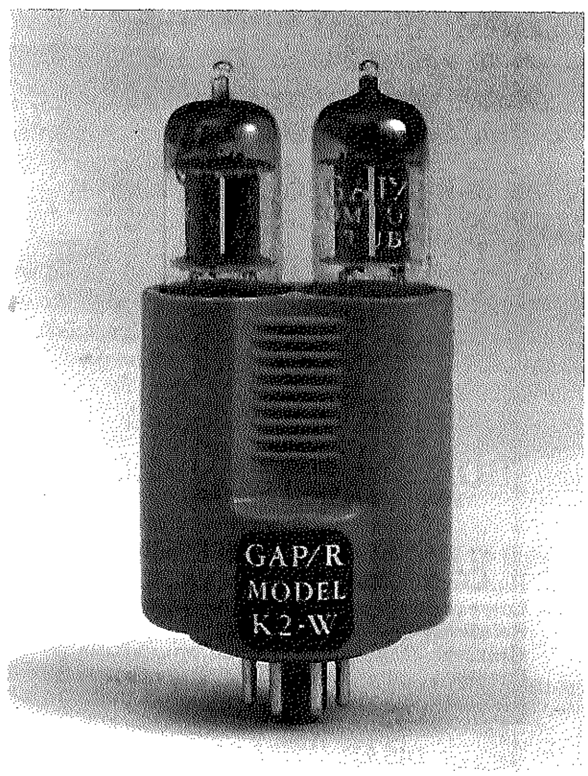
FABRICATION TECHNIQUES FOR PRECISION CIRCUITS

Throughout the history of electronics system designers have used "integrated" circuits, that is to say functional blocks performing a particular task which are not redesigned for each occasion but reused repeatedly. The practice of naming circuits demonstrates this: "Colpitt's Oscillator", "Schmitt Trigger", and "Eccles-Jordan Multivibrator" being just a few examples. In the beginning people built these units for themselves, but very early on it became possible to buy ready-made circuit functions, packaged and tested, for assembly into larger systems.



The practice has continued to the present, but the functionality, complexity, and reliability of individual blocks has become steadily greater while their size, cost, and power consumption has steadily diminished. The invention in the early 1960s of the monolithic integrated circuit, where a number – today a very large number – of individual circuit elements and their interconnections are fabricated in a single minute piece of a semiconductor, accelerated the process enormously but was by no means the start of it. This section of our Seminar considers the different techniques used to manufacture precision analog circuit blocks today.

Prepackaged circuit elements are commonly grouped in four categories: boards, modules, hybrid integrated circuits, and monolithic integrated circuits. Why the term "integrated circuit" should be reserved for the last two is by no means clear, but the practice is too widespread to change.

COMMON TYPES OF INTEGRATED CIRCUIT ELEMENT

BOARD	**Function is sold, ready assembled & tested on a printed circuit board.**
MODULE	**Discrete components and encapsulated ICs are built into a circuit element using normal macro electronic assembly techniques – and then tested and encapsulated.**
HYBRID IC	**Unencapsulated chip components are assembled on a substrate or header (which may also carry thick- or thin-film circuitry), bonded to the package, substrate, and each other by standard integrated circuit bonding techniques, and then tested and packaged.**
MONOLITHIC IC	**Standard integrated circuit chip.**

BOARDS & MODULES

There is little difference between boards and modules, other than the obvious fact that you can see the components on a board, and we shall consider them together. Unencapsulated boards are preferred to modules in situations where there is high-power dissipation and free air flow minimizes temperature rises, and where the circuit element is intended to be mounted in a "card-mount" system.

BOARDS & MODULES

USE THE SAME CONSTRUCTION TECHNIQUES

AND OFFER THE SAME ADVANTAGES & DISADVANTAGES

They differ only in their packaging or lack of it.

When prepackaged circuit elements first became available, they were all boards or modules. Today boards and modules are a minute percentage of the total market. Nevertheless, the absolute quantity and the value of the total number sold continues to rise – it is only their market share that has fallen. They continue to be used because they offer the ultimate in performance, they are are easily customized, and they are often preferable to "home-brew" designs in having a guaranteed performance level.

BOARDS & MODULES

ADVANTAGES

Highest Possible Performance
Lowest Tooling/Development Cost
Relatively Easily Customized
Greatest Variety of Possible Components
Greatest Opportunities for Adjustment
Specified & Tested as a Complete Function

DISADVANTAGES

High Unit Cost
Large Physical Size
Slightly Lower Reliability

Boards and modules may use any type of component, even ones such as transformers and variable capacitors which are difficult or impossible to fabricate in hybrid or monolithic form. Their performance may be optimized during manufacture by component selection and adjustment, they may be reworked without difficulty during manufacture so their yields are very high, and they have relatively low tooling costs so they may quite easily be customized, even for short production runs.

On the other hand they are individually constructed, so their unit cost is high and large production batches offer few economies of scale. They are also relatively large and, because of their method of construction, slightly less reliable than a hybrid or monolithic circuit with the same functionality.

They are therefore used where their outstanding performance or the ease with which they can be customized in small quantities outweigh their disadvantages of cost and size.

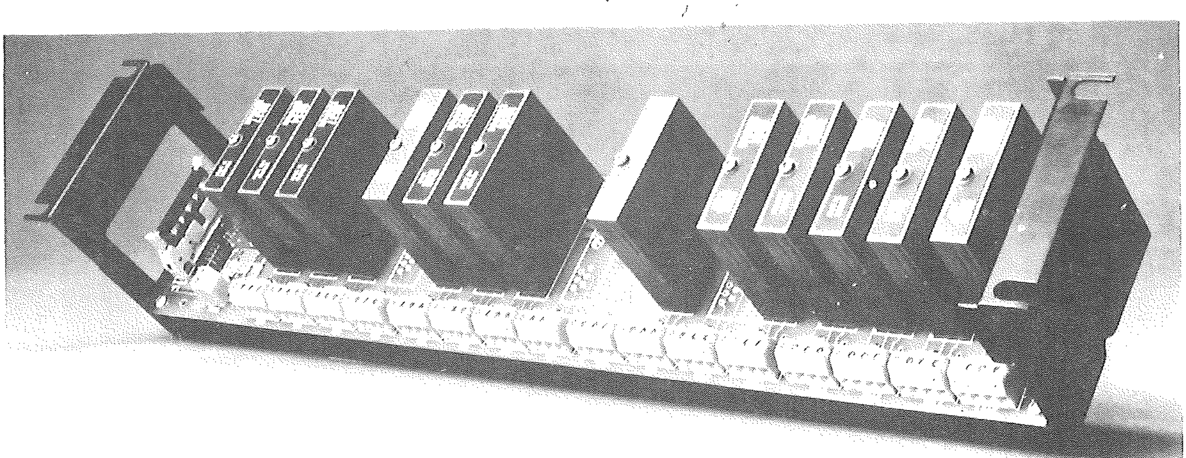
TYPICAL BOARD PRODUCTS

Very Fast High-Resolution Converters.

TYPICAL MODULES

Electrometer Op-Amps
Very High-Resolution Converters
Isolated Functions (Large Voltages Possible Between Input & Output)
Industrial Measurement & Control

There is one area where the larger size of modules is an advantage, for instance, in industrial measurement and control where systems are assembled and serviced by electricians rather than electronic technicians. Modules are large enough and robust enough to be handled with normal tools and be installed with clamps and screw terminals and will survive in an industrial environment. ICs, on the other hand, must be handled and mounted with great care and are vulnerable to blows and corrosion. Thus, many manufacturers make ranges of modules for industrial applications which can easily be installed in the field. Some of them are very sophisticated, but others could easily be replaced with a single IC save for the advantages of robustness and ease of installation.



SURFACE MOUNT MODULES

ADVANTAGES

Lower Cost than Conventional Modules
Wider Component Range than Hybrids or Monolithic
Automatic Assembly for Lower Unit Cost

DISADVANTAGES

Economically Viable Only when Manufactured in Large Quantities Due to Higher Tooling Costs

TYPICAL PRODUCTS

Isolation Amplifiers
Industrial Modules
Data Converters with Integral Computation

NOTE: These modules are fabricated using surface mount techniques – they are not necessarily mounted in this manner themselves.

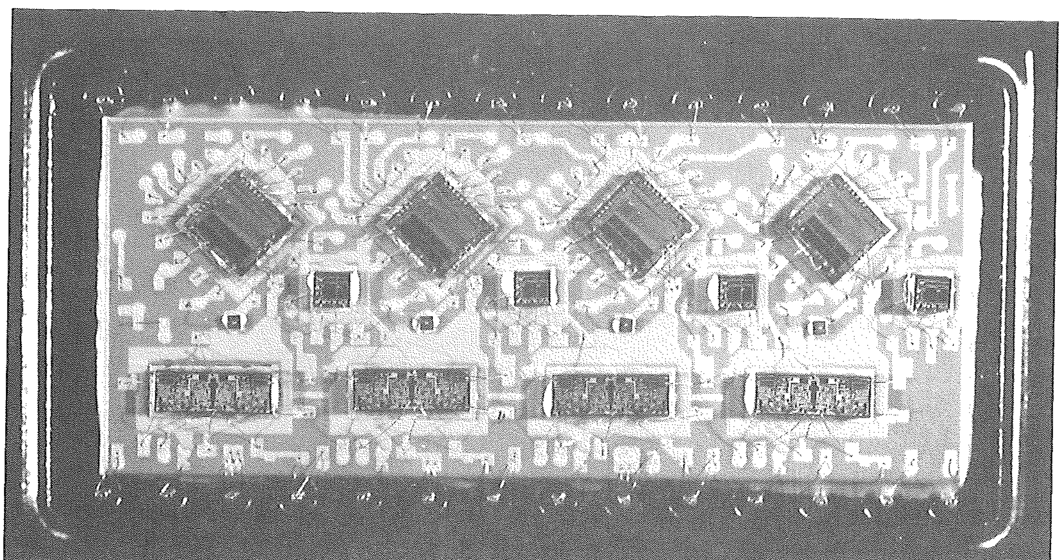
Within the last few years the introduction of electronic components in surface mount packages has revolutionized the automatic assembly of printed circuit boards and has created a new type of modular component – one which is manufactured in large quantities by these automated assembly methods and which contains components which are difficult or impossible to incorporate in hybrid or monolithic ICs. These modules, which are generally smaller than traditional modules, are often not trimmed or adjusted during manufacture and are therefore less expensive. Because of the greater tooling cost of such automated assembly, they must be manufactured in larger quantities to be viable. The first example of such modules was the AD202, an isolation amplifier of medium performance and very small size which costs about one third as much as an isolation amplifier of comparable performance built using conventional module assembly techniques.

AD202 FEATURES

Small Size: 4 Channels/Inch
High Accuracy: ±0.05% max Nonlinearity
High CMRR: 150dB
Wide Bandwidth: 5kHz Full Power
High CMV Isolation: ±1000V pk Continuous
Isolated Power Outputs

HYBRID INTEGRATED CIRCUITS

Hybrid integrated circuits are circuits built using the same assembly and handling techniques as monolithic ICs but containing more than one chip. They may vary in complexity from such circuits as the AD515 or the hybrid AD574, which contain just two monolithic chips, mounted in a package similar to that of a monolithic IC, and connected to each other and to the package pins, to the hybrids used in the most complex systems which contain hundreds of monolithic chips, capacitors, and other components, mounted on multilayer thick or thin film ceramic substrates carrying both precision and nonprecision resistors.



Hybrid circuits are smaller than modules (which means that they may have lower power ratings) and somewhat more reliable. They are assembled using microelectronic techniques of mounting and bonding rather than simpler, larger scale methods – which prevents the use of some types of component (large transformers, thermionic tubes and large variable capacitors come to mind – though Analog Devices' Memory Devices Division does manufacture hybrids containing several small 400Hz signal transformers per hybrid). Their main advantages from the manufacturer's viewpoint are that they allow the use of several different IC technologies in a single device to produce devices which would not be possible in monolithic technology, they may be reworked (to a certain extent) during manufacture, and they tend to have shorter development times and lower development costs than monolithic circuits and so may get to market sooner and for less development cost. To counter these advantages they are more expensive to manufacture (since they can rarely be assembled automatically and are more complex in structure than monolithic circuits).

HYBRID INTEGRATED CIRCUITS

ADVANTAGES

Small Size
High Performance
Shorter Development Times
Can Use Several Technologies at Once

DISADVANTAGES

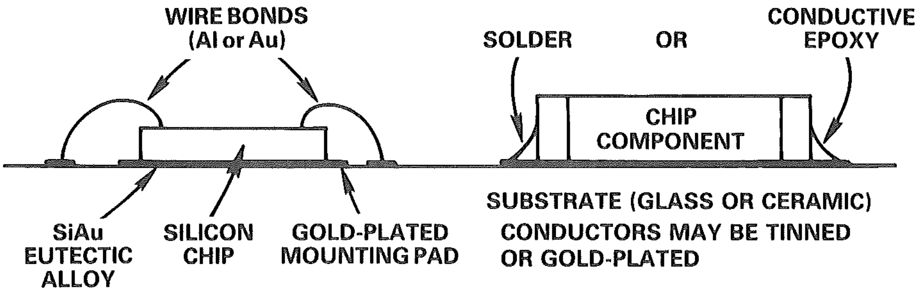
Higher Price than Monolithic ICs
Very Slightly Lower Reliability

From the user's point of view, though, the manufacturer's problems are irrelevant. In a hybrid IC, the user finds high performance of a complex function in less space (generally no larger than the package of a monolithic IC), at a lower price, and with higher reliability than a module. The user does not usually care whether a particular function is performed by a monolithic or a hybrid circuit – provided it is performed well at an economic price. It is quite common for circuits to start their production life as hybrids and be integrated on a single monolithic chip after a few years – either because the technology to do so has only just become available or because the volume required by the market has made economic the development of a monolithic version.

The components used in hybrid ICs are monolithic semiconductor chips (mounted and unmounted and both ICs and discrete devices), chip capacitors, chip resistors, and thick- and thin-film resistors. There are also less common components such as inductors and miniature transformers. These components may be mounted directly onto the metal or ceramic header of the device package or onto a glass or ceramic substrate carrying single- or multi-layer conductors and thick-film resistors, thin-film resistors, or both (thin-film resistors are made of metal film deposited on the substrate by chemical means such as evaporation, sputtering, or electroplating and have high stability and high accuracy, while thick film resistors, which are slightly less stable and accurate but available in a wider range of values, are made from a conductive paint or paste [made from metal powders or metal oxides and sometimes, but not always, fired after application to produce a conducting ceramic] which is painted, sprayed, or silk-screened onto the substrate – both types can be trimmed to improve accuracy and matching).

The components may be mounted by solder, adhesive, or conventional chip bonding (where a low melting-point silicon-gold alloy is formed by scrubbing the silicon chip on a heated gold-plated area where it is to be mounted – this eutectic alloy solders the chip to the substrate or header). Electrical connections are made to unencapsulated silicon chips by standard wire-bonding techniques and to other components by solder or, occasionally, conductive adhesives or paints – normally components other than unencapsulated chips have their electrical connection made by their mounting material.

MOUNTING COMPONENTS IN HYBRID ICs



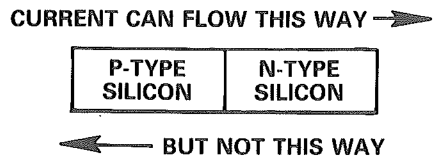
After assembly hybrid circuits may be tested before the package is closed – and components replaced if necessary. The package is filled with dry air or dry nitrogen before being sealed. The caps of hybrid packages are generally attached by soldering, resistance welding, or, occasionally, with adhesives.

MONOLITHIC INTEGRATED CIRCUITS

The silicon monolithic integrated circuit has revolutionized electronics, and society, over the last quarter century. By using essentially simple physical/chemical processes of epitaxial growth, diffusion, and selective etching, it has been possible to build and interconnect millions of electronic circuit elements in a single small "chip" of silicon.

The processes involved are, by now, well known. If we have ultra-pure monocrystalline silicon and add controlled, and very small, amounts of group III (boron) or group V (phosphorus or arsenic) elements as impurities the conductivity of the silicon is increased and the "doped" silicon is said to be P-type or N-type respectively. If two adjacent regions in a silicon crystal are P-type and N-type, their interface is known as a "junction" and has useful electrical properties – the most obvious being that it is a diode and allows current to flow from P to N but not the other way. By controlling the doping and the geometry of the doped regions it is possible to fabricate various different electronic components in the silicon.

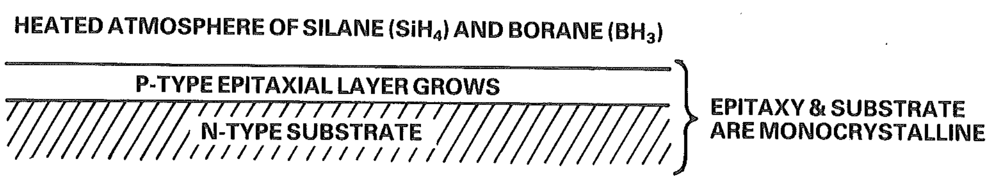
BASIC SILICON JUNCTION (DIODE)



There are two common ways of forming junctions, epitaxy and diffusion. Epitaxy consists of growing silicon of one type on a substrate of another type. This is done by heating the substrate in an atmosphere of silane (SiH_4 – the silicon analog of methane) containing a little phosphine, arsine, or borane to provide the dopant. If this is done correctly an "epitaxial layer" of new silicon grows on the existing silicon and the whole structure, new and old, is monocrystalline. If the correct dopant is used the new silicon will be of the opposite type to the old and a junction occurs at their interface.

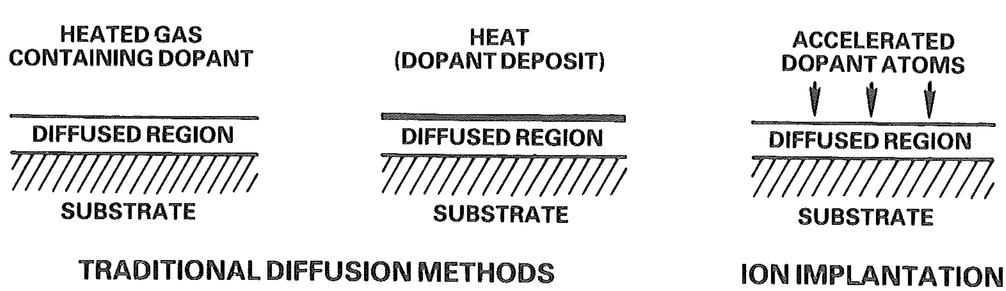
EPITAXIAL GROWTH

(P ON N IS SHOWN – N ON P IS EQUALLY POSSIBLE)



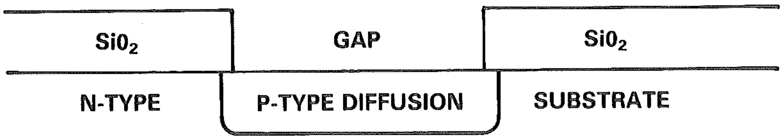
A diffused junction is formed by heating silicon of one type in the presence of the material producing the other type (N-type silicon is heated with boron or borane, P-type with arsenic, phosphorus, arsine or phosphine). Dopant atoms migrate into the silicon to produce a region of the other type. Diffusion may also be accomplished by "ion implantation" where atoms of the dopant are accelerated in a particle accelerator and allowed to strike, and penetrate, the surface of the silicon – ion implantation can give better control of both diffusion depth and density profiles and makes possible better devices than can be achieved by older methods of diffusion.

METHODS OF DIFFUSION



The critical feature which makes silicon integrated circuits so complex is the ability to mask the surface of the silicon so that diffusion occurs only in certain areas. If silicon is heated in oxygen or steam it oxidizes and forms a thin coherent layer of silicon dioxide (SiO_2 or silica) over its surface. If this layer is etched away in places before diffusion takes place, then the dopant will only reach the silicon where the oxide has been removed – which allows us to determine where diffusion will occur. This layer of silica also insulates any conductors deposited on it from the underlying silicon.

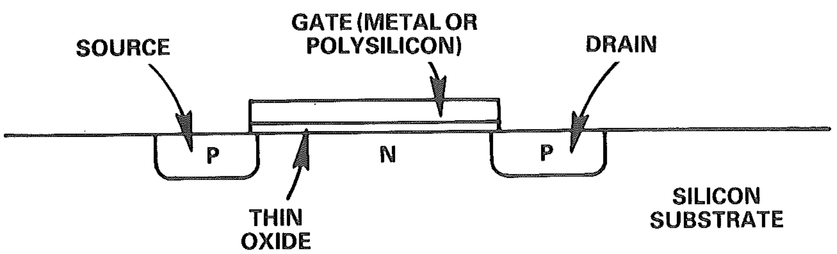
MASKING THE CHIP WITH SILICA ALLOWS DIFFUSION TO BE SELECTIVE



Very thin layers of this silicon dioxide also form the "gates" of a particular type of field-effect transistor called a "metal-oxide-silicon" field-effect transistor or MOSFET.

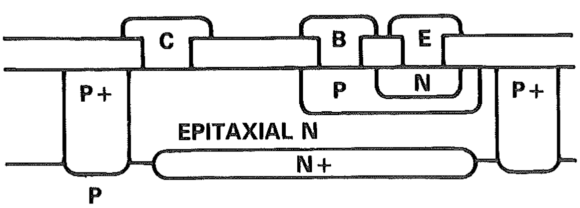
MOS (METAL OXIDE SILICON) TRANSISTOR

This is a P-Channel One – N-Channel Types are Equally Possible

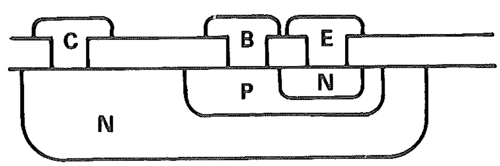


Using only diffusions and thin oxides we can produce a variety of different electronic devices in the surface of a chip of silicon. These include transistors (junction, field effect, and MOS), diodes, zener diodes, resistors (long thin strips of diffusion), and small capacitors (which may be formed either from the capacity of reverse-biassed junctions or as parallel plate capacitors with thin oxide as the dielectric).

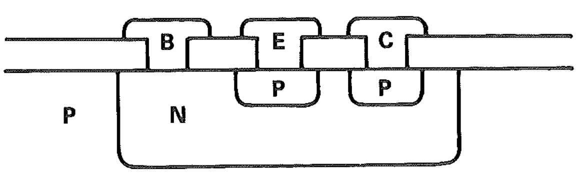
SOME STRUCTURES USED IN MONOLITHIC ICs



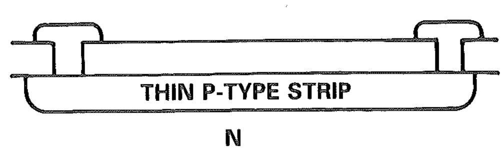
NPN EPITAXIAL TRANSISTOR



NPN DIFFUSED TRANSISTOR



PNP LATERAL TRANSISTOR



RESISTOR

These devices are connected together by aluminum conductors formed by coating the whole chip with aluminum and then etching it to the required pattern. Chips are manufactured hundreds or thousands at a time on a "wafer" of silicon which is cut up into individual chips after all the manufacturing processes are complete.

There are many different kinds of monolithic integrated circuit processes. Each has its own advantages and disadvantages and it is virtually impossible to make all types of integrated circuit components on a single chip. We are not concerned in this seminar with purely digital techniques but it is worth noting that the development of digital integrated circuits has involved increases of packing density from tens of devices per chip in the mid-sixties, when the first commercial ICs became available, to around ten million devices per chip today. Analog chips have developed differently.

The purpose of a precision analog IC is to perform with high analog accuracy. In the quarter century since the first analog ICs were sold, the improvement in accuracy and functionality has matched that of digital circuits but this has not involved comparable increases in component density. Today's most complex analog chips rarely contain more than ten thousand devices and frequently no more than a few hundred – but their performance would have appeared impossible a decade ago.

Developments in circuit technology for precision analog applications concentrate on precision, accuracy and stability rather than packing density. It is well known that if two transistors have identical geometry and are fabricated close together on the same chip they are likely to be well matched – but to improve that match has taken years of study and experiment in processing, device geometry, and material sciences.

At Analog Devices we started our precision analog circuit manufacture with two processes: an epitaxial bipolar process and a CMOS process. The bipolar process makes good NPN transistors and resistors, and fairly good PNP transistors and is therefore excellent for low-frequency amplifiers and computational circuits but does not make particularly good logic.

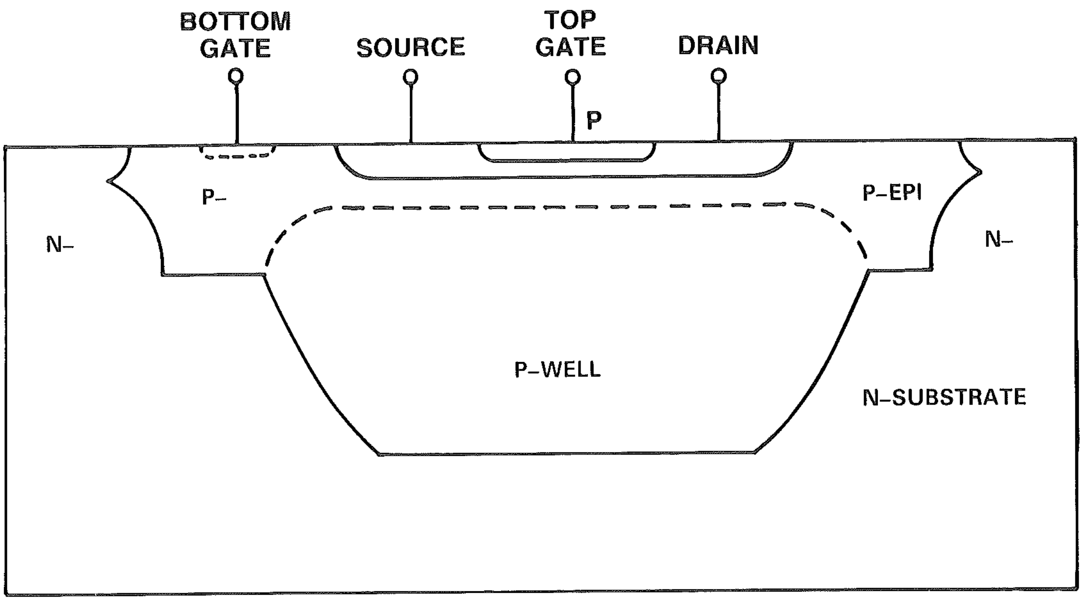
CMOS, on the other hand, makes only P-channel and N-channel MOS devices. CMOS is excellent for logic and switches with high speed and low dissipation but is unsuitable for amplifiers since it is noisy and has poor offset matching.

	BIPOLAR	CMOS
Devices	NPN & PNP transistors Zener Diodes Resistors	N- & P-Channel MOS (Sometimes) NPN Transistors Resistors
Advantages	Low Noise Low Amplifier Offsets Good References	High Speed, Low Power Logic High Density Low Ron Switches Bidirectional Switches
Disadvantages	Poor, Low Density Logic High Amplifier I_b Unidirectional Switches	Poor Noise Performance Poor Offsets No References

The disadvantages of each process led to our process engineers working to overcome them. The first improvement to the bipolar process was to allow it to produce junction field-effect transistors (FETs). Unlike a bipolar transistor an FET does not have a base current proportional to its collector current but only a small gate current resulting from reverse leakage in the gate diode. Amplifiers made with this BiFET process could therefore have much lower bias currents – but at the cost of poorer offsets and bias currents which doubled for every 10°C temperature rise. Because the collector (drain) currents of the input devices are no longer proportional to their bias currents it is unnecessary in FET input amplifiers to limit the current (and hence the frequency response) of the input stages in order to limit the bias current – BiFET amplifiers, therefore, are frequently faster than bipolar ones.

	BIFET
Devices	JFETs NPN & PNP Transistors Zener Diodes Resistors
Advantages	Low Noise Low Bias Current High Frequency Operation Good References
Disadvantages	Offset Voltages Worse than Bipolar (But Much Better than CMOS) Bias Currents Double Every °10°C Bias Currents Ill-Matched Worse Offset TC

JFET

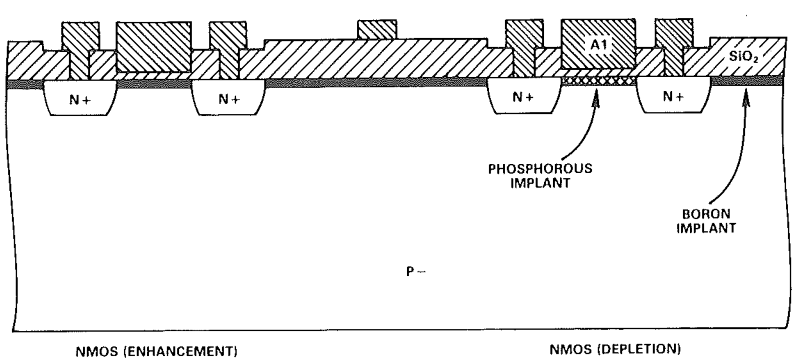


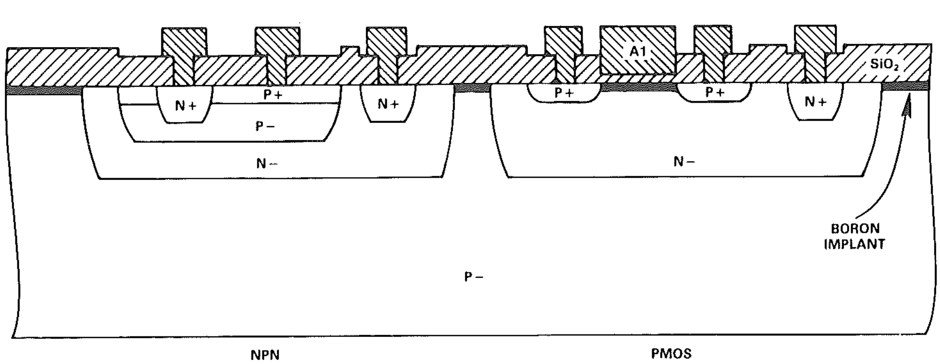
JFETs do little for logic circuitry. The next development was to create a bipolar process which could also make MOS devices of both polarities – a bipolar plus CMOS process. This process, called BiMOS II (since it is now in its second generation), is a non-epitaxial process which will make a wide range of of components and is as good a logic process as it is an analog one.

BiMOS II

Devices	**N-MOS & P-MOS FETs** **JFETs** **NPN & PNP Transistors** **Resistors**
Advantages	**Excellent Amplifiers** **Excellent Logic**
Disadvantages	**Greater Process Complexity** **No Buried Zener Diodes** **Limited Voltage Ratings**

CROSS SECTIONAL VIEW OF BIMOS II PROCESS

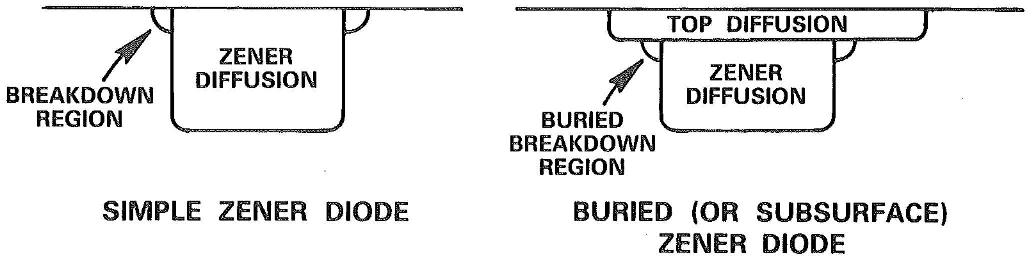




Two minor drawbacks of BiMOS II are its lower breakdown voltages (which prevent it from being used with ± 15V supplies without special circuit techniques) and its inability to make a buried zener diode.

Buried zener diodes make a major contribution to the accuracy and stability of precision analog circuitry. A zener diode is a diode which is fabricated to have a reverse breakdown voltage which is quite accurately defined and is used as a reference. Zener diodes are frequently noisy and unstable. If we consider the structure of a simple zener diode we can see why this should be so.

ZENER DIODE STRUCTURES



Impurities, Mechanical Stress and Crystal Lattice Dislocations Near the Surface of the Silicon Cause a Zener Diode There to Be Noisy and Unstable. If the Diode is Buried Below the Surface Region, Its Performance Will Greatly Improve.

The breakdown of a simple zener diode takes place at the surface of the silicon. Near the surface there are more impurities, mechanical stresses, and crystal lattice dislocations – all of which contribute to noise and long-term instability. (It is interesting to look at an operating planar zener diode in the dark. It is sometimes possible to see a point electroluminescence at the zener breakdown point – this often jumps around the periphery of the diffusion in an unpredictable way, indicating noisy operation of the device.) If we place a diffusion over the zener diode diffusion it is possible to cause the zener breakdown to occur below the surface of the silicon in a region with far fewer impurities, stresses and lattice dislocations. The resulting zener diode is less noisy and has far better long-term stability. The diffusion used to bury the zener may be of the same or the opposite type to the one it is burying, depending on the process.

The AD588 monolithic reference, which uses a buried zener diode as its primary reference, has an absolute accuracy of better than 100ppm and a temperature coefficient of under 1.5ppm/°C.

AD588 FEATURES

FEATURES
Low Drift – 1.5ppm/°C
Low Initial Error – 1mV
Pin-Programmable Output
+10V, +5V, ±5V Tracking, –5V, –10V
Flexible Output Force and Sense Terminals
High Impedance Ground Sense
Machine-Insertable DIP Packaging
Guaranteed Long-Term Stability – 25ppm/1000 hours

The CMOS process engineers were not resting while the bipolar engineers were working towards BiMOS II. They started with a simple CMOS process which made excellent CMOS devices and laser-trimmed resistors (which we shall discuss later in this section) and nothing else – this makes for excellent logic, switches and MDACs, but lousy amplifiers and no references.

They therefore developed Linear Compatible CMOS (LCCMOS or LC^{2}MOS) which added PNP and NPN bipolar transistors, buried zener diodes and N-channel JFETs to the basic P-channel and N-channel MOS FETs of the CMOS process. This has added the possibility of making amplifiers, comparators and references on CMOS chips and therefore greatly increased the range of practicable monolithic devices.

LC²MOS

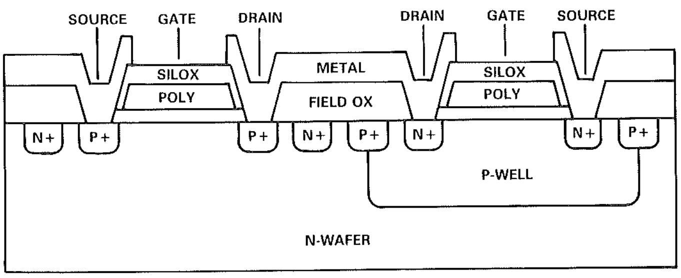
Devices
- NMOS, PMOS, JFET
- PNP & NPN Transistors
- Resistors
- Zener Diodes

Advantages
- Excellent Logic & Switches
- Good Amplifiers & Comparators
- Quite Good References

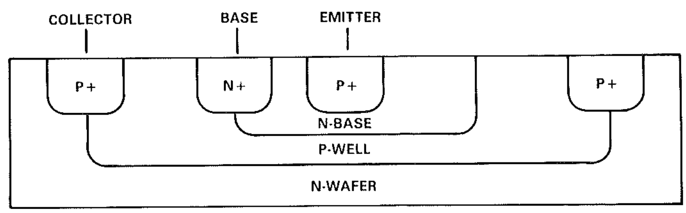
Disadvantages
- Greater Process Complexity
- Limited Analog Output Drive
- Limited Speed in Analog Structures

LC²MOS PROCESS

CMOS ELEMENTS

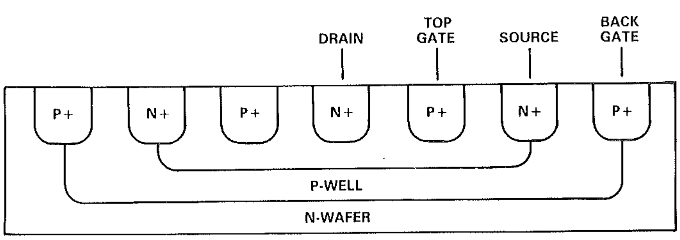


PNP BIPOLAR TRANSISTOR



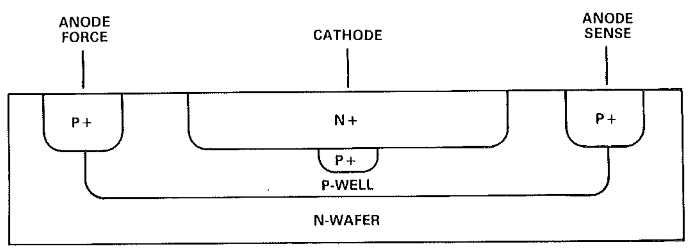
- Breakdown Voltage 10V
- Beta 130
- Ft 1GHz
- Noise 2nV/$\sqrt{Hz}$ at 1kHz
- Match 100μV

N-CHANNEL JUNCTION FET



- Breakdown Voltage 8V
- Vp2V
- Match 20mV
- Noise 9nV/$\sqrt{Hz}$ at 1kHz
- Leakage 1nA at 125°C

BURIED ZENER DIODE



- Vz 6.1V
- TC +25mV/°C
- Noise 60nv/$\sqrt{Hz}$ at 1kHz

It would seem as we consider these process developments that quite soon the BiMOS and the LC²MOS processes will converge and become identical and thereafter all precision analog circuits will be manufactured with this ultimate process. This is not about to happen.

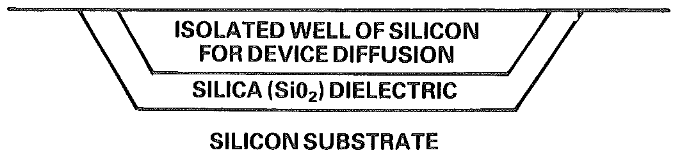
For many circuits, the basic bipolar and CMOS processes are more than adequate. They do not require the extra features of the more complex processes – and they can be made more cheaply by not using the extra complexity (BiMOS has twice as many diffusion steps as the basic bipolar process – and therefore requires the generation of twice as many masks). Moreover, although both BiMOS II and LC²MOS have excellent analog and digital characteristics, they are still, respectively, primarily analog and primarily digital processes and the type of product for which each is best suited does differ markedly.

Therefore, while we can expect to see continual convergence of process parameters, two different lines of development will continue for the foreseeable future. We can also expect to see the older, simpler, cheaper processes continuing to be used in the many new designs which will not require the advanced features of the newer processes.

Meanwhile another development is taking place. A major limitation on the speed of monolithic circuits is the difficulty of fabricating PNP transistors which are as fast as the NPN ones on the same chip (or vice versa – but usually it is the NPNs which are fast). Level shiftlers and output stages, which perform best when manufactured with complementary transistors, are therefore much more difficult to design.

It is possible to make fast PNP and NPN transistors on the same chip by dielectric isolation techniques (which are also used in the same types of analog switches) but the cost of the processing required to produce the little glass-lined "wells" full of silicon that the process requires is prohibitive for many applications.

DIELECTRIC ISOLATION

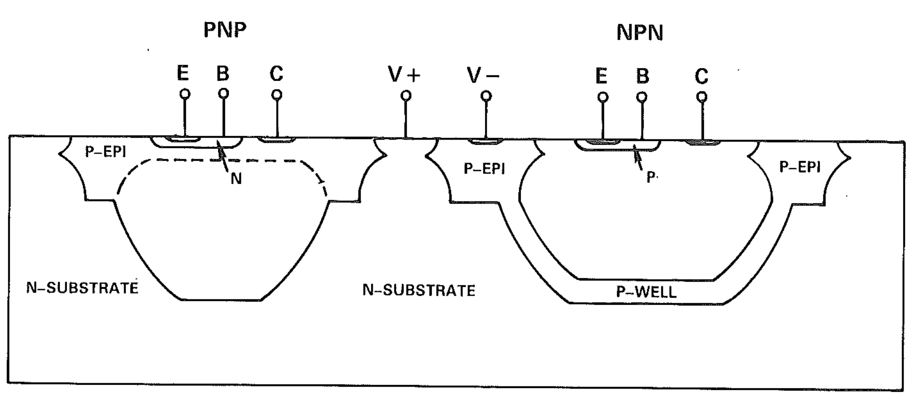


Analog Devices has therefore developed its "Complementary Bipolar" or "CB" Process (which has nothing to do with Citizens' Band Radio) which produces NPN and PNP transistors both having Ft of about 1GHz and is capable of making amplifiers with gain bandwidth products of over 1GHz and DACs with settling times of tens of ns. CB process is relatively new but it has already been used to make the AD5539, a 1GHz op-amp, and the AD568, a 12-bit DAC with settling times to 0.5LSB of <50ns.

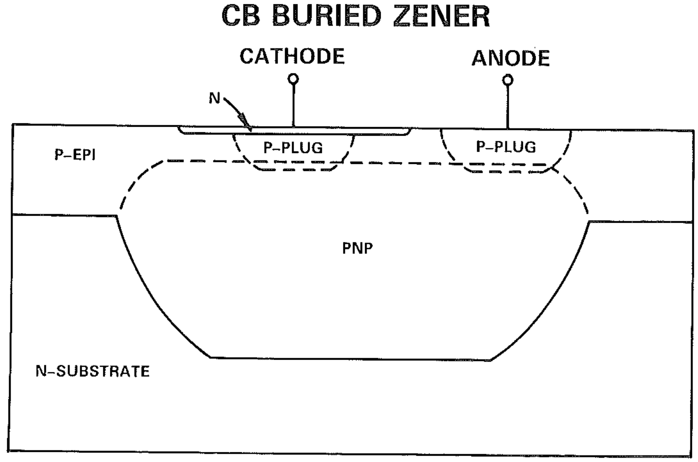
CB PROCESS
(Complementary Bipolar)

Devices	Fast PNP & NPN Transistors Resistors
Advantages	High Speed High Power Low Noise Complementary Architectures
Disadvantages	Limited Voltage Rating Limited Logic Complexity

CB COMPLEMENTARY TRANSISTOR PAIR



CB BURIED ZENER



Although the CB process permits the manufacture of far faster complementary circuits than has hitherto been possible, the Ft of transistors made with it remains under 1GHz. Where even faster precision circuitry is required, another new process, using very small geometries and very precise ion implantation, allows the fabrication of NPN transistors with Ft of around 3GHz (PNP Ft in this process is only 25MHz) while still retaining the features required for precision circuitry: precise offset and beta matching and the ability to fabricate laser-trimmed SiCr resistors on the chip without compromising its other features. This is known as the "Flash" process.

FLASH PROCESS

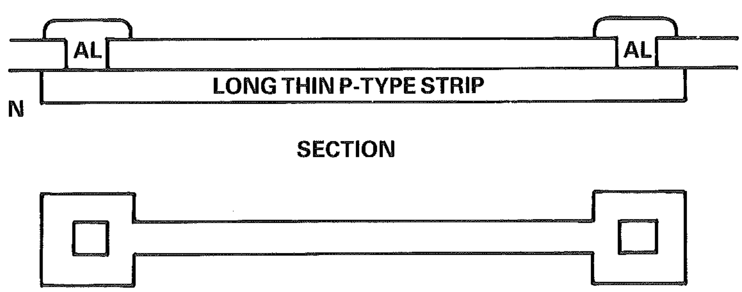
<u>Devices</u>	3GHz NPN Transistors 25MHz PNP Transistors Laser-Trimmed Resistors
<u>Advantages</u>	Very High Speed High Precision Low Noise
<u>Disadvantages</u>	Limited Voltage Rating Relatively Slow PNPs

In addition to its slow PNP transistors, the small geometry of the flash process limits its breakdown voltage but these disadvantages are trivial beside its blinding speed and analog precision. It is being used to design a range of amplifiers and multipliers whose performance will greatly exceed anything which has hitherto been possible, either in hybrid or monolithic form.

There are other details of the design and manufacture of precision analog integrated circuits which we do not have time to discuss in this brief summary (device geometries are optimized for analog performance, not minimum size, – which is why one sees so many round transistors in amplifiers and so few in microprocessors; transistors only match if they really are at the same temperature – so temperature gradients on a chip are sometimes of critical importance, which causes analog designers to lay out for minimum temperature gradient in critical areas rather than for minimum chip size; and voltage drops of millivolts in current-carrying conductors MATTER). There remains one feature of precision analog integrated circuits which must be discussed as it is critical to their performance: precise stable resistors.

Traditionally, resistors on integrated circuits have consisted of a long thin strip of diffusion biassed so that it is isolated from the silicon in which it lies.

DIFFUSED RESISTOR



SECTION

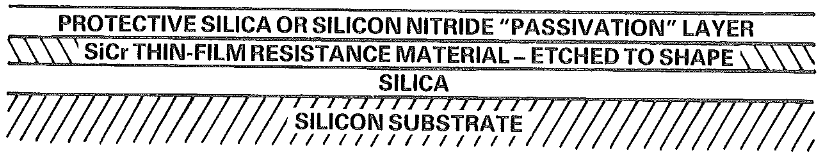
TOP VIEW

If the N-Type Material is More Positive Than the Resistor, It Will Obviously Be Isolated From It.

The accuracy of such resistors is pretty poor and they have large temperature coefficients. The matching of two adjacent and similar resistors can be around 1% but on the whole they cannot be considered precision parts. Nevertheless, with the greatest care in both design and processes it is possible to make a DAC with diffused resistors which has a DNL of 12-bits and an INL of 11-bits. To do better requires different techniques.

Analog Devices uses thin-film resistors deposited on the silica layer of the chip. These resistors are evaporated onto the silica and then photo-engraved to shape just like the aluminum conductors on the chip. They are made with an alloy of Silicon (Si) and Chromium (Cr) and are known as SiCr resistors. They have a temperature coefficient of well under 50ppm/°C and matching accuracy of 0.1% (their overall accuracy is only about 15% – this is because they are manufactured for minimum TC rather than maximum accuracy and the two requirements may conflict).

THIN-FILM RESISTOR ON A CHIP



Accuracy	**15%**
Matching	**0.1%**
(May Be Laser-Trimmed to	**<0.01%)**
TC	**<50ppm/°C**
TC Matching	**<0.25ppm/°C**

Using such precise resistors it is possible to manufacture 8-bit and 10-bit ladder networks and even DACs with 16-bit DNL (but only 13-bit INL). But these resistors have another feature which enables us to make far more accurate components, and to use them to make very precise amplifiers and computational circuits: they can be trimmed to better than 0.01% during manufacture.

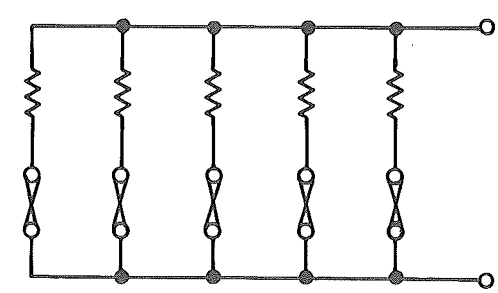
There are three commonly-used methods of trimming an analog IC: fusible links, zener zap, and laser trim. The first two are quantum processes – that is to say, they allow a resistor to be switched in or out of circuit during the manufacturing process. If there is an array of resistors, quite an accurate trim may be possible but it is inherently quantized. Laser trim allows adjustment with virtually infinite resolution.

In a fusible link trim each resistor is connected in series with a very narrow link of aluminum conductor. Each resistor which is not required has its conductor pulsed with a current high enough to fuse the link. While effective, this technique is dirty – it contaminates adjacent areas of the chip with flecks of aluminum – and is not popular for precision analog applications where such contamination may cause long-term instability.

TWO QUANTIZED METHODS OF TRIMMING RESISTANCE DURING INTEGRATED CIRCUIT MANUFACTURE

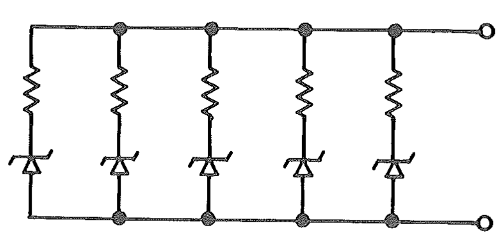
FUSIBLE LINKS

When Fuses Are Blown, They Open-Circuit Their Resistor But May Contaminate the Chip Surface with Vaporized Aluminum.



ZENER ZAP

Non-Contaminating But Still Quantized

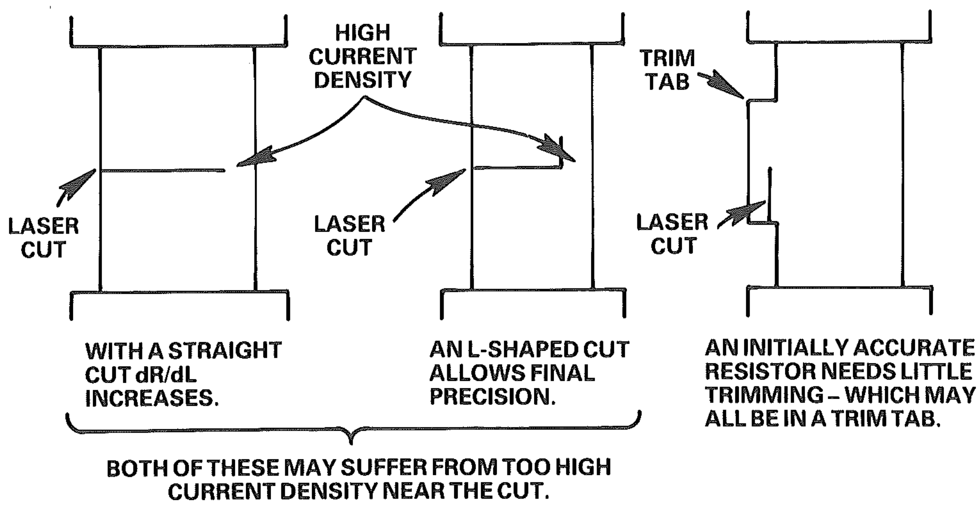


Zener zap is similar but the aluminum link is replaced with a very small diffused zener diode. When this zener diode is destroyed by a current pulse there is no visible damage and no debris to cause contamination. Many manufacturers who have not mastered the problems of laser trim use zener zap to trim the offset of operational amplifiers and where Analog Devices second-sources such amplifiers we use the same technique (for example, in the AD OP-07). In general, though, we find that the greater resolution and control of laser trimming offers major advantages.

This trimming is done by cutting a slot in the resistor with a laser. The basic idea seems simple – after all, Darth Vader has a laser and he blows up planets with his – but is in fact extremely demanding. Since many of the techniques involved are unpatentable it is not possible to give explicit details of the process but a number of points must be considered.

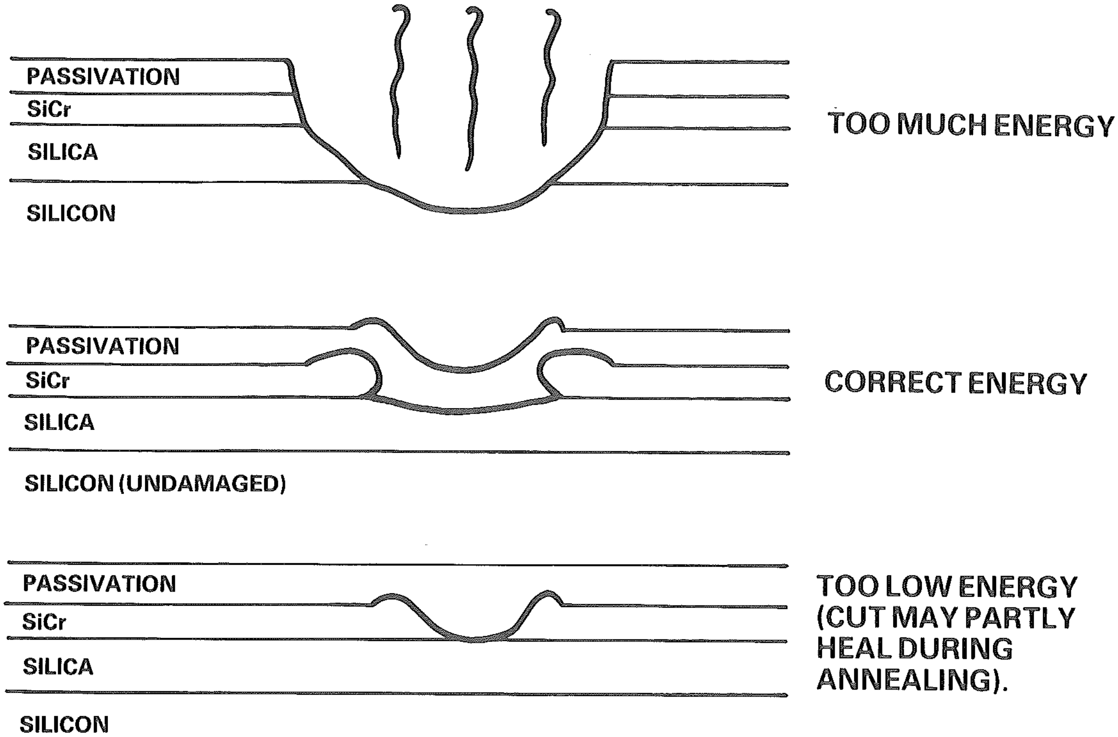
1. The resistor material – it must have good electrical characteristics and long-term stability (even after trimming) and must cut cleanly.
2. The shape of the resistors, and the geometry of the cut by which they are trimmed – if the resistor is initially inaccurate, a large trim will be necessary, but if we just cut across the resistor, the rate of change of resistance with cut will rise as the cut continues until just when we require greatest precision we have the greatest rate of change. An L shaped cut helps with this last problem but an initially accurate resistor which requires little trimming makes the task far more easy – it may be trimmed with a single cut on a special "trim tab" on the side of the main resistor.

LASER TRIM – GEOMETRIES



3. The laser spot size and shape.
4. The laser energy – should it be pulsed or continuous, and, if pulsed, at what energy and what rate? (Too much energy will damage the silica substrate and the underlying silicon and may perforate the passivation; too little will leave resistor material in the cut which may migrate and cause long-term instability.)
5. The laser wavelength – both for optimum energy transfer and to avoid unwanted interference, effects in the transparent passivation and substrate layers (which have thicknesses comparable with the wavelength of the laser light).
6. Etcetera, etcetera, etcetera, and so forth.

LASER TRIMMING – ENERGY



To summarize, the ability to fabricate, and laser trim, very precise and stable thin-film resistors, enables Analog Devices to make the most advanced precision monolithic analog ICs in the world. Well-defined and stable semiconductor processes are very important, but the most critical technology, and one which we have spent fifteen years developing and improving, is our ability to make, and trim, precise, stable resistors on the chips of all our different semiconductor processes.