Elliott Sound Products

ESD Protection

ESD Protection For Electronic Circuits

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Introduction

Most circuits require a minimum of input protection, especially conventional preamps, power amps and other audio circuits. However, for test instruments or other circuitry that will be used in potentially hostile environments protection is essential. The same applies for electronics that are used in sound reinforcement, as there could be up 100m of cable that can be charged to 48V by phantom power. The phantom supply is limited to 7mA (each wire of the balanced pair), but the cable capacitance is such that several *amps* may be available for a few microseconds. It will usually be less, but that's not something you can count on.

Most CMOS digital ICs (including microcontrollers, PICs and CMOS opamps) have inbuilt protection diodes, but they are tiny (being located on the die), and they are incapable of handling any appreciable current. Without at least a limiting resistor in series with the input, it's not hard for a static discharge or other 'event' to cause internal diode failure. Few CMOS datasheets specify the ESD (electrostatic discharge) capabilities of the device, and you have to look for 'generalised characteristics' data for the device family (which may or may not be readily available). The limits are generally very low.

The 'human body model' is one test criterion, where a 100pF capacitor is charged to the desired test voltage, and discharged into the IC via a 1.5kΩ resistor. The test voltage depends on the level of protection claimed, and can range from 2kV to 8kV. Like so many things in electronics, it can be very difficult to find definitive data for anything even slightly esoteric, and ESD testing regimes are no exception. Even when located, the data are not always easy to comprehend unless you have experience in this area. The risetime of the discharge determines the worst case peak current. Depending on the source, this may range from a few nanoseconds up to perhaps 1µs or so. Again, definitive information isn't easy to find, but I suggest that you assume the worst. A 100pF cap charged to 2kV will create a peak current of 570mA with a 1µs risetime, increasing to 1.33A with a 1ns risetime. The peak current increases in direct proportion as the test voltage is increased.

In general, it would be unwise to expect the internal protection diodes to provide adequate protection for any circuit used in a hostile (or potentially hostile) environment. This doesn't only apply to inputs, and outputs can be just as easily damaged if subjected to ESD. We tend to think that outputs are 'immune' from damage because they are low impedance, but expecting a CMOS logic circuit's output stage to withstand a pulse of over 1A involves a high level of wishful thinking.

The ESP app note AN-015 - Input Protection Circuits provides some basic information that has been available for some time, but this article is far more complete, and has more information for the protection of digital logic circuits. It's not often that CMOS inputs are exposed to the forces of nature, but with microcontrollers and PICs becoming more common for even trivial tasks, there are more opportunities for things to go wrong.

1.0 Inbuilt Diodes

Almost all CMOS logic ICs have internal protection diodes or protection networks, but the current rating is very limited. The same applies to microcontrollers and PICs, along with CMOS opamps. JFET and bipolar opamps generally do *not* have protection diodes, but they are not immune from ESD damage. Some CMOS logic ICs are rated for a diode current of up to ±20mA, but this is easily exceeded by even 'small' ESD events. External diodes can handle far more current, but at the expense of relatively high capacitance (around 4pF for a 1N4148 diode). Peak current for the 1N4148 is 1A for 1 second, or 4A for 1µs.

Something that is rarely considered is shat happens if (when) a high-voltage, high-current source is applied to a diode-protected input, using the 'standard' protection scheme shown in Fig. 1.1. The upper diode will conduct when the input is 0.6V greater than the supply voltage, and if enough current is available (which may only be a few milliamps), the positive supply is forced high. The regulator doesn't help, because almost all regulators are designed to *source* (supply) current, but the cannot *sink* (absorb) current if the output voltage is forced high. It's easy for an improperly wired piece of external equipment (such as a power amplifier) to supply 30V or more with considerable current. If that happens by accident and 30V AC is fed into the input of a DAC or other logic-level circuit, it's quite apparent that it will be destroyed fairly quickly (if not instantly).

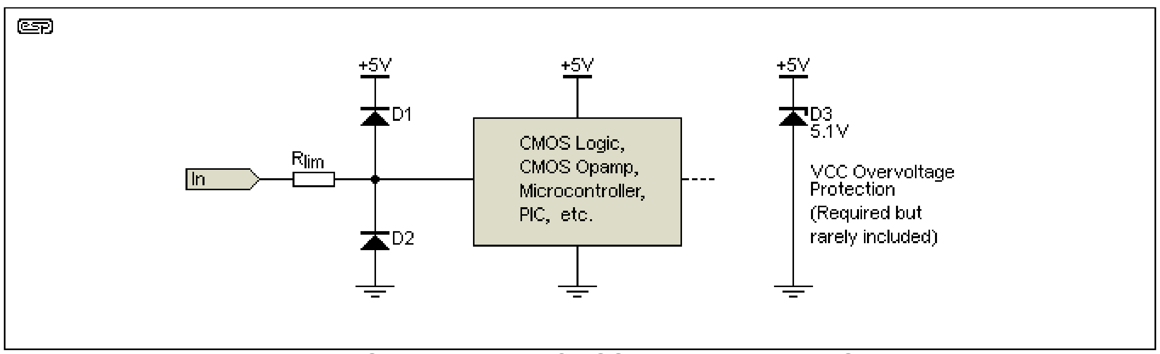

Figure 1.1 - Standard Basic CMOS Diode Protection Scheme

The arrangement shown is seen in countless circuits, both DIY and commercial. Provided the value of R_{lim} (current limiting resistor) is high enough, it provides adequate protection for many circuits. However, if ESD 'events' are expected, R_{lim} needs to be a fairly high value, and that can cause the circuit to suffer from poor high-frequency response. With analogue circuits it can also introduce noise. A value of between 1k and 10k is fairly common. As with so many things in electronics, a compromise is required. Beware of positive input voltages! If R_{lim} is 1k, a 30V input will force 25mA into the positive supply (VCC), which can cause the supply voltage to rise to a destructive level. Higher voltages are worse.

The VCC overvoltage protection zener is uncommon, but it should *always* be included. The zener voltage should be slightly higher than the supply voltage, selected so that VCC cannot rise above the device's absolute maximum voltage rating.

For a single-supply circuit as shown, negative voltages are not a problem, as D2 can carry up to 200mA (1N4148), so if R_{lim} is 1k, the circuit is protected for up to a -200V input. The protected device may or may not be able to withstand the -1.5V or so that will appear at its input. The data should be included in the datasheet. R_{lim} should generally be the highest value you can use for the IC in use, while considering transition speed.

Zener diodes can provide very robust protection, but they are far from perfect. Leakage current is a problem that can show up as unexpected distortion, so in some cases you may have a difficult decision. The power supply may need to incorporate a parallel zener to absorb any voltage above the nominal regulated supply (e.g. 16V zeners in parallel with ±15V supplies, or an alternate scheme devised). By using parallel zeners for each supply rail, while the regulators cannot sink any fault current, the supply rail(s) can only be increased by 1V before the zeners conduct. This extra protection is essential if equipment is liable to be subjected to abuse.

It's not foolproof of course, and if a sufficiently powerful input signal is provided, something *will* fail. However, the remainder of the circuit should be saved. One of the issues we face is a compromise between protection and noise. If the input resistor were to be increased to (say) 10k, even a 100V input can only produce 10mA, but that much resistance would be quite unacceptable for a low level preamp (phono, tape head, microphone, etc.). Just the resistor will generate a noise voltage of 1.8µV (20kHz bandwidth), limiting a 1mV input to a signal to noise ratio of 27dB! Even a 100Ω resistor will generate 180nV of noise (37dB signal/ noise with 1mV), so for very low noise circuits any series resistance is very limiting.

Noise is (usually) not a major issue with logic circuits, because they operate with fixed levels (e.g. 0-5V, 0-3.3V, etc.), but for signals from the outside world almost anything is possible. Once ICs are installed on a PCB, most are fairly well protected against damage, but *any* pin that interfaces with external equipment (outside the main chassis) is at risk. Table 1 shows just how hostile the outside world can be!

Condition	Typical Reading (Volts)	Highest Reading (Volts)
Person walking across carpet	12,000	39,000
Person walking across vinyl floor	4,000	13,000
Person working at bench	500	3,000
16-lead DIPs in plastic box	3,500	12,000
16-lead DIPs in plastic shipping tube	500	3,000

Table 1 - 'Typical' ESD Voltages [1]

The table shows measurements published by Fairchild for various conditions, with a relative humidity of 15% to 30%. The figures were originally determined by T.S. Speakman (see note below) and it's very likely that these figures have been used (at least in part) to determine the 'human body model' for ESD.

> T.S. Speakman, "A Model for the Failure of Bipolar Silicon Integrated Circuits Subjected to ESD", 12th Annual Proc. of Reliability Physics, 1974.

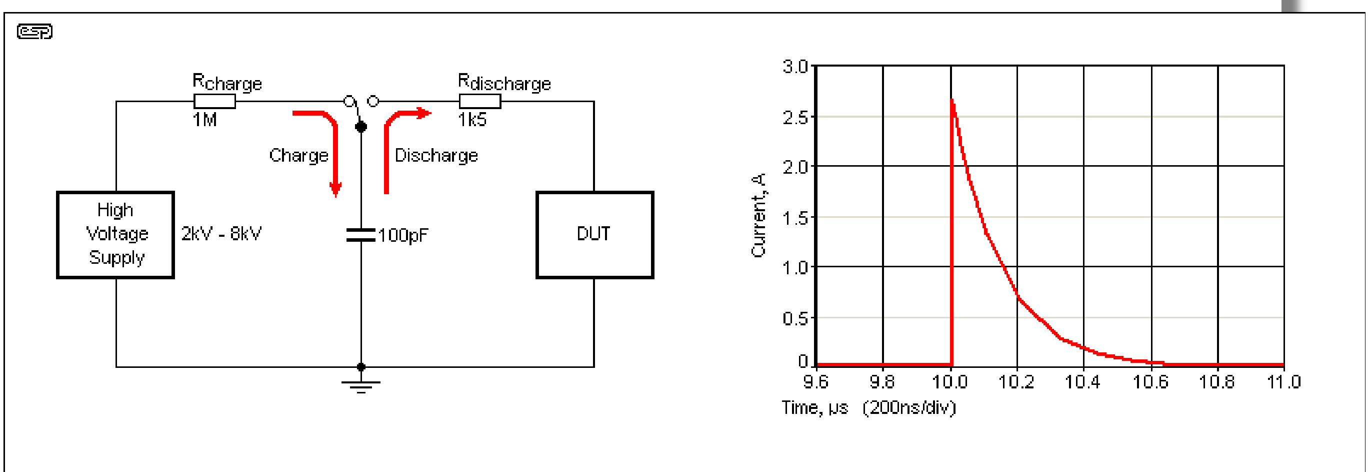

Figure 1.2 - Human Body Model For ESD, With Discharge Curve

The arrangement shown above is the standard representation for the so-called 'human body model' (HBM). The capacitance is 100pF, and the resistance is either 1.5k or 330Ω (IEC 610004-2), depending on the standard being followed. There's also a 'machine body model', used to test machine-to-machine vulnerability. It's shown in reference 5 (as is the HBM), but for the latter the time scale of the discharge is wrong - it shows milliseconds instead of microseconds. This error is repeated countless times on the interwebs.

At the 10µs mark, the charged capacitor (4kV for this example) is connected to the DUT (device under test), and the current rises (almost) instantly to the maximum (2.67A). Within 400ns the current has fallen below 250mA, and after 1µs it's down to 3mA. The peak current is almost solely dependent on the applied voltage. This is why anti-static work mats and wristbands are used in production and repair facilities, and although they are high-resistance (for user safety) they prevent static build-up by providing a constant discharge path. By their very nature, static charges are high-impedance, and are easily discharged even by a 1MΩ resistor.

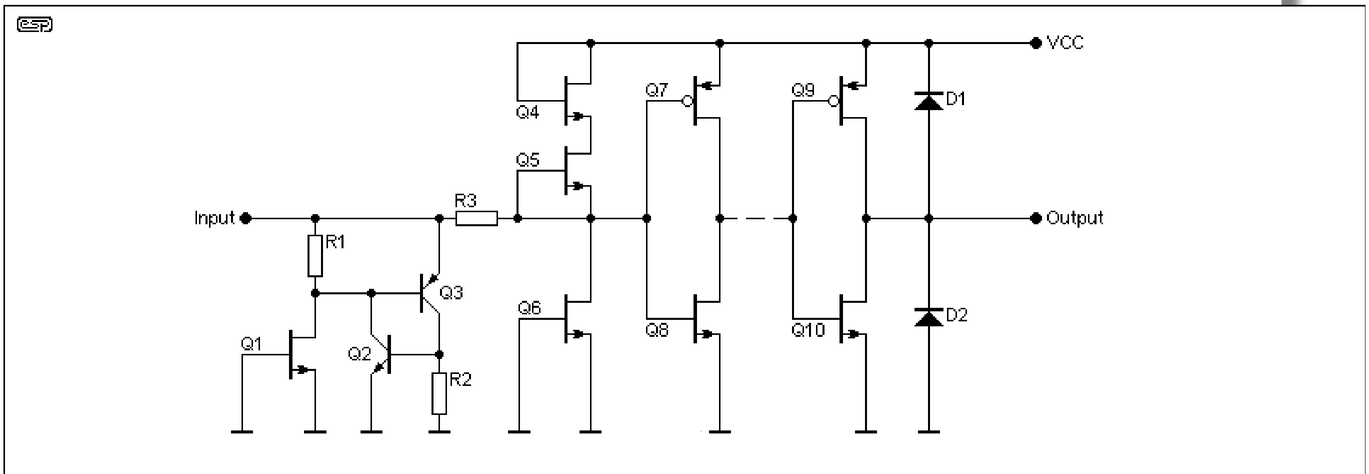

Figure 1.3 - TI AHC Series CMOS Protection Circuit

It's not easy to find detailed info on CMOS or microcontroller internal protection circuitry. The above was found almost by accident, and shows the arrangement used in TI's AHC (advanced high speed) CMOS ICs. The BJTs appear to be parasitic, and exist between the CMOS circuitry and the substrate (the silicon layer upon which the CMOS transistors are formed). I've not been able to get much further info, although it is pointed out that the two parasitic BJTs form a thyristor that can cause latch-up if the input is greater than VCC+0.5V or less than -0.5V. In reality, this is probably pessimistic and latch-up is unusual. An ESD 'event' can cause latch-up problems because it's rarely possible to clamp the input range to less than 0.5V. Schottky diodes are one solution, but they have (relatively) high leakage that may compromise high-impedance circuits.

2.0 External Protection

External protection circuits range from a duplication of the input protection already provided, using bigger diodes and additional resistance, to relatively complex circuits using a combination of resistors, diodes and zeners, sometimes with some capacitance as well. The arrangement used depends on the desired impedance levels, frequency response and/ or speed of operation. The protection needed for an oscilloscope's input circuits will be very different from that needed for a microphone preamp for example. In some cases, RF JFETs will be used as diodes in order to minimise capacitance, something often seen in oscilloscope front-end circuits.

BJTs (bipolar junction transistors) can also be used as diodes, and they will often have lower leakage and (possibly) lower capacitance than JFETs. Within CMOS ICs, the diodes will be MOSFETs, but there will also be parasitic diodes that are created during production. These are usually slower (and less well defined) than MOSFETs. A relative newcomer are TVS diodes (transient voltage suppressor), which are available in a number of voltages, 'surge current' ratings and peak power dissipation. The can be unidirectional (like a diode) or bidirectional (like two zeners in reverse series). TVS diodes are far more predictable than MOVs (metal oxide varistors), but they are not precision components. Of the available options, TVS diodes are probably the best choice as they are very rugged, but their junction capacitance is such that they will be unsuitable for high-impedance, high-speed circuitry. For example, a 12V bidirectional TVS diode may have as much as 1nF junction capacitance.

The capacitance of zener diodes is rarely quoted, making it hard to know if they will be alright or not at the impedance and frequency. In general, expect a 400mW, 5.1V zener to have a capacitance of up to 800pF (I measured a few without bias and obtained 124pF on average). The reading was obtained with two in opposed series (cathodes joined) to prevent forward conduction. The total capacitance was 62pF, so each must have a capacitance of 124pF as they are in series. The capacitance falls as reverse voltage is applied until the zener breaks down. So, while a zener diode (or a pair in series) may not be quite as rugged as a TVS, it will have lower capacitance. Compared to a JFET or BJT (diode connected), both the zener and TVS have vastly more capacitance, limiting their usefulness for high frequency operation.

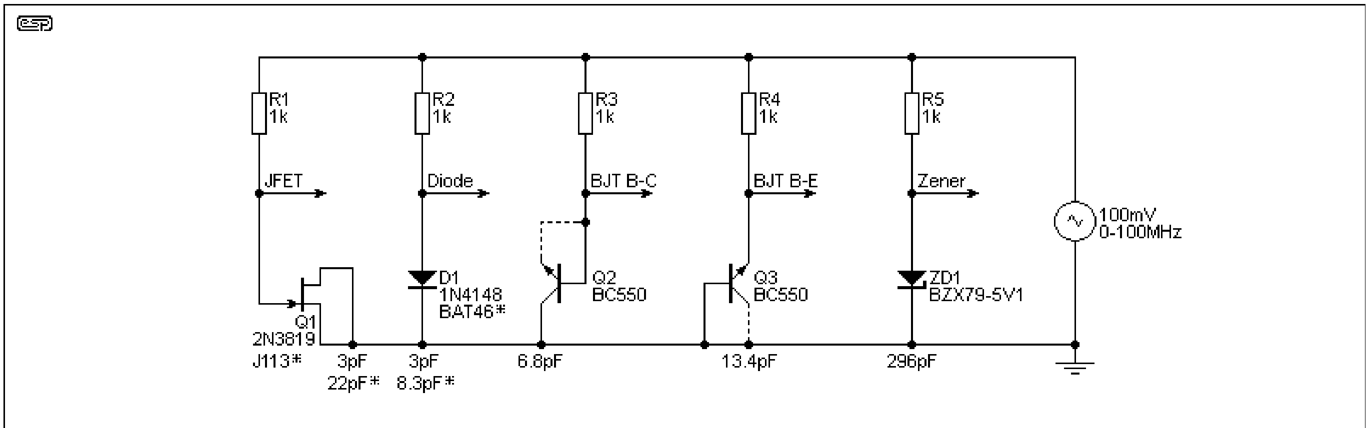

Figure 2.1 - Diode Configurations

The diode connections for testing (via simulation) are shown above. The JFET has drain and source shorted, but that's not a requirement. The two BJT configurations (base-emitter and base-collector) have very low leakage, but their capacitance is higher than the JFET or 1N4148. The base-emitter configuration has a limited reverse voltage (around 5V, but it's inconsistent) and also has higher capacitance than the base-collector connection. If at all possible, the base-collector connection is the better choice, even though leakage current is a little higher (6.5pA vs. 5pA at -5V). Note that connecting the unused pin (collector or emitter) is optional.

With a feed resistance of 1k, the zener was 3dB down at 537kHz, and the BZX79 datasheet claims only that the maximum capacitance is 300pF at 1MHz. By comparison, the following table shows the -3dB frequency of five different diode connections (simulated, *not* measured). The lowest capacitance 'diode' is a JFET, but it depends on the type - I simulated a 2N3819 (VHF/ UHF amplifier). Other more common types (e.g. J113) will be far worse). The stimulus was a 100mV peak sinewave to ensure that all 'diodes' remained non-conducting. The 1N4148 is a surprise, and the datasheet claims a maximum capacitance of 4pF with zero bias (2pF for the 1N4448 which is harder to get). Calculating for 4pF and 1k series resistance gives 39.8MHz, so the simulation is probably fairly close to reality.

Device	-3dB Frequency	Capacitance
2N3819 VHF/ UHF JFET	53 MHz	3 pF
1N4148 Small-Signal Diode	53 MHz	3 pF
BC550 (B-C) BJT	23.5 MHz	6.8 pF
BAT46 Schottky	19.2 MHz	8.3 pF
BC550 (B-E) BJT	11.9 MHz	13.4 pF
J113 Switching JFET	7.1 MHz	22 pF
BZX79C5V1 Zener	537 kHz	296 pF

Table 2 - Simulated Response Of Various Diodes/ Diode Connected Semiconductors

Most switching FETs will be similar to the J113, having much higher capacitance than those designed for RF amplifiers. It's quite clear that the 1N4148 diode is a good choice for high speed, but they are fairly fragile and easily damaged by a severe overload. The BAT46 (or similar) Schottky diode looks promising, but its surge current is very limited (750mA for <10ms). If we use the 4kV human body model, the peak current is about 2.5A with a risetime of 5ns. The maximum possible is 2.66A (4kV / 1.5kΩ), assuming instantaneous contact. This is within the ratings for a 1N4148 (4A for < 1µs), but a Schottky diode may not survive.

Schottky (actually *all*) diodes have another issue that's rarely looked at - at high currents, the forward voltage climbs rapidly. At just 800mA peak, a BAT46 will have almost 1.2V across it, and at the same current, a 1N4148 will have a forward voltage of over 1.4V. The same limitations apply to all diodes. You could use higher current diodes of course, but they have larger junctions and higher capacitance. For example, a 1N4004 has a capacitance of around 53pF and a -3dB frequency (using a 1k feed resistor as for the other tests) of 3MHz. You might expect that high-speed diodes would be better, but that's not necessarily the case. A BYV29-400 (ultra-fast diode) has a capacitance of 240pF, but it's a *big* diode (9A). A more sensible BYT01-400 (1A ultra-fast) has a capacitance of 45pF and a -3dB frequency of 3.5MHz.

You can measure the capacitance of a TVS, large diode or zener by connecting two in series (cathode to cathode) and using a capacitance meter. For a bidirectional TVS you don't need two. This prevents the meter from forward-biasing the diode junction, and the capacitance you measure for the two diodes is half that for a single diode. So if you measure (say) 28pF for two diodes in series, each has a capacitance of 56pF. This is useful if you need particularly robust protection, and you can test the diodes that you have available. High-capacitance means that frequency response will be limited because it represents a load that the source has to be able to drive in use.

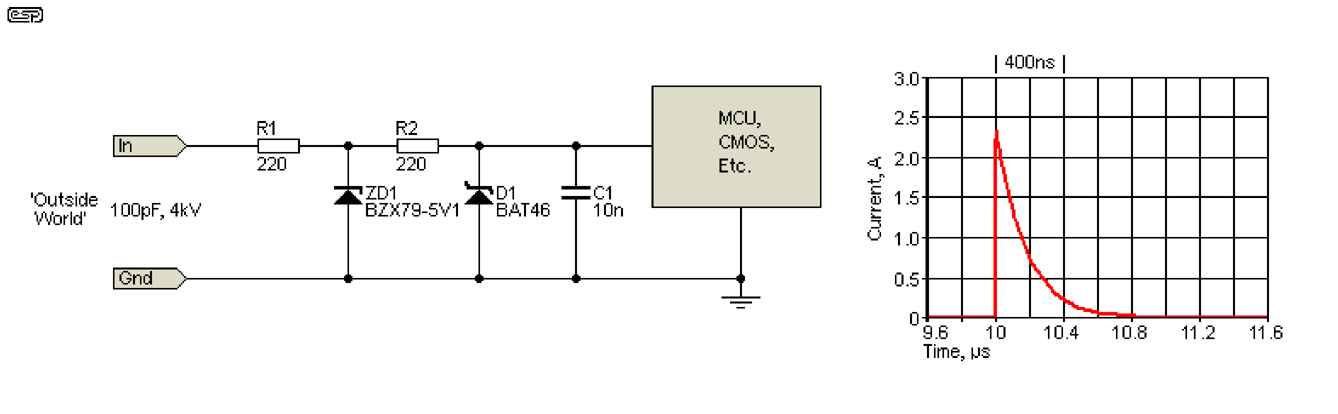

Figure 2.2 - CMOS Input Protection Circuit

One example of an input protection circuit is shown above. This would be suitable for any CMOS (or TTL - transistor-transistor logic) IC using a single 5V supply. The input is protected against high voltages by the zener diode, reverse voltage by the Schottky diode, current limited by the two 220Ω resistors and speed-limited by the capacitor. It's deliberately speed-limited by C1, which can be reduced if you need an input signal of more than ~15kHz. The maximum peak current from a 4kV external discharge is under 500mA, and the input won't rise above 7V (generally *just* within ratings for 5V parts). The voltage will exceed 5V for less than 1µs.

3.0 Output Protection

Output circuits are generally considered to be fairly rugged, using collector/ emitter outputs (BJTs), or drain/ source outputs (MOS/ CMOS). However, if they are exposed to the outside world, they can still be damaged by ESD or just by having a low-impedance signal fed into the output terminal(s). Because output circuits are generally low to very low impedance, they are generally far less likely to be damaged than inputs. Regular readers will be aware that I *always* include a 100Ω resistor in series with the output of any opamp circuit, and this serves two purposes. It prevents oscillation with capacitive or resonant loads (such as coaxial cable), and it provides at least some protection against low-level ESD events. In an industrial environment (or where +48V phantom power may be present), the resistor is not enough. Diodes, zeners or a TVS should be used if there's any likelihood of damage in normal usage.

Many CMOS ICs have protective diodes on their outputs, but others don't. Damage via the output terminals is less common than input damage, but anything exposed to the outside world is at some risk. Diodes are common, but there is rarely an output resistor so there's nothing to limit the current from an ESD discharge. A pair of diodes is the most basic form of protection, but again, there has to be a zener or TVS diode to limit the supply voltage if a positive voltage is applied to the output circuitry.

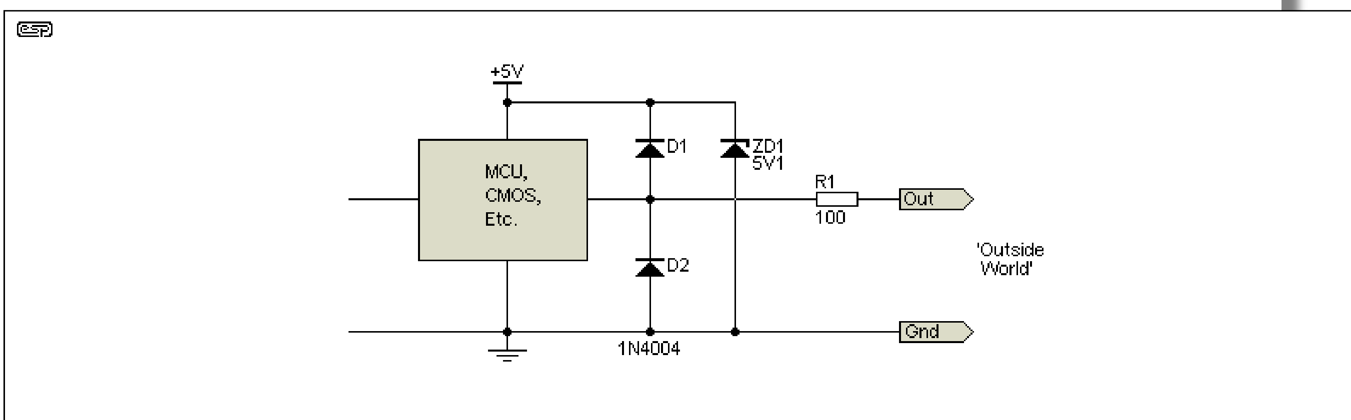

Figure 3.1 - CMOS Output Protection Circuit

With opamp circuitry (e.g. audio circuits), it's good practice to include a 100Ω resistor in series with the output. This limits instantaneous (ESD) current, but it's also required to ensure that the opamp doesn't oscillate when connected to a resonant transmission line (i.e. a shielded cable). Most opamps are intolerant of a capacitive load, and the capacitance of a length of coaxial cable is often enough to cause oscillation. Protection is another matter, and if the environment is hostile (test labs, industrial applications, etc.) then that has to be considered. 48V phantom power is perfectly capable of destroying either the input or output of an opamp circuit that isn't designed *specifically* to be compatible with P48V equipment. The circuit shown above is the very minimum, but may not be sufficient.

It's uncommon to see any form of protection for opamp circuits used in audio circuitry, because problems are rarely encountered in normal use. More care is needed in for industrial applications, but even there few problems will be found. For circuits using a bipolar supply, the lower diode (D2) would be returned to the negative supply, and another zener used to ensure the supply voltage can't be forced above the maximum. The zener voltages are more likely to be (say) 13V for ±12V supplies or 16V for ±15V supplies. The zeners should never conduct unless the supply voltages are forced to exceed the design value.

The protection circuits will always be a compromise. In many cases, no protection will be used at all, but in others it may need to be very comprehensive. Many designers tend to work with a fairly narrow field, and they will know what's needed for the type of equipment they work with. If problems are found later, a retro-fit solution is always possible, but expensive. Most people agree that it's better to get it right the first time.

4.0 Internal Supply Over-Voltage

The idea of using just diodes to (hopefully) clamp the fault voltage to the supply rail is fatally flawed if there is no protective zener included. As shown, a 30V fault voltage is applied to the input, and this could come from anywhere. It could be AC or DC, transient or permanent, and due to incorrect wiring, a fault in the remote equipment or a stray strand of wire getting into something it shouldn't. With a 220Ω limiting resistor, the current will be just under 114mA, and this could easily exceed the normal current drain of the circuitry. We'll assume that the circuit normally draws 50mA.

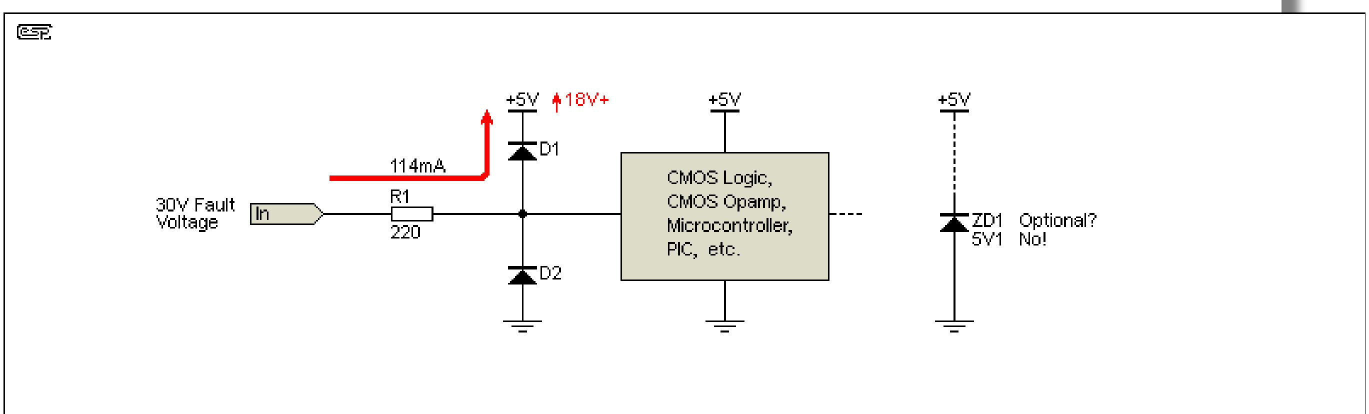

Figure 4.1 - Fault Current Path

When the fault voltage is applied, it will attempt to force 114mA into the input via R1, and then to the +5V supply via D1. There's nothing to prevent the 5V supply from rising, so it will be elevated to something higher, limited only by the load current of the circuit. If we assume that it still draws 50mA (unlikely but possible), the supply will rise to over +18V. Some CMOS ICs *might* tolerate that, but if the circuit is a PIC or MCU of some kind, expect bad things to happen.

Adding the protective zener in parallel with the supply (5.1V) means that the maximum supply voltage will be limited to about 5.4V (the zener has internal resistance and does not limit the voltage to 5.1V), but this should be acceptable for almost all circuits. The situation is made (much) worse if the circuit normally draws less than 50mA (even multiple CMOS ICs may draw less than 10mA). If our CMOS circuit only draws 5mA, the fault voltage will rise to over 28V, which means certain death for the ICs.

The zener is not 'optional', because without it the protection circuit is worse than useless. It might make you feel better because you've included it, and you may never have a 'proper' fault that proves its operation one way or another. If you *do* have a real fault situation, there's every chance that the 'protected' circuit will fail. The presence of supply bypass caps means that they can absorb brief faults, and if greater than around 100µF will absorb brief (< 1.5ms) with only a small voltage rise (depending on the normal current drawn).

I've covered this elsewhere, but in most cases it receives minimal attention, even by people who should know better. A regulator is thought to provide a stable supply at the design voltage, but regulators have a big limitation - they can only source current to the load! If an external voltage is applied to their outputs, regulators are unable to sink (absorb) the over-voltage, and if it's high enough, even the regulator may fail. It's good practice to include a reverse-connected diode across any regulator, as that will limit the reverse voltage to 0.7V or so, ensuring that the regulator isn't damaged. These are also considered 'optional' by some, but IMO they are not***!***

Look at Project 05 or Project 05-Mini. Both include these essential diodes, and they are included in many other projects that include a regulator. If the diodes are omitted, even testing a circuit using an external supply (during test or repair for example) can result in failed regulator ICs.

One regulator that can supply *and* sink current is a shunt regulator, but these are rarely used because they draw the maximum allowable current at all times. This means that they are very inefficient, and if high current is needed the power dissipated can be far greater than is desirable. A resistor and zener is a simple example of a shunt regulator.

5.0 Switchmode Power Supplies

There is a 'special' trap waiting to catch you out if you have equipment powered by a SMPS. It's not well-known, but more than a few people have been caught out. Almost all SMPS have a voltage on the 'ground' that is created by internal Class-Y capacitors that are required to allow the supply to pass 'radiated emissions' tests for EMI (electromagnetic interference). The capacitance is usually small (rarely more than 2.2nF), but that's more than sufficient to cause failure of input *and* output circuits.

The phenomenon is covered in reasonable depth in the article SMPS Kill Equipment ... ?, and it's very real. It's not helped at all by the fact that the common RCA connector connects the input/ output first, followed by the ground/ shield. Any external stored charge is transferred to the circuitry *first*, which is decidedly sub-optimal, but normal with all RCA connectors.

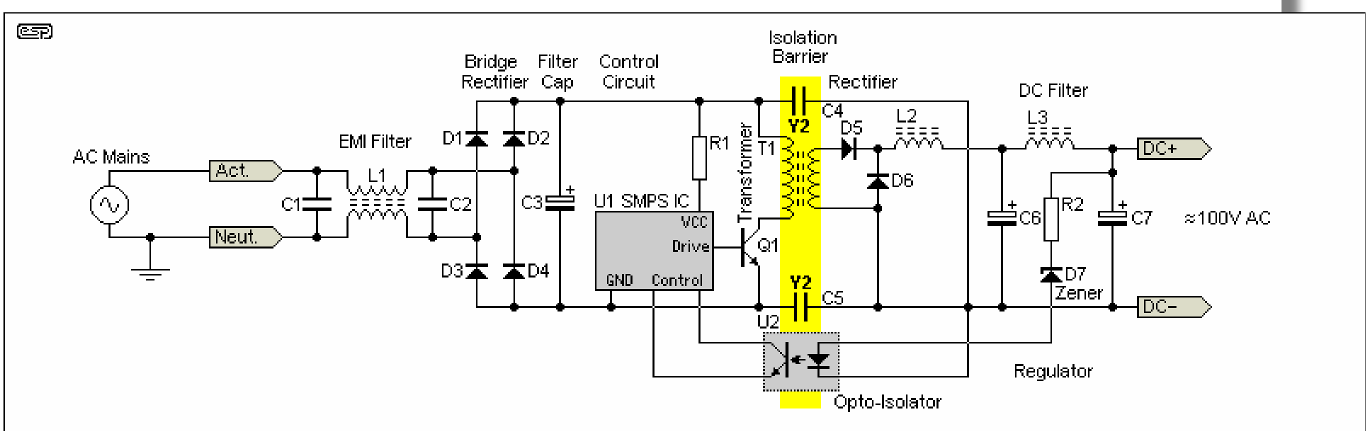

Figure 5.1 - SMPS Y2 Capacitor Problem

Whether you like it or not, the neutral is *always* earthed (grounded), either at the local distribution transformer or at each premises where it enters the meter box. The DC output is floating until it's terminated to earthed equipment, and the voltage will be around 100V AC with 230V mains. It's high impedance because of the Y2 safety capacitors, so the current is low (about 100µA with 2 × 1nF Y2 caps). If external gear is connected at the wrong time (at the AC peak), the instantaneous current will exceed 200mA, and with RCA connectors that's straight into the input of the connected equipment! Fortunately for all of us, there is usually a high-impedance path to ground (often through us), and the peak will not be as severe. Can you count on this? *No!*

The only ways to prevent damage are to provide very good input/ output protection circuits, or to ensure that connections are never made or broken while power is applied. In many cases, this will require disconnection of the mains lead, because the SMPS is often on full-time, and its output is switched. Ignore this at your peril, as it's a very real problem.

Conclusions

The overall conclusions are fairly clear. For most audio circuits we don't need to take special precautions, but extreme care is needed for circuitry that is powered from a switchmode power supply (SMPS) (whether internal or external). Always disconnect the power before connecting input/ output leads to any circuit powered by a SMPS. Most of the recommendations shown are fairly basic, but if implemented properly will save equipment from damage. For 'benign' applications, we often don't need any protection at all, because the chances of a destructive fault are so low.

Elsewhere, even the circuits I described may not be sufficient because of the operating environment. Electronics in cars are particularly vulnerable, because the nominal 13.8V DC supply can jump to over 40V with what's known as a 'load-dump'. These occur when a high-current load is disconnected, or if the battery is disconnected (accidentally or deliberately) while it's being charged. Other systems can also create voltage spikes that are quite capable of causing damage in any electronic system that's not properly protected.

Most of us will (hopefully) never destroy the circuits we use by electrostatic discharge or other faults, but that can lead to complacency - just because something hasn't happened does *not* mean that it won't or can't. Most of the parts we use are surprisingly robust, and while I have killed parts, it was part of a deliberate test rather than an accident. If you know that equipment will be used by people who know nothing about electronics in potentially hostile environments, it's worthwhile to take as many precautions as you think will be needed.

Remember that if someone 'blows up' something that you built, it's *never* their fault! Many (most?) people will claim that they used the equipment as instructed, and didn't do anything wrong. The gear simply 'blew up' for no reason, and the fact that they installed the battery in reverse (or other 'accident') will not be revealed. It's something service people have had to deal with since the dawn of electronics. Even when it's quite obvious that a misguided and heavy-handed attempt at self-service caused additional damage, nothing is admitted in most cases.

"It wasn't me, I wasn't there, and no one saw me!"

Most service techs have heard that (or something similar) countless times. It won't change any time soon. ☹

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