{bo} can be specified to be lower than their V_{piv}[12]. In this manner one can ensure that the SCR's will never fail due to over-voltage. A positive current flow from gate to cathode, however, reduces the "avalanche turn-on" to just 1-2vdc. This is the normal "switched" high-current operating mode.

A thyristor uses a silicon structure that is similar to that of the power-diode as described above. The major difference is that another pn junction is joined, in series, with the standard diode pn junction as shown in **Fig. 1b** and **Fig. 2b**. When electrons are injected into the 2nd "p" region by way of the GATE terminal, and the anode to cathode voltage is greater than 2-5 volts, an "avalanche condition" is reached and forward conduction of DC current will take place.
However, the external circuit resistance has to be low enough to allow the DC holding current, I_H, to flow freely. **This is the primary reason why one cannot test an SCR with no load, a user mistake that is all too common, even today, more than 50 years after the first applications of thyristors.**

Once the SCR is turned on, the "p-gate" n junction is opposite in polarity to the other two junctions, and the On-State voltage drop of the SCR, **Vf,** is similar to that of a simple power diode plus the series resistance of the silicon pellet itself. Unfortunately, this forward voltage drop ---a similar heat generator as the power diode--- increases with temperature and RMS current flow. The SCR **Vf** is not only higher than a power diode ,1.4vdc vs. 0.80vdc, but the more complicated silicon structure of the SCR reduces the maximum allowable case temperature to 125 deg.C (for zero amperes) or to 100 deg.C for reasonable operating currents. Typical power diodes of similar pellet size can operate at full-rated current 50-100deg.C higher than the SCR.

The reverse voltage, **Vpiv**, characteristics of the SCR ---owing to the single pn junction effect--- is almost identical to the power diode. But, this silicon device has several other peculiar characteristics that many inexperienced circuit designers fail to take into account:

1) Turn-on time:

T_d, is the time, typically 1-2 microseconds, that it takes for the forward voltage across the SCR to decrease to less than 5% of the anode to cathode voltage.

The turn-on time refers to the "plasma" of electrons spreading across the junction at about 0.1mm/microsecond. For larger devices over 50mm in diameter this "delay time + the rise time" can be as long as 500 microseconds (or 0.5 milliseconds). That is a relatively long time when one considers that one half-cycle of the AC power mains is only 8.3 or 10 milliseconds.(60hz vs. 50hz power).
The AC power mains are usually capable of supplying over 10,000 amps (10kA) at voltages from 240vac to 600vac. Most industrial plant mains will range from 15kA to 50kA. Since the SCR's primary use is to switch each AC half-cycle to the ON state, one must think very hard about the consequences of this "switch" in these applications.

Example:
A single SCR device can switch a 480vac half-sinusoid into a "load" of 1-2 megawatts quietly and efficiently for years or even decades. But if a user makes a mistake and/or the "load" impedance goes to zero, (i.e. a bolted short-circuit fault), the SCR switch will allow the full mains "available fault current", usually between 10,000 amps up to 50,000 amps, to flow "right now". The resulting mass destruction of a poorly protected switch room and the copper bus-work has to be seen --and heard-- to believe it.

An SCR is only a simple "ON" switch. It does not turn off the power from an industrial main*. Only by decreasing the SCR current to less than the I_H holding current, typically 100ma,(by having the decreasing voltage of a typical industrial half-sinusoid go to zero) will the SCR go into the "OFF" state. Power diodes are worse since they are always "ON" in the forward polarity direction.

If either device suffers PIV reverse voltage failure or over temperature due to lack of proper cooling, one can have an "industrial strength" massive failure. The result is normally a "welded contact" melting of the silicon pellet in the SCR case.

No disconnect switch or "circuit-breaker" is fast enough --as of this writing-- to prevent a loud, "bolted-fault explosion". There is, however, a relatively simple way to prevent any damage whatsoever. All power silicon ---that is directly connected to the AC mains--- must be protected with a "2 millisecond" FUSE [11]. So-called "I^2t" fuses will not be sufficient simply because we have found several American and foreign fuse manufacturers whose "I^2t" fuses do not melt at the peak currents they claim or they simply clear in ½ cycle when the "mains current" through the SCR declines to zero. On several occasions we have observed and recorded these so-called "I^2t" fuses explode. Our company, located very close to a 2900megawatt utility power plant, has a robust 14,000 amps of "available fault current" for our fuse tests, but there are many plant installations that have 2-3 times that value.

As an aside, if any engineer says that their product is tested for 50ka or 100ka, ask him to show where and how this test was conducted. This writer has witnessed fuse tests at 650vac and 29,000 amps which took out an entire busbar-supporting masonry wall in a chlorine plant power room that was connected to a 47,000kva service-entrance transformer. The measured peak available fault current was only 29,000amps instead of the owner's claimed 56,000 amps.

*So-called GTO (gate turn-off) thyristors had limited usage in certain custom-built inverters many years ago. Today, the IGBT power transistor has virtually replaced the GTO SCR in all low-voltage, up to 650vac, applications.

Now let us look at several considerations dealing with turning on the junction of the SCR:

a) Vbo avalanche turn-on:

Previously mentioned in the Zener diode section, as well as in 3. above, avalanche turn-on is a current multiplication process that occurs only in strong electric fields. Therefore, any mechanism that can increase the energy of the electrons at the middle pn junction (J2) of a 4-layer semiconductor is potentially capable of turning on a SCR. The high-energy electrons knock more electrons out of the silicon atoms leaving holes which then accelerates the process even faster until the junction turns "ON" with a non-destructive ---if the junction is not heavily doped with impurities--- flow of a current "plasma" as previously discussed. The normal means of achieving this are:

a) Vbo
b) dv/dt or rate of change of the anode-cathode voltage
c) Minimum gate turn-on
d) Igt or the "transistor effect"
e) Radiant energy or light activated SCR, i.e. LASCR

b) dv/dt turn-on:

All pn junctions have capacitance, and this capacitance is directly proportional to the size of the pn junction. If a steep rate of voltage rise (microsecond "noise spikes" on the mains) is impressed on the junction, a charge current will flow which exceeds the dv/dt rating of the silicon, typically, 100v/usec. causing instant turn "ON".

c) Minimum gate turn-on current:

Similar to the di/dt failure is the tendency of circuit designers to apply insufficient gate turn-on voltage to drive the plasma-spreading all the way across the area of the thyristor. In order to save on the gate circuit power source, this type of failure may not damage the thyristor for some period of time. Then the inevitable failure occurs which may be attributed to some other false reason. Unfortunately, the power semiconductor manufacturers have often oversold the simplicity that anyone can bolt their semiconductor blocks on any commercially available heatsink with any microprocessor --all the rage—driven trigger circuit without consideration of these basic characteristics of the modern thyristor.

d) Igt or the "transistor effect"

If $\mathbf{V_{drm}}$ is high enough to drive sufficient $\mathbf{I_H}$ holding current through the circuit, then a proper $\mathbf{V_{gt}}$ and $\mathbf{I_{gt}}$ applied to the gate terminal will turn the SCR "ON" immediately. A short pulse can do this as well as a full ½ cycle DC level, if the load current is not too inductive. For a highly inductive load, a single short pulse may be insufficient. A chain of pulses or a DC square-wave will be necessary in this case. GE used its previously developed unijunction transistor for this application to minimize gate losses and to simplify the SCR "trigger circuit". Prior to this, some of the first SCR Power Control manufacturers used large, inefficient, magnetic amplifiers to provide their gating circuits.

e) Radiant energy turn-on:

Radiant energy within the spectral bandwidth of silicon striking and penetrating into the silicon atomic structure can release a large amount of hole/electron pairs. When this energy reaches the level of minimum **Igt** level, the device will turn ON. Thyristors with a translucent area cut into the SCR package will allow it to be turned ON by light or by the more traditional gate current level.

2) di/dt limitations:

As previously described in 1), "the turn-on" of a thyristor takes place very rapidly, a few microseconds in 3mm-22mm diameter pellets. With center-gate devices, see **Fig.2a**, a good visual analogy of this is similar to throwing a pebble into the middle of a small pond. The concentric waves emanating from the pebble splash simulate the plasma spreading electrons from the gate. Unlike a pond, however, if a large source of electrons, from a capacitor, or a high current flows immediately from anode to cathode before the electron plasma has a chance to turn-on the complete bulk silicon area, all this fast flowing current will try to crowd into the very first 2-3mm of silicon just around the gate. This small "ON" area will quickly overheat from the fast rising anode-cathode current and melt the silicon around the gate into a "welded" condition. This destroys the device.

This condition is termed a "di/dt" failure. All thyristors have specified maximum values of di/dt from typically: 40amps/usec. to 150-200amps/usec. This parameter has become fairly standard for resistive and inductive loads at 50/60hz. For inverter-class, high frequency, fast turn-on thyristors, these values are too low and will require specialized gate constructions that energize the plasma spreading over a much wider area of the silicon pellet.

For conventional thyristors, one can easily cause di/dt failure by simply using an incorrectly sized RC protection "snubber" network (used to prevent random dv/dt turn-on). Too large a capacitor combined with a low ohmic value of the R, damping resistor, will result in a di/dt failure of the thyristor in only a few hours of operation.

For the unwary, a similar di/dt failure can be caused by phase-angle control into a large filter Capacitor that are commonly used on DC power supplies.

3) Reverse gate bias (also "shorted emitter" structure)

is often used as a method to improve the dv/dt capability of the thyristor, in addition to the RC snubber and the device's inherent rating. The reason for this is that if a solid-state power control is to be used to replace the standard electro-mechanical contactor, (which have an air-gap in the OFF state or "galvanic isolation"), it must be up to the job in every way. Customers will not want to coddle the "new solid-state" technology for its peculiarities if it is truly going to replace the old way of switching large amounts of electricity. A simple 1/2w 100ohm resistor connected from the thyristor gate to cathode connection is sufficient to nearly double the thyristor dv/dt capability.

4) Temperature Limitations:

One must realize that the zero-current case-temperature of all standard thyristors has been, since 1960 or so, limited to 125deg.C. There are power-control manufacturers, even today, who are totally unaware of this basic factor in the application and cooling of power thyristors.

EXAMPLE-1:

In the 1960's the SCR had become so popular ---mainly with a companion diode--- in the DC drive industry that power semi-conductor manufacturers were called upon to make larger current size pellets from the 18mm-22mm maximum size, i.e.300 amps, that were in the largest ¾ inch stud package.

The coal mine equipment market --oddly enough-- was the driver of the ¾ inch stud power diode which was used in the thousands by mines to convert their erratic and bulky rotary motor-generator (MG) sets to the much lighter and smaller AC-DC rectifiers that they could use almost anywhere to provide heavy-duty, easily repaired-in-the-field DC power for all their underground mine machinery. Unfortunately, this large package with is copper stud and copper pigtail was labor intensive and required difficult skills to insert and "hard-solder" the silicon diode pellet.

Figure 3. 30mm Power Thyristor Pellet and Case

Figure 4. SCR-Diode Block with 15mm pellets

General Electric then introduced the first "press-pack", or "hockey puck" package in 1967. By inserting the silicon pellet in a sandwich of two copper pole faces***,** one could use electron-beam automatic welding to seal these three metallic pieces in a simple ½ inch or 1 inch thick disc construction, see **Fig. 3.**
The customer supplied an appropriate clamp to squeeze the disc SCR and/or diode between either one or two flat-based aluminum copper extrusions. This package design solved the high-current heat transfer problem by maximizing the amount of conduction heat transfer with the lowest possible voltage drop from the pellet to pole-face to the flat surface of the heatsink extrusion. In 1987, just before GE decided to close up their main power semiconductor facility in Auburn, NY, GE developed a new heavily-doped silicon to eliminate the molybdenum (or tungsten) wafer mounting disc. This silicon was tightly bonded to the SCR silicon wafer and eliminated the different coefficients of expansion that were the Achilles heel of all large SCRs.

*** In Fig.3 one can see where a well-known semiconductor manufacturer used 23mm pole faces To clamp a 30mm SCR pellet. Allegedly, “this was not a mistake”. But power control manufacturers must always be alert to ensure the overall quality of their product. This “mistake" was caught in a routine maximum power heat transfer test. In the test of a 4 SCR, 3-phase, 480vac, 600 amp power control, 2 SCRs of the exact same rating from two different manufacturers were installed in each phase. One pair ran over 20deg.C hotter than the other. On cutting the devices open, we found the pole face diameter of the "hot" SCR to be 7mm smaller than the diameter of the silicon pellet as seen in Fig.3.**

Unfortunately, we also know that many power control vendors do not do such tests simply because virtually none of their controls will pass a 50deg.C ambient plus 50deg.C "case rise" test that we have done on these company's products. This shoddy design practice is found most often on the so-called "compact DIN rail" products as well as the common practice of placing a SSR block on "stock heatsinks" sold by large electronic distributors. Another characteristic of these "compact" units is the lack of any fuse to protect the SCR control from the very common "load fault" condition. No wonder surveys[17] list "blown-up" and "overheating" of SCRs as the primary reasons for failures.

EXAMPLE-2:

In the mid-1970's a German manufacturer of power-semiconductors introduced a product line of so-called "semiconductor blocks", see **Fig.4.** This was considered an ingenious innovation simply because it solved a thyristor packaging problem while allowing the semiconductor manufacturer's to sell 2 SCR's in one package, or 2 diodes, or one diode and one SCR. Even four or six devices have been successfully marketed since that dismal introduction. This also simplified mounting and cooling these blocks dramatically. Wonderful……., the semiconductor manufacturers get a higher price, the control manufacturer does not have to think or use any brain power to build a power-control. Easy!!!!!.

But all this simplicity, etc. comes at a high price. How can one cool two power semiconductors when they are mounted only 10mm or 16mm away from each other? Not to worry, "we will use special heatsinks designed for fan or water cooling". "We can also make the control much smaller which will please our customers".

Reality, unfortunately, tells a different story. SCR over temperature failures became so common that control manufacturers started offering "failed SCR detection". Surveys [(17)] by various technical journals in this country are overwhelmed with the customer's number 1 complaint: **"Why do SCR controls have such a high failure rate"?????**

Do a close inspection of **Fig.4.** This "block" uses two thyristors, that can be rated by the unscrupulous for over 150 AC amperes when connected as "an AC Switch" inverse-parallel circuit. Even the manufacturer of this block has a rating data sheet showing that a massive, 4kg, fan-cooled, 0.3deg.C/watt, heatsink would be required to keep these two thyristors from melting down at any ambient temp. over 50deg.C.

Further inspection will also reveal the "classic overtemp." at the baseplate location of the 15mm silicon pellets as they were trying to dissipate the 170-200watts of heat they were generating at greater than 150amps.

The only way one can safely and reliably use such blocks is to have them custom-built with only one thyristor centered in each block. Putting 2 of these single thyristor blocks on a more reasonable 2.5kg, 0.55deg.C/watt natural-convection heatsink will now provide a 30% temperature safety factor without risking fan or water cooling failures.

*** * * * * * *Understanding the semiconductor's current and temperature rating data: * * * * * * * ***

Most rating sheets for phase-angle and zero-fired SCR's are a graph of case temperature in deg.C (y-axis) vs. average current in amperes (x-axis) for different phase-angle degrees of conduction. For general usage into resistive and motor loads, one can choose the 180deg. conduction plot down to 90-100deg.C. At this point, note the x-axis average current for one SCR, divide by the rms/average current ratio for an AC switch (0.455) to find the true RMS current through 2 anti-parallel SCRs.

100 deg.C case temperature allows for a 50 deg.C ambient temp. with 50 deg.C temp. rise of the SCR's at their design current level. Note that the "zero ampere" case temperature is only 25-30 deg.C higher than this design point. This is probably the single most important reason that proper design NEVER places 2 power semicontors on a single heatsink with only a few mm of separation.

5) Sensitivity to radiation exposure.

a) Fast neutron bombardment of silicon results in permanent damage to the crystal lattice which will increase gate current requirements as well an increase in the devices holding current. It is less damaging to lower voltage SCRs where the thickness of the n and p junctions is less than those pnpn structures for higher power silicon.

b) Gamma radiation --electron excitation-- provides high energy electrons which would simply act as a "spreading plasma" or leakage current that would cause the SCR to turn on when it was in its normal OFF state.

C: Triacs:

Bill Gutzwiller, with his knowledge of SCR power circuits, invented the TRIAC bilateral switch which greatly simplified the circuitry of static switches and phase-angle by taking the place of two back-to-back SCR's and much of the associated control components. For General Electric's Power Semiconductor division in Auburn, NY this was the first economical "breakthrough" that would bring solid-state power control into the vast commercial market of appliances, light dimmers, hand tools, sewing and vending machines. It was Gutzwiller's third patent, granted in 1966 after his SCR patent in 1962 and control systems patent in 1965. He and Gordon Hall had assembled a small team of 7-8 engineers who were very good at creating the first SCR manual in 1960 while writing application notes at a furious pace to show GE's customers how to properly use these new power semiconductors for safe and long term reliability.

The TRIAC is similar to an SCR in being able to switch kilowatts of AC power in both directions: anode-cathode and cathode-anode. It is an AC switch not just a DC switch as is the SCR.

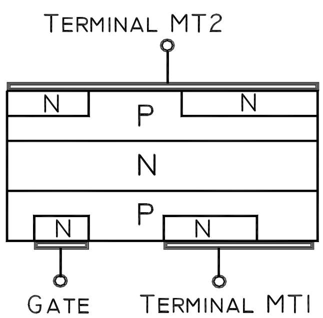


Figure 5a. Simplified Pellet Structure

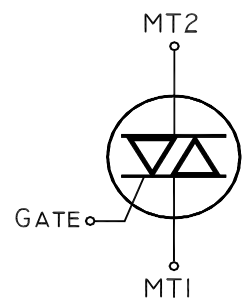


Figure 5b. Circuit Symbol

However, the basic silicon pellet structure for such a device is more complex than a SCR, and this complexity creates a number of limitations on its usage.
Note Figure 5a, which shows the necessary modifications to the basic SCR pnpn silicon structure.

-to be continued-

D: Large silicon MOSFETS and IGBT's.

E: Silicon-carbide thyristors and diodes.

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