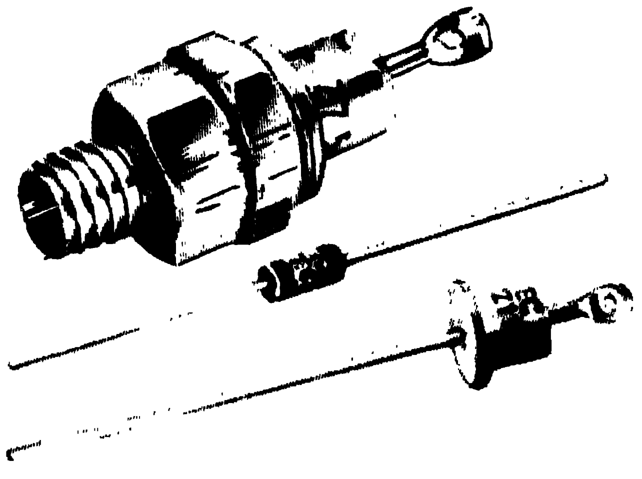
Zener Principles Revisited

(PART - I)

A.V. Jacob



The boundaries of electronics are continuously expanding due to the revolutionary conceptualisation and fabrication of electronic devices. The province of 'device-and-circuits' did not surrender to the explosive flare-up of integrated circuits, which started in the early 1960's. Even though among the jungle of integrated circuits discrete components got reduced to a mere blemish, which spoilt the beauty of the PCB layout, nobody could question their capabilities in protecting the organised jungle. Discrete transistors and diodes still enjoy superiority in the functioning of most silicon marvels. In recent years emphasis has been almost completely on the development of the semiconductor diodes.

More than a dozen semiconductor diodes have come to the fore in the last few decades. Of these rectifier diodes including detectors, zener diodes and LEDs are ubiquitous. The development of discrete devices, such as transistors and diodes and their associated technology, did not come about overnight. Much research by many companies and institutions was needed for more than three long decades and millions of dollars were spent. But through many decades the pace of technological progress changed dramatically. The integration of several existing technologies paved the way for an envisioned chaos. Many of the discrete components had ceremonial burials in the substrates of integrated circuits. Fortunately, the life and times of such devices could be investigated without formal exhumation.

Zener diode is not a babe in electronics. In the first half of the 1950's zener devices entered into the world of silicon marvels just as a condiment amongst transistors, resistors and capacitors. By its very nature a zener diode looked like an ultramodern device, and hence designers who wanted to move with the times were too eager to go in for it. The concept of zener breakdown seemed a harebrained idea at first, but then it proved that it could revolutionise "Electronics under the Sun." Now the zener kingdom is spread from the discrete components to VLSI, and it continues to expand to each and every possible nook and corner of electronics. Present-day electronics can survive without zeners, but cannot flourish. In popularity, zener devices are second only to transistors. If properly designed, one can install a zener device in a circuit and forget it.

The story of zeners began as early as in 1934, much before the deluge of discrete semiconductor devices. Dr Clarence Zener, an American physicist, predicted the possible breakdown mechanism (see box) in dielectrics or insulators. Later when semiconductor junction diodes were fabricated and used, three possible breakdown mechanisms were observed and one of them was exactly what Zener had predicted. The remaining mechanisms, Avalanche and Tunnel, are also extensively observed in junction diodes under suitable doping concentrations and applied potentials. Diodes rooted from these three breakdown conditions are available worldwide. Modern zener diodes are as wrongly named as they are unfairly treated. If a device has to be named after the innovater it should be 'zeners' below 4 volts and 'avalanche' above 8 volts rather than only zeners, because most of the zeners are produced to operate in the avalanche region, which has an altogether different breakdown mechanism.

The quintessential zener breakdown occures only below 4 volts of reverse bias while avalanche takes place above 8 volts of reverse bias, and both these are present between 4 and 8 volts. Nowadays, the zener and avalanche mechanisms are collectively known as 'zeners', even though their modes of operation are essentially dissimilar. This quizzical situation was forced on the consumer by the electronics *pundits* in the early 1950's. The vague outlines of compromise do exist in the imbroglio.

Zener parameters

The critical parameters of a zener diode in practical designs could be defined with the help of an ideal zener model. A simple but workable zener model is a combination of a battery of voltage V_Z connected in series with a resistor R_Z. A current I_Z flows opposite to the direction of V_Z. For a given family of zener diodes, principally three fundamental parameters decide the nature of its function (see Fig. 1). They are V_Z, R_Z, and I_Z. The derived supplementary parameters are: power capability, operating temperature, temperature coefficient, noise factor, peak inverse voltage, junction capacitance and package.

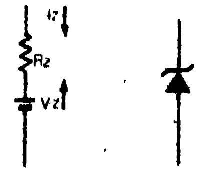
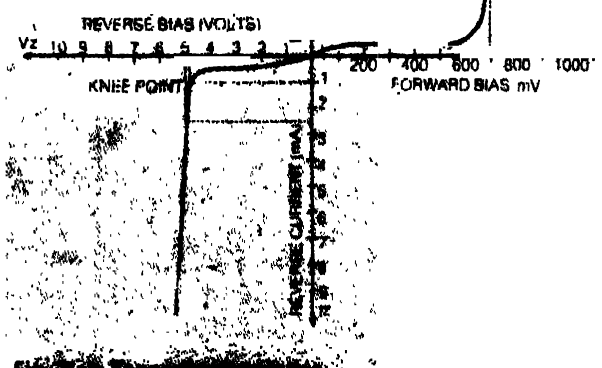


Fig. 1: Ideal Zener Diode.

Zener breakdown voltage, better known as 'zener voltage', ranges from 3.3 volts to 200 volts. The preferred values are 3.3, 4.7, 5.1, 6.2, 9.1, 10, 11, 12, 13, 15, up to 200 volts. These voltages could be increased in steps of 'contact potentials' of germanium or silicon diodes (0.3V and 0.6V), by connecting in series with the zener devices. For special applications there are high-voltage zeners which are tailored according to the needs of the specific problem. Just like resistors, zeners are also tattooed along with its tolerance. A near zero per cent of 20% tolerance levels are normally found in the market. As a standard norm, with no suffix on the device type, tolerance level is 20%, a letter A is added for 10% and letter B means 5%. However, this is not a hard and fast rule. There are different standards accepted by various manufacturers. Tight tolerance zeners with 1% to 3% are also available in the market. Moreover, data sheets specifications do not necessarily always show the same characteristics for the similar type of zener devices.



[illegible]

Zener impedance R_Z and zener current I_Z are interrelated (Fig. 2(a)), simply because reverse breakdown voltage is not totally independent of zener current. However, the steepness of the zener region depends on the doping at the time of manufacture. The resistance in this region falls to a very low and constant value. It implies that when a zener diode is operating in the breakdown region, a small increase in voltage will produce a large increase in current. Indeed, zener impedance increases with the increase in breakdown voltage. A 12-volt zener 1N4057 has an impedance of 25 ohm, a 75-volt zener 1N4073 has 250-ohm while 1N4085, a 200-volt zener has 1350-ohm at a specified current level. The maximum occurs at the 'knee current'. Below the knee current dynamic impedance shoots into a very high value. Zener impedance is an influential factor in voltage reference circuits.

In the majority of the zener devices in order to operate over its knee voltage or in its well defined region of operation a current of about 1 mA must be applied through the device. The maximum permissible value of zener current is always restricted using a resistor in series with the zener. It is safe to use the zener in its recommended current range. An easier and popular term 'power rating' is more expressive because it is the product of zener breakdown voltage and maximum zener current. Commonly available power ratings are 400mW, 1W, 3W, 10W and 50W. Other power ratings are also available for specially tailored devices. As in the case of any electronic component, a safety margin of 25% to 50% is generally adopted to avoid possible high drain complications.

Power derating with ambient temperature, a common weakness with the majority of semiconductor devices, is perhaps maximum in the case of zener diodes. For example, a 250mW, 5% tolerance zener 1N4099 has a derating factor of 1.44mW/°C. This zener can dissipate 250 mW at 25°C, 200mW at 50°C and 125 mW at 100°C. In power devices, package and related heatsink designs are adequately pertinacious. Zener diodes are available in different packages such as light-weight (0.2 gm) hermetically sealed rugged all-glass case to heavy (30 gm and above) screw-cap types. Heatsink facilities are provided in high-wattage zener to encounter the heavy derating factors. Usually low-wattage (25W) soldering irons are preferred and soldering should be done very quickly, even though they have a rated soldering time of 60 to 90 seconds. In case the terminals need to be bent, a distance of 5 mm from the body surface should be left before bending the terminal leads as needed. Normal non-destructive storage temperature is around -55°C to 175°C.

Low-power zeners are available either in hermetically sealed cases of metal and glass or in plastic encapsulation. The former work better at higher temperatures and are reliable in severe environmental conditions. Plastic devices, which are historically unrelaible, have been drastically improved in recent years. They have remarkable reliability when operated in their specified conditions and are usually less expensive than the hermetically sealed devices.

Zener diodes, like any other diode, do possess a forward breakdown too! This parameter varies from device to device within a range of 100 to 1000 volts. A viable arrangement for only forward biased end results may be problematic because of the existence of negatively biased breakdown voltage. However, a controlled forward biasing is not at all destructive.

Junction capacitance, which yields no useful results in zener diodes, regulates the speed parameter in its switching operations. Typically, it varies from 20 to 700 pF. For any family of zener diodes, junction capacitance decreases with the increase in reverse voltage because of the expansion of 'depletion region'. For example, a 3.9-volt zener may exhibit a junction capacitance of 500 pF while the capacitance is 10 pF in a 100-volt zener diode. Temperature is one of the factors which helps fluctuate the junction capacitance in zener devices

Thermal dependence of zener and avalanche mechanisms are opposite in nature. Avalanche breakdown, which occurs above 8 volts, increases with temperature while zener breakdown voltage decreases with temperature. Between the pure zener and pure avalanche types of breakdown there is a region in which temperature coefficient is zero. Zener diodes with reverse breakdown around 6 volts exhibit this characteristic. The majority of buried zener diodes in integrated circuits have selected a breakdown voltage closer to the zero region of the temperature coefficient. Temperature-compensated discrete zener diodes are made by exploiting the differing thermal characteristics of forward and reverse biased junctions. A forward biased junction has a negative temperature coefficient of approximately 2mV/°C and reverse biased junction up to 5 volts has a positive temperature coefficient of same amount.

Because of the overlapping of the characteristics of zener devices, temperature coefficient takes a near zero level at a definite optimisation point. If this current is maintained by a well-regulated constant source, thermal drift could be eliminated. An ordinary rectifier diode biased in forward direction connected in series with a reverse biased zener also can neutralise the temperature drift to a considerable extent. Often a well-defined cluster of forward and reverse biased junctions results in a highly reliable drift-free zener reference (Fig. 2(b)).

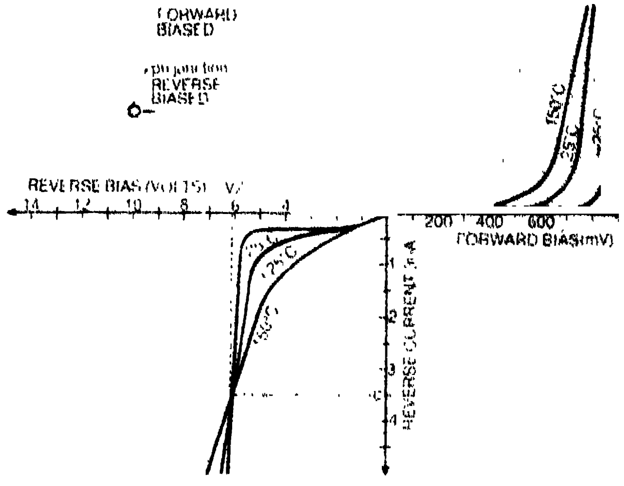


Fig. 2(b): Temperature compensated zeners.

Zener noise

Zener devices generate noise when they are biased in the zener range. It is classified into 'microplasma noise' or 'white noise' which usually emerge with constant amplitude up to a frequency range of 200 kHz, and 'resistive noise' due to the internal resistance associated with the device. For zener diodes,total noise density exceeds 250 microamperes.

Microplasma noise is the major constituent of zener noise density. This is closely related to zener breakdown phenomenon. Since zener devices are doped heavily, the electric field across the depletion region is very intense, of the order of 300k volts cm $^{-1}$. This can disrupt the bonding pattern within the atom and generate carriers in excess. Under the reverse bias conditions, charge carriers could be drawn through a narrow depletion region

TABLE I

Variation of Temperature Coefficient, Impedance and Knee Current of JEDEC Registered Zeners

Type	*Zener Voltage* Z_z *volts*	I_{zt} *mA*	Z_{zt} *Ohm*	dV_z *Volts 25°C to 100°C*
1N 4057	12.4	10	25	0.047
1N 4059	16.8	10	30	0.063
1N 4061	21.0	10	35	0.082
1N 4064	30.0	10	50	0.113
1N 4066	37.0	7.5	80	0.139
1N 4069	51	7.5	110	0.191
1N 4071	62	7.5	135	0.232
1N 4074	82	5.0	270	0.307
1N 4078	105	2.5	700	0.394
1N 4081	130	2.5	840	0.488
1N 4083	150	2.5	1020	0.563
1N 4085	200	2.5	1350	0.750

without chaotic collision between charge carriers and molecules. Under this tunnelling process a constant amplitude noise voltage of many different frequencies are generated. Indeed, noise density increases sharply as the current increases. Typically, noise density is around 35 microvolt per square root cycle at 50 microamperes and comes down to 10 microvolts at 0.5 mA (for 1N4115)

The 'resistive' type zener noise is similar to thermal noise. Conduction band electrons, which are loosely held by the atoms tend to move randomly in different directions, colliding with other atoms in the structure. The resulting noise has a wide spectrum. The amount of noise produced is dictated by temperature, bandwidth of the system and the size of the zener device. Normally, this type of noise voltage increases with temperature, bandwidth and zener resistance. Zener noise density is specified and the bandwidth, junction temperature, and the current level at which the system is operating.

Elimination or reduction of zener noise at lower frequencies can be done by a properly selected filter capacitor. However, in many applications, this method may result in the degradation of voltage regulating properties. Moreover, zener capacitance decreases as the zener voltage increases. High-voltage zener bridle the propagation delay than the lazy low-voltage conglomeration.

Under the biased conditions any junction can be re-

The Zener Story

The innovations of an American Physicist Clarence Melvin Zener on the behavior of the dielectrics subjected to high voltage were first cited in the Proceedings of the Royal Society of London. According to his theory, the breakdown in dielectrics is asociated with the inter-band transitions induced by very large fields (10^6V cm^{-1}). In these high fields electrons could be disrupted from the valence band and raised to the conduction band. This process is fairly fast enough to produce a large breakdown current. Zener's "theory of dielectric breakdown" did not hint at any immediate practical possibilities in the dormant world of semiconductor technology. Even Zener could not have fully appreciated the relevance of his investigations to the Silicon world.

During the late 1930's and early 1940's, silicon and germanium received a great deal of attention for the fabrication of contact diodes. By this time the effect of impurities, which deteremined the electrical behavior of semiconductors, was understood without much ambiguity. Techniques to grow single crystals of silicon and germanium had also reached near perfection. Before long, p-n junction diodes and transistors came into existence. Amazingly, the phenomenon of breakdown currents was observed in the p-n junction diodes too! This resulted in the generation of a new class of [illegible]iconductor devices called 'zener diodes'. In the early 1950's production of zener diodes matched the production of transistors. Zener devices won wide acceptance among consumers, mainly because of their ability to excel over the giant cold cathode gas-filled voltage regulator tubes. To top it all, just as today, miniaturisation become a primary criterion of electronic devices.

In the year 1958, breakdown mechanisms in the p-n junctions gave a complete and clear-cut picture, by the prediction of the tunneling effect in the germanium p-n junction by Dr Leo Esaki, a reputed member of a small research group at the Sony Corporation, Tokyo. Another mechanism, called avalanche breakdown, was also observed in p-n junctions. This showed that there are three possible mechanisms in the breakdown of p-n junctions, viz, zener or field emission, avalanche and tunneling mechanisms. Zener effect is predominant below 5 volts while avalanche takes over above 8 volts, and both these effects are present between 5 and 8 volts. Incidently, a majority of the present-day zener devices have breakdown voltages exceeding 8 volts. Since zener diodes include avalanche and zener breakdown mechanisms in various voltage levels, their christening was only historical — not functional. Critics got the bone of contention; zener diodes are a technical misnomer. Indeed, Clarence Zener is not only a genius, but also very lucky!

Born on December 1, 1904, Zener hails from Indianapolis, America. He was educated in Stanford University and finished his Ph. D from Harvard University in Physics. The majority of his innovative works were completed while he was in Bristol University, England. Later he taught Physics in Washington University and City college of New York. During the peak of the Second World War he joined the University of Chicago as a Professor of Physics. After the War he accepted the associate directorship of research laboratories in Westinghouse Electric Corporation. In the late 1960's Carnegie-Mellon University, Pitsburg, accepted him as the professor of Physics. He is a reputed member of National Academy of Science of the U.S. Within this span, Zener received numerous covetable awards in Theoretical Physics and Engineering.

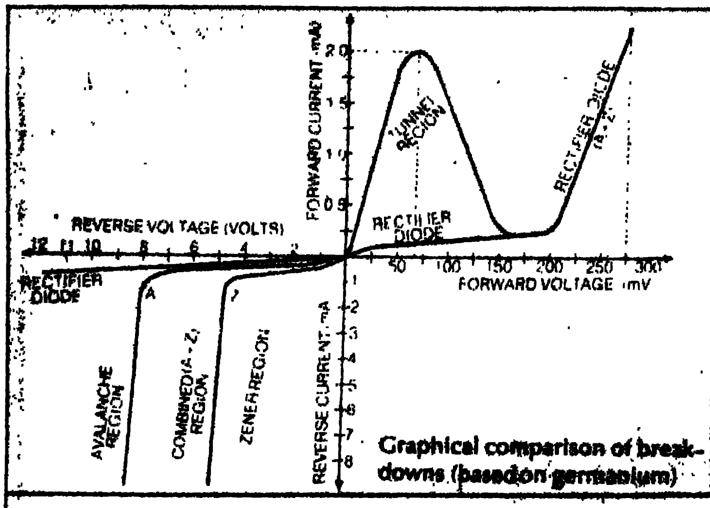
Before Zener

Long before the advent of zener diodes there was a group of electronic dinosours called 'cold cathode gas filled voltage regulator tubes'. These are filled with inert gases such as neon at proper pressure. A constant voltage drop is developed across the tube when the gas is ionised. The property of VR tubes, which is used to regulate the voltage across the load, made them superior among their contemporary devices used for the similar purposes.

Anode of a VR tube is a thin wire at the centre of a metallic concentric cylindrical anode of very large area. If the tube gets sufficient starting voltage, a discharge will first occur on a small area of the cathode, and as the terminal voltage is increased this area grows larger, permitting more current to flow with very little increase in its terminal voltage. A current of 5 mA is required to keep the gas ionised properly, It can, however, draw currents up to 40 mA. If the DC potential across the VR tube is reversed, less current will flow through the tube, although it can regulate small load currents. In some VR tubes the anode is painted with a radioactive substance for better ionisation. If the envelope is broken it poses potential health hazards too !

Break up of Breakdown

A p-n junction diode is a combination of p-type and n-type semiconductors. On one side there are positively charged carriers called



Graphical comparison of breakdowns (based on germanium)

General Comparison of Breakdowns

Parameter	Avalanche	Zener	Tunnel	Unit
Thickness of dep. region	10^{-6}	10^{-7}	10^{-8}	cm
Impurity concentration	10^{20}	10^{22}	10^{24}	atomcm^{-3}
Breakdown voltage	above 8	below 5	below 0.1	volts
Temp. Coefficient	positive	negative	stable	
Bias	reverse	reverse	forward	
Frequency	1M	100K	50G	Hz
Max.current	200	3000	10	mA
Max. junction capacitance	25	200	10	pF
Max. power	100	50	0.01	watts

'holes' and on the other side negatively charged carriers or electrons. The boundary between these two regions is called a p-n junction. The junction is demarcated by a neutral region called depletion region. The net flow of charge in any one direction with no applied EMF is zero. If the n region is negatively biased with respect to the p region, current will flow because of the motion of electrons from n region into the p region and holes from the p region to the n region. If the voltage is reversed, electrons and holes will be pulled away from the junction area, resulting in a very high opposition to the flow of current.

Even if the internal current is composed of both electrons and holes, the external current is constituted by electrons only, since external conductors have only electrons for electrical conduction. Whether the semiconductor is intrinsic or extrinsic, every electron detachment from the bond leaves a hole or electron vacancy in the valence level. Since free electrons and holes are simultaneously created at the destruction of the bond, it is referred to as the generation of electron-hole pairs.

Avalanche breakdown

As the reverse applied voltage becomes larger, thermally generated electrons in the junction region are accelerated towards their opposite polarity of the applied voltage. These are normal leakage currents in any diode. A[illegible]y move through the junction, they collide [illegible]n other atoms and dislodge outermost electrons of the atoms of the rystal structure. The newly liberated lectron can then gain high velocity under the increased reverse voltage to free other valence electrons. The generation of electron-hole pairs is just like a chain reaction, and it is called 'carrier multiplication'. The whole process escalates to a point at which there is a rapid transition from a reverse blocking state to a negative conduction state. The production of free electrons is like the sliding of a mass of detached snow suddenly down a slope, thus the name 'avalanche breakdown'.

Avalanche breakdown occurs usually beyond 8 volts, and it depends upon the concentration of charge carriers. Avalanche breakdown voltage increases as the temperature increases. This is because of the amplitude of atomic vibration fixed in their lattice increases with temperature. The increased lattice vibration shortens the distance the carrier traverses before hitting the atom on its path. Obviously, a reduction in momentum follows the increased lattice vibration. Particles with insufficient momentum cannot initiate avalanche phenomenon. Hence voltage has to be raised to produce a mean momentum just enough to create an avalanche of electron-hole pairs.

Zener breakdown

A strong electric field in the region of the junction also can disrupt the bonding forces within the atoms and generate carriers. Since the depletion region is of the order of a few micrometres, the application of low reverse bias across the depletion region will produce a field of the order of 10^6V cm^{-1}. This field is high enough to separate valence electrons from their nuclei. Enormous amounts of electron-hole pairs are produced prior to the breakdown. This type of breakdown is called zener breakdown and is present below 5 volts.

The value of zener breakdown voltage decreases as the junction temperature increases. Valence electrons of the atoms in the crystal lattice acquire more energy by the increase in junction temperature. This weakens the bond pattern, resulting in the reduction of breakdown voltage.

Tunnel effect

Tunnel effect was first predicted by Dr Leo Esaki in 1958. This effect takes place in a p-n junction diode which is doped until it reaches the limit of solubility of the impurities in the semiconductor material. In this heavily doped condition the depletion region reaches the level of a few fractions of a micrometre Under a nominal external voltage, charge carriers attain sufficient energy to tunnel their way through the barrier. The velocity with which the carrier tunnels through the junction is comparable to that of light. Hence frequency characteristics are extremely high. Since the tunnel effect occurs at very low voltage, normally less than 100 mV, tunnel devices have very little power consumption. On further increase in the forward bias, tunnel diode behaves like an ordinary diode.

The White and Pink Show Off

Noise, a potential 'electromagnetic weed', is the unwanted amplitude variations of the required signal in any electronic circuit. It is unwanted simply because it always menacingly interferes with the reception, transmission or processing of the desired signals. Thermal agitation of electrons, sunspot activity, solar flares, ignition systems, to name a few, are the [illegible] amongst the circuit designers.

White noise has a complex waveform. It is found over a broad but well defined bandwidth. Theoretically, it can be constituted from all the probable frequencies up to infinity. The power density of the spectral domain is almost constant. So it has equal energy in each and every frequency domain. White noise is equally spread in the audible range too! It is just like a beam of light, composed of different colours, visible to the human eye. It may help to produce 'snow' on the picture tube, but its name has an altogether different root.

Pink noise also has many of the white noise properties. The major difference is that it contains equal energy levels in each octave of its spectral domain. The characteristic frequency ratio corresponding to the octave interval is two, each next higher octave possesses twice the number of discrete frequencies below it. Since the pink noise has to acquire equal amounts of energy in each and every octave of its spectrum, the low frequency components of pink noise have higher amplitude than high frequency domains.

Noise is often quoted in terms of signal-to-noise ratio, abbreviated as S/N. However, other units, such as volts per square root of frequency, are also popular. S/N is the ratio of the signal power to the noise power. If the signal power is 100 times the noise power, then S/N is 100. Higher the S/N, better the device.

'Noise figure' or 'NF' is another parameter used to specify the immunity of a device to the noise. For any electronic device NF is the ratio of a input S/N to the output S/N; and is usually expressed in decibels (dB). NF tends to be unity if the device does not add any noise to the desired input signal. A higher NF of a device is an indication of its weakness in protecting the desired signal from the expected assault of noise voltage.

garded as a parallel plate capacitance. This parasitic capacitance, better known as 'transition capacitance', is related inversely as the width of the depletion region. An external capacitance parallel to the zener increases the capacitance effectively, which in turn decreases the resonant frequency of the circuit.

The diac controversy

The 'diac' a bijunction, negative resistance pnp triggering device, appeared in the market with an unfortunate and misleading symbol, that has no resemblance to the actual functions of the device. The unfortunate symbol was a combination of two back-to-back zener diodes. Later it changed to another confusing symbol (Fig. 3(b)) which directly hints at a parallel combination of diodes. However, the symbol shown in Fig. 3 (c) is gaining popularity and is more meaningful since diac consists of two junctions which are heavily and equally doped to project a mirror image breakdown characteristics. Its structure is essentially that of a transistor. The device blocks the flow of current for both forward and reverse voltages up to the breakover voltage V_{bo}. On further increase in current, the diac exhibits a negative resistance region.

Zener nomenclature

More than 600 types of zener diodes have been registered with the Joint Electron Device Engineering Council (JEDEC), and a few thousand have been marketed under the manufacturers' type number. It would be a Herculian task to bring all the zener devices manufactured and marketed by different agencies into a single volume. In India itself more than 15 manufacturers are in the field. Few of them follow JEDEC specification, and the rest are adherent to Continental nomenclature in addition to their own house numbers.

According to JEDEC designation, all semiconductor diodes are identified by the prefix 1N, which hints at the number of junctions involved in the function of the device, followed by a sequence number. Well over a thousand semiconductor diodes have been specified by JEDEC and 60% of them are zeners. About 200 zener devices have an associated temperature compensation, the remaining zeners are meant for general purposes.

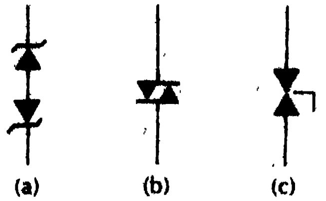


Fig. 3

Continental systems had adopted a collection of two letters followed by a serial number. Usually B or C will appear as the first letter, in which the former represents silicon based devices and the latter stands for gallium based devices. The second letter is Z, indicating that the device is a zener diode. The numbers may represent the type of application. A version letter, which usually appears at the end, is used to designate the tolerance. In addition to that the letter R indicates the reversal of polarity in the configuration of the device. The normal

TABLE II

Zener Noise Density

Type	*Centre Freq. K Hz*	*Zener Current mA*	*Noise Voltage Microvolt rms*
1N 821	20	7.5	0.1
	200	7.5	0.9
1N 935	20	7.5	8.0
	200	7.5	18
1N 941	20	7.5	43
	200	7.5	25
1N 2620	20	10	24
	200	10	20
1N 3154	20	10	1.0
	200	10	2.8

JEDEC registered data; bandwidth 500 Hz.

polarity is considered to be the connection of cathode to the case of the device. Polarity band or notch indicates the position of the cathode.

The old semiconductor nomenclature usually bears a OAZ followed by a serial number, where O means that the device is a semiconductor, A stands for a diode and Z indicates a zener. This system is almost obselete by the advent of JEDEC and Continental systems of nomenclature.

Principal designations for zener devices amongst Indian manufacturers are FZ, 1Z, 3Z (EC), CMZ, CBZ, CAZ, CZ, CV (CDIL), SZ (Semiconductors), HZ (Hindustan), ZM (Ruttonsha) ... as usual, a subliminal effort of individualisation and puppeteering of the hapless customers. And there is no sign of salvation in the near future from this shabby assault on the customers by the hopelessly ambiguous type coding. Can't we have a unique and easily accessible nomenclature for semiconductor devices, at least among Indian manufacturers?

The environment of resonant information centered around Z has been short circuited unintentionally in very many cases. The well-known EZ and GZ rectifier series of the valve system caused much confusion in the zener field on their way to oblivion. Siemens Low Speed noise immune Logic or LSL series FZ 100 consists of basic gates, JK flip-flops and counters. The majority of Philips FRD xxx Z series are Random Accessible Memories. All the Zilog and Ferranti chips have Z as the first letter. The Ferranti's ZN414 which is an integrated circuit in three lead TO-18 housing, is an RF to AF detector. Anyway, a tree is known by the kind of fruit it bears. We can't remove a speck out of another's eye since we have a log in our own.

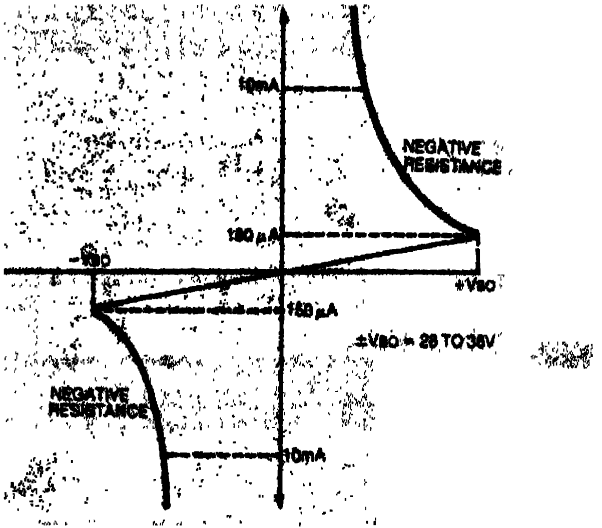


Fig. 3(d): The Dial controversy.

Ideal 'zeners' without zeners

A well-knit transistor combination can also produce similar breakdown characteristics as that of a zener diode. Constant voltage levels even well below 3-volt are possible by this technique. These reference devices are synthesised using transistors and resistors on a monolithic integrated network. Even though the power handling ability is quite low, these devices have an extremely comfortable temperature coefficient, which is the critical factor in the majority of potential applications. Table III gives an approximate comparision of reference networks of semiconductor devices.

TABLE III

Monolithic Zener Reference

Type	*Ref. Voltage*	*Drift With Temp. Millivolts/°C*	*Max. Current mA*	*Dynamic Impedance ohm*
LM 103	5.6	−5	10	15
LM 113	1.22	100	20	0.3
LM 129	6.9	0.07	15	0.6
LM 136	2.49	18	10	0.2
LM 299	6.95	0.0034	10	0.5
LM 399	6.95	0.0014	10	0.6

Buried zener diodes

MOSFET belongs to the first successful integration of semiconductor device with integrated circuit processing. The basic modes in the fabrication of MOS devices are the 'depletion' mode and the 'enhanced' version, of which the former is more frequently used. They have a high resistivity substrate to minimise the influence of substrate bias on 'threshold voltage.' Boron implantation technique in the channel provides the best trade-off between 'threshold voltage' and 'punch-through' voltage. In VLSI, the effective channel length is only a few micrometres and the thickness of gate oxide is 600°A, while line width ranges up to 5 micrometre.

The potential problem in the fabrication of MOS is the sneak paths of capacitive coupling associated with the fringing of the electric fields. In an ideal case the electric field intensity in the gate electrode must be perpendicularly incident. An increase in the gate insulation will result in distorted field intensity at the drain depletion region. The breakdown voltage is controlled by the proximity of the gate electrode to the depletion region. The radius of curvature of the junction region called the 'junction curvature' holds the trump card of the breakdown voltage. For a given impurity concentration the breakdown voltage increases with the increase in junction curvature. However, the reduction in the average breakdown voltage has been observed as a direct function of the separation of the edge of the drain diffusion and the gate electrode. This is because of the overall redistribution of electric lines of force near the drain region, causing the high level fringing of fields towards the gate electrode. This sort of reduction in breakdown

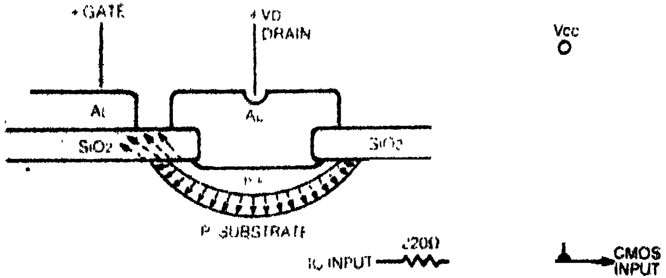


Fig. 4: Buried zener diodes.

voltage is acute if the gate electrode is grounded or even if it is left floating. The resistivity of the substrate or high doping concentration have very little effect on the reduction of breakdown voltage. Thus a conventional MOS gives rise to a process limited breakdown voltage of the order of 25 to 40 volts (Fig. 4).

The premature breakdown voltage in MOSFETs is extensively utilised to provide 'zener protection' for the MOS devices. This zener shielding prevents the effects of high voltage spikes and static charge rupture. A grounded gate electrode acts as a 'zener diode' of the conventional diffused structure. Since the oxide layer between the gate and the semiconductor is of the order of few tens of angstrom units, it is easily ruptured by relatively low values of transient voltage. Even human beings can become charged to voltages beyond 20 kV, just because of the friction between the skin and many types of materials such as silk, fur, plastics and synthetic clothings. Buried zeners provide a built-in protection against voltage, transients. If the input voltage is greater than the breakdown voltage, the process limited zener diode will conduct — restricting the maximum voltage applied to the gate electrode. This also chops off the input voltage of opposite polarity applied at the gate, because of the forward biasing of the newly formed zener at the gate input. However, this is not important in Enhancement version of the MOSFETs, because they don't require an opposite polarity voltage to achieve the 'on-off' operation (Fig. 4).

Zener diodes formed by the process facilities have a breakdown below the chip surface. This reduces the noise factor and long-term instabilities caused by the mobile charges in the surface of the oxide layer. The typical noise voltage is of the order of 3 nV per square root of frequency. Such buried zeners act as an excellent reference too! The buried zener reference on the 12-bit A/D converter AD567 is laser-trimmed to 10 volts, within one per cent error limit. AD567, introduced by Analog Devices Inc., in 1980 uses a buried zener design combined with an on-chip 'Silicon-Chrome' thin film 'application resistors' which are also laser-trimmed to the final reference level. AD567 is a 14-DIL chip which gives the 10-volt buried zener reference at pin 6 for the external application in the system.

(To be concluded next month)