



[Design femtoampere circuits with low leakage - Part 2: Component selection](#)

Paul Grohe, Texas Instruments Precision Systems Group - June 15, 2012

Part one of this article defines and describes the designs that carry these low currents, explains the problems that arise when you design these circuits, and examines the application of shielding and guarding methods. In Part 2, we examine how your component selection affects the performance of your low-leakage circuits and discuss how noise creeps into low-leakage designs.

Component effects

Resistors

High-impedance circuits, by nature, involve the use of high value resistors. Values range from hundreds of kilo-ohms up into the hundreds of Megohms and even as high as tens of Teraohms.



Figure 1. Glass Enclosed Multi-Gigohm Resistors

Beyond the normal resistor errors that we expect, the familiar tolerance and temperature coefficient (tempco), there are other errors that are important in these circuits.

Large resistors generate lots of noise. Mr. Johnson's beloved thermal equation¹ produces very large numbers when solving for these very large resistance values. A 10Meg resistor generates 2.4 μ Vp-p of noise in just a 1Hz bandwidth. A 1Gigohm resistor generates 24 μ Vp-p noise in just a 1Hz BW.

Theoretical Resistor Noise @ 25°C

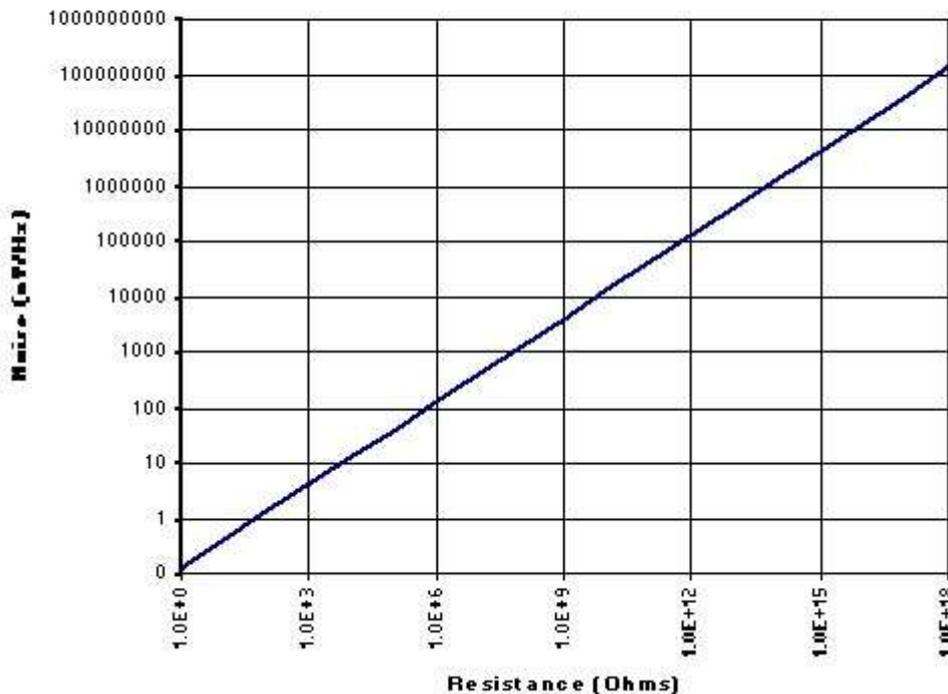


Figure 2. Resistor Thermal Noise

A quick way to get the rough nV/Hz RMS resistor noise at room temperature (25°C) is to multiply the square of the resistance by 0.13 (or 0.128299).

Resistor noise in $nV\sqrt{Hz} = 0.13 * \sqrt{R}$ (Multiply RMS by 6 to get Vpp).

In most cases, you will find the noise is greater than the expected signal level. It is important to limit the measurement bandwidth to just what is required. Every extra Hz of bandwidth is just adding more noise.

The exotic materials used in the construction of the high-value resistors can also add additional noise, which can add to the theoretical noise. It is not unusual to find the noise slightly higher than what was calculated for the resistance value.

Resistors can also have a significant parallel capacitance. The typical ¼ watt resistor can have 0.15pF to 0.5pF in parallel with the resistor. When dealing with high impedances, every pF counts, especially with the high value feedback networks.

One trick to reduce the series capacitance is to use several resistors in series instead of one resistor. This way the capacitive strays are placed in series.

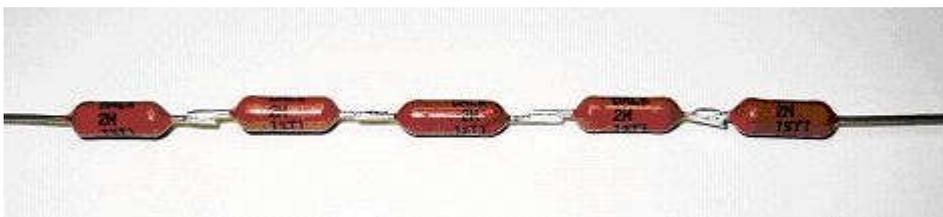


Figure 3. Resistors in series to reduce capacitance

If one 10Meg resistor is 0.2pF, then two 5Meg resistors in series are 0.1pF, five 2Meg resistors are 0.04pF, and ten 1Meg resistors are 0.02pF. More than five is getting into diminishing returns. The resistors should be soldered end-to-end and all placed above the board for best results. Two or three surface mount resistors can be mounted vertically on the same pad.

High value resistors can also have a voltage coefficient, where the value of the resistance changes as the voltage across the resistor increases. This is most apparent at high voltages (>100V), and is usually not a big problem for small signal feedback resistors since the voltages across them are very low or zero.

Some of the resistors, particularly multi-Gigohm surface mount types, are made out of exotic substrate materials, and may require silver solder or other special soldering precautions. Examine the resistor datasheet very carefully, and read the manufacturers application notes.

The bodies of high value resistors should not be touched, and should be handled only carefully by the leads to prevent getting body oils on the resistor body surfaces. These resistors may also have a thin protective silicone coating to seal out moisture that must be protected. Gloves are recommended if handling by the resistor body is necessary. Resistors with values in the thousands of gigohms are generally encased in a glass body to reduce leakage and protect the element. Again, read the datasheet carefully for any warnings or special handling and cleaning instructions.

Capacitance

There are two types of capacitors: intentional and unintentional. "Intentional" capacitors are the ones you purposely place in your circuit, and "unintentional" are the ones you did not place there but are naturally hanging off every node of your circuit. These unintentional capacitors are known as "strays", as any conductor facing another conductor is a capacitor.

Because of the ultra high impedances generally involved with low current measurements (>Gohm), the effects of device and stray circuit capacitance are very prevalent and cannot be ignored. A few pF of stray capacitance, which normally one would not even think about in a "normal" circuit, can become a big nuisance in high impedance circuits. Time constants in the multi-gigohm and picofarad world can range into the seconds, even minutes.

Component and stray capacitance will usually dictate the ultimate bandwidth of a circuit, and not the bandwidth of the amplifier. So minimizing stray capacitance is critical if any bandwidth is required.

Capacitor "Soakage", or Dielectric Absorption

Capacitor "Soakage", or Dielectric Absorption is a capacitors seeming ability to "remember" what voltage it was previously charged to after being discharged.

One can think of the soakage model as a second capacitor with a very large series resistance in parallel with the main capacitor.

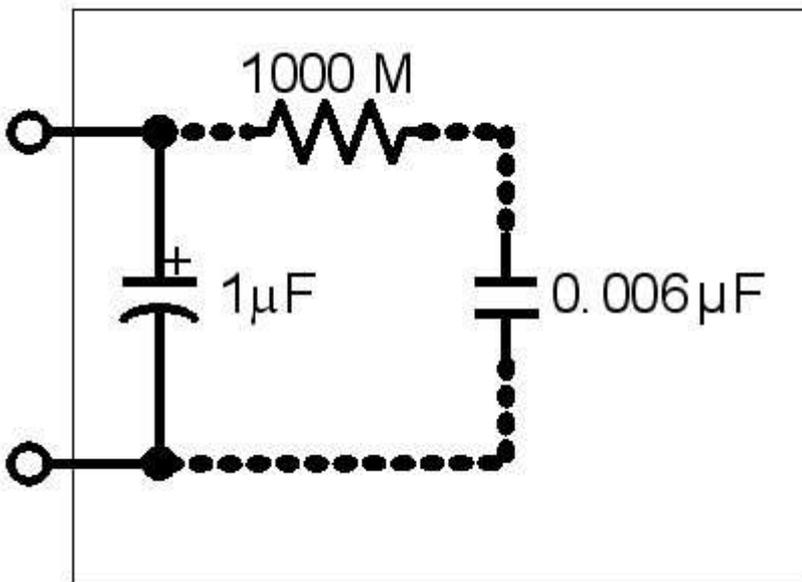


Figure 4. Model of Capacitor Soakage

Simply shorting the main 1uF capacitor does not completely discharge the "parallel" capacitor completely because of the series resistance. The parallel capacitor then re-charges the main capacitor slowly through the series resistance. The result is the main capacitors open-circuit voltage slowly creeps up to a value close to the original charge voltage.

Because of the high impedances generally used in low current circuits, this effect can be a noticeable part of a measurement, particularly in sample and hold, integration capacitors, and even the capacitance of some insulation materials.

The type and quality of dielectric or insulation determines the amount of soakage. Teflon and Poly capacitors are very good, whereas tantalum, ceramic and most electrolytic capacitors can be poor. Even other materials, such as PC boards, connectors and insulators can have these absorption effects. Bob Pease wrote an article² in which he tested several types of capacitors for leakage. As expected, Teflon and various Poly capacitors topped the list of lowest absorption, and tantalum, mica and ceramic had the highest.

Nodes should be grounded or kept at minimal potentials when idle to minimize dielectric absorption. Capacitors should be shorted with a small value resistor when idle. Avoid keeping large voltages on measurement nodes for extended periods and do not let integrators "rail" for long periods.

Op-amp input bias current effects

Op-amp input bias current effects

The "Bias Current" of the Op-Amp is generally the first hurdle to overcome and can be the dominant error current in a high impedance circuit. The effects over temperature and input voltage also cannot be ignored. Every Op-Amp datasheet mentions the bias current specification. But what is it and why is it so important? There are three major types of input devices for op-amps; The Bipolar junction transistor (BJT), the Junction FET (or JFET) and CMOS MOSFET devices.

The bias current for a bipolar input is the base current for the input transistor.

Bipolar bias current values range from several microamps for very high-speed bipolar devices, down into nanoamps for slower, precision devices. Since bipolar input devices are rarely used for sub picoamp current applications, we will focus mainly on JFET and MOSFET devices.

The bias current for a JFET is much lower than a bipolar transistor, but the gate is still a P-N junction and has the leakage properties of a reverse biased diode. The bias currents of JFET devices, like the popular LF4xx or TL0xx series, range down into the 10's of picoamps and into the low hundreds of femtoamps.

The CMOS MOSFET device has the gate insulated from the channel by a thin layer of oxide, like a little glass window. CMOS device leakages are typically in the dozens of femtoamps to almost immeasurable.

However, for CMOS op-amps, the gate current is but a tiny part of the "bias current" typically seen on the input pin of the CMOS Op-Amp.

The oxide "glass" that forms the gate insulator is only a few angstroms thick, and will be easily ruptured by overvoltage - sometimes as low as 10V. This necessitates some protection if the device is to survive in the real world.

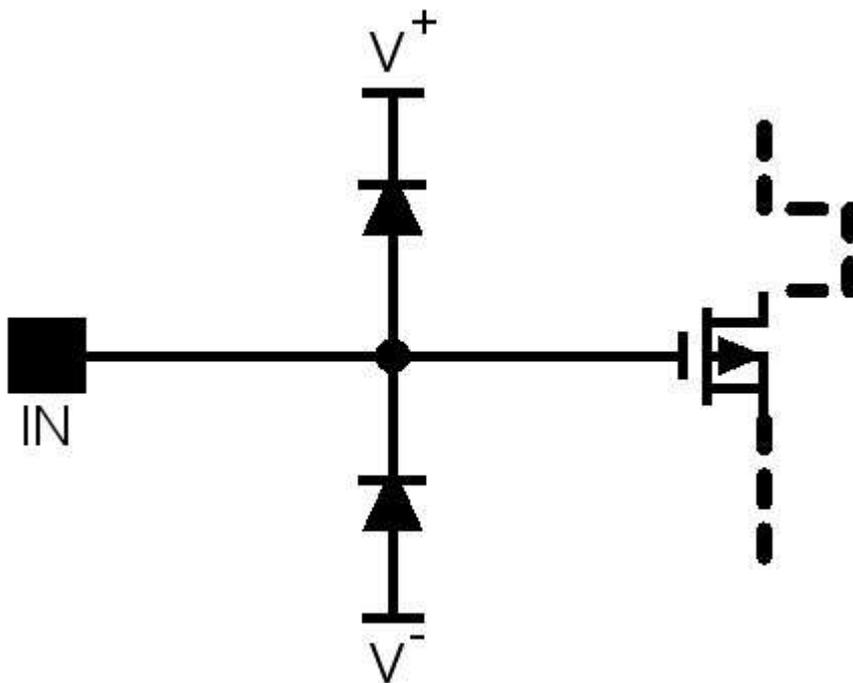


Figure 5. Input Protection Diodes

To prevent rupturing the oxide, each input has two ESD protection structures ("diodes"); one to V+, and one to V-, to clamp any excess input voltages to the power supply lines.

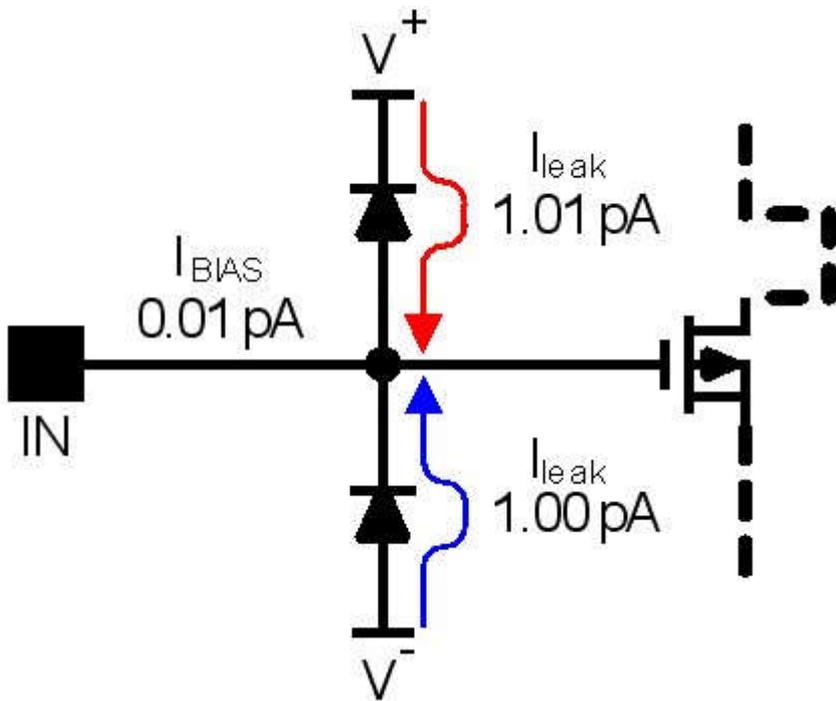


Figure 6. Diode Leakages Cancel

These ESD protection structures do leak, but both structures leak equally, and to opposite power lines, so the net result is the leakage currents tend to cancel out at the input pin. Tight processes control and careful layout allows matching of the structure leakage currents to within a few femtoamps at room temperature on the die. This is almost impossible to do with external discrete diodes.

But because nothing is perfect, there is always a slight mismatch between these two structures. So what you are seeing as "bias current" on the input pin is mostly the difference in the leakages of the ESD protection structures, as well as any stray leakages of the die or package.

Because these ESD structures are basically diodes, they have a leakage profile that follows that of a diode over temperature. As the diodes get warmer, the leakage increases.

The rule of thumb is that the bias current of a CMOS Op Amp will roughly double every 10°C. So a 2fA current at 25°C should become roughly 2pA at 125°C.

Input Current vs. Temperature

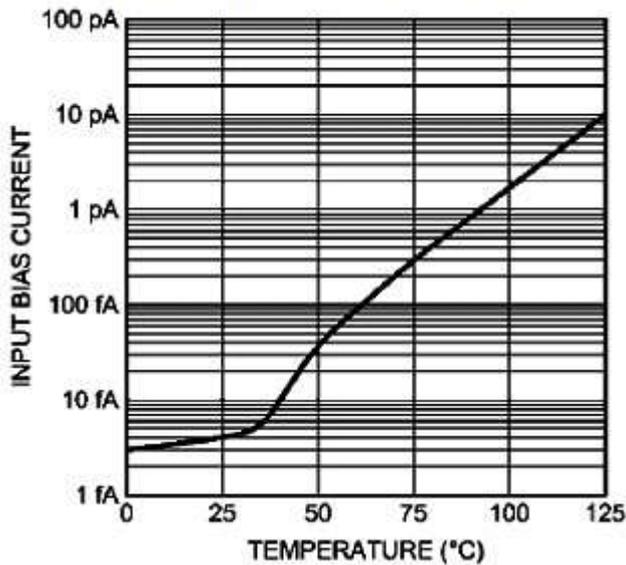
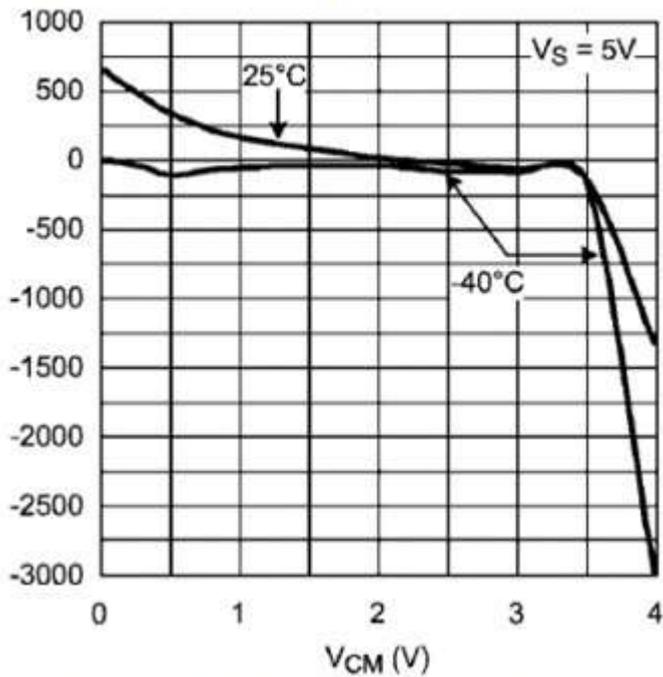


Figure 7. Example of LMC6001 Bias Current over Temperature

In reality, this rule of thumb is true mostly at the upper operating temperatures (above 40°C), and the curve will deviate at the lower temperatures due to internal die trace and package leakages becoming a bigger part of the theoretical current, as shown in figure 7.

Because the bias current is a balance between the two ESD diodes, this creates a low-current "sweet spot" in the middle of the VCM range (mid-supply) where the currents cancel.

Input Bias Current Over Temperature



Input Bias Current Over Temperature

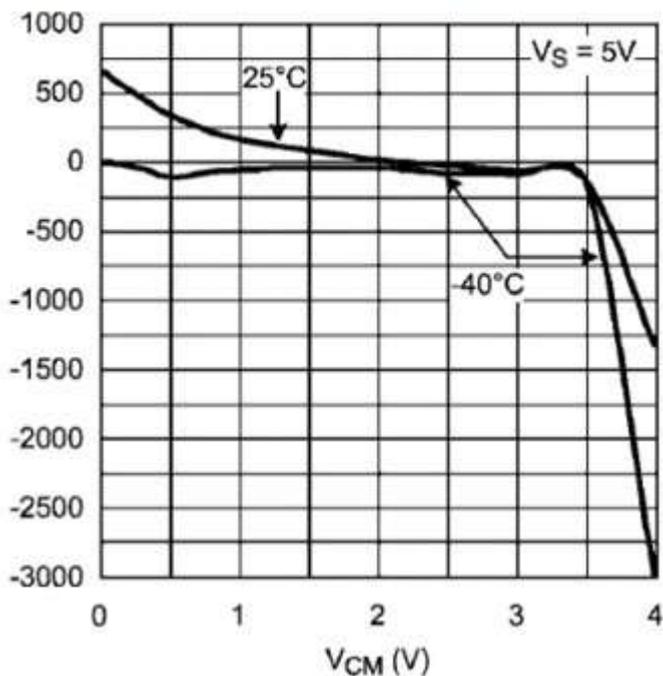


Figure 8. Example of Bias Currents over Common Mode and Temperature (LMC6001)

Notice how the curves pivot around 2.5 V over temperature. Always try to design the circuit so that the input voltages are around the center of the input voltage range for the lowest bias current and temperature effects.

As the input voltage gets within 1-2V of the supply, the bias current will start to creep up as one of the diodes starts getting pinched off and the balance is lost.

Input resistance

A quick word about the term "Input Resistance" as it applies to JFET and MOSFET op-amps. It is somewhat of a misnomer. It is tempting to think of the input as a high resistance, usually in the range of Gigohms to Terohms. But it is risky to think that the input of the op-amp looks purely

resistive, when it is actually more like a bi-directional current source. Bias current can flow out of, or into, the source circuitry, causing errors in both positive and negative directions.

As you can see in the previous graphs, this current can change direction over common mode, over temperature, or even through device-to-device variations. The "load" the op-amp presents to the source is neither a fixed value or unidirectional. The designer should see the input bias current error as a random bi-directional current and take the appropriate precautions to accommodate these shifts (offset adjusts trimming, zero checks, etc).

Another assumption about "input resistance" is that it is constant over frequency. It is not. The Teraohm input resistance numbers are only good only at DC. At any frequency other than DC, the "input resistance" is now the impedance of the total input capacitance. The "impedance" at DC may be Teraohms, but that can come crashing down into the lower Megohms at 1KHz if the input capacitance is high. At AC frequencies, you will be fighting the input capacitance.

When using CMOS or JFET amplifiers, the second "bias current canceling" resistor, commonly used with bipolar devices, is generally not needed, and will just add to the system noise.

Counteracting bias currents or leakages

In some cases, it will be necessary to counteract the effects of bias current or leakages.

The most common brute-force solution is to offset the circuit reference voltage to cancel, or "zero out", the error. But what happens when you cannot baseline-offset, as in the case of an integrator? The first circuit that comes to mind is probably a large resistor from the input to an adjustable voltage source, as commonly done in "normal" current circuits to compensate for offsets. This can work, but the input impedance is reduced and the extra noise of the large resistor is added to the input (plus any current noise contribution), and at low currents, these resistors can become quite large.

There are better ways. Every circuit and design is unique, but there are a few basic circuits that can be adapted for use.

If a driven guard is used, it may be possible to add a positive or negative offset to the guard voltage to compensate for leakages. This is only recommended for "fine tuning" of the baseline by only a percent or two.

If offsetting the guard is not possible, then a "probe", or pseudo guard, can be used. This is where an electrode or trace is purposely placed in close proximity to the input trace and driven to some potential to counteract the leakage. The probe or trace then "leaks" through the medium and into input trace, counteracting the leakage.

If the leakages come from one particular source (PC board for example), then the guard-offsetting or "probe" techniques are self-compensating (i.e., if the leakage current increases due to temperature or humidity, so does the compensating current). Combined leakages from several sources are more difficult to compensate.

It is also possible to use a reverse biased diode between the input and a small adjustable potential (several mV). The adjustable voltage allows the user to precisely control the amount of diode "leakage" into the input. However, this may introduce some extra noise and a variable capacitance to the input. One advantage is that the "leakage" will follow the diode tempco curve and is best for offsetting leakages due to semiconductor devices. Diode-connected transistors can often be used in place of diodes for lower leakages.

Noise sources

Noise sources

External noise can be introduced into a circuit in several ways.

Electrostatic coupling

Electrostatic coupling is generally the most common way noise is introduced into high impedance circuits.

Electrostatic coupling can be thought of as long-distance capacitive coupling. The radiating surface or conductor comprises one of the plates of the capacitor, and the circuit nodes become the second plate of the capacitor. Even the equivalent capacitance of fractions of a picofarad can couple significant signals into sensitive high impedance nodes.

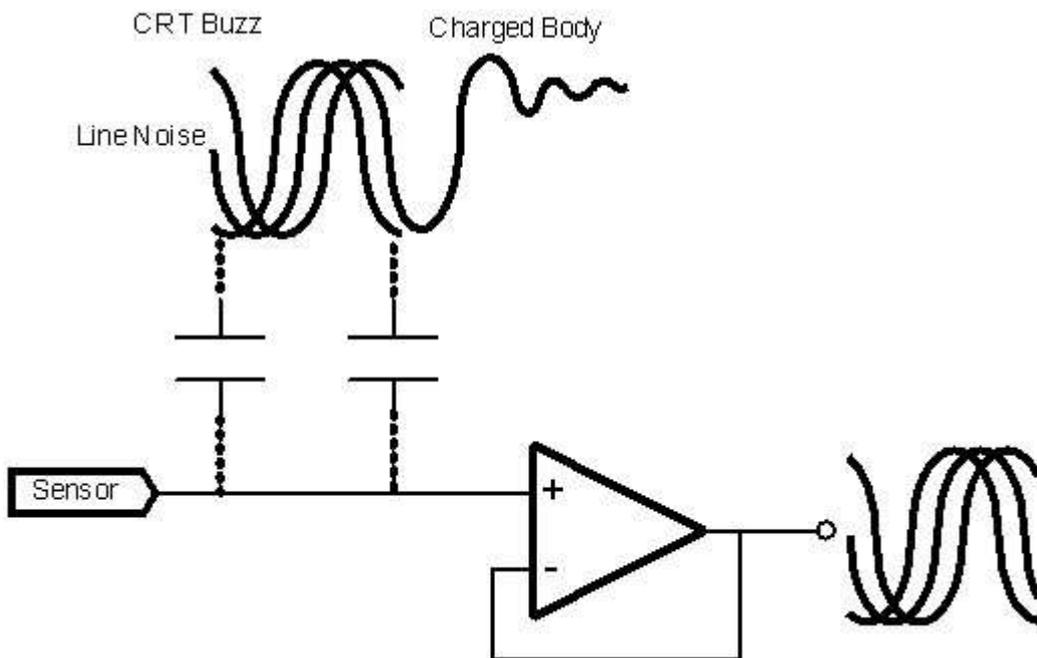


Figure 9. Model of Electrostatic Coupling

If the interference, say power line noise, increases as you move your hand close to the circuit, and reduces if you touch ground, then you are suffering from electrostatic coupling.

The most common effect of electrostatic coupling is the "proximity" effect, or the ability for a sensitive circuit to "see" your hand moving from centimeters away, or the "antenna" effect, where the circuit can "sense" another signal (power line noise) from a distance.

To explain this, we have to look at the capacitance rate of change formula.

$$i = \Delta v / \Delta t * C$$

For a given charge, any change in capacitance will cause a change in current. Alternately, for a given capacitance, any change in voltage will cause a change in current (Δt never stops in real-time). Therefore, any conductor that is either physically moving (changing capacitance), or has a changing voltage on it (a fluctuating signal), will induce current into the circuit through the electrostatic "capacitor". So a conductor running near by that is either physically vibrating or contains a fluctuating voltage, can couple noise into the high impedance circuit. A loose and unshielded power wire can also cause the output to "wobble" when the fixture is moved due to this effect.

Luckily this is one of the easiest noise problems to fix. All that is required to avoid electrostatic coupling is to insert a solid third "plate" between these two "plates" to break the electrostatic path.

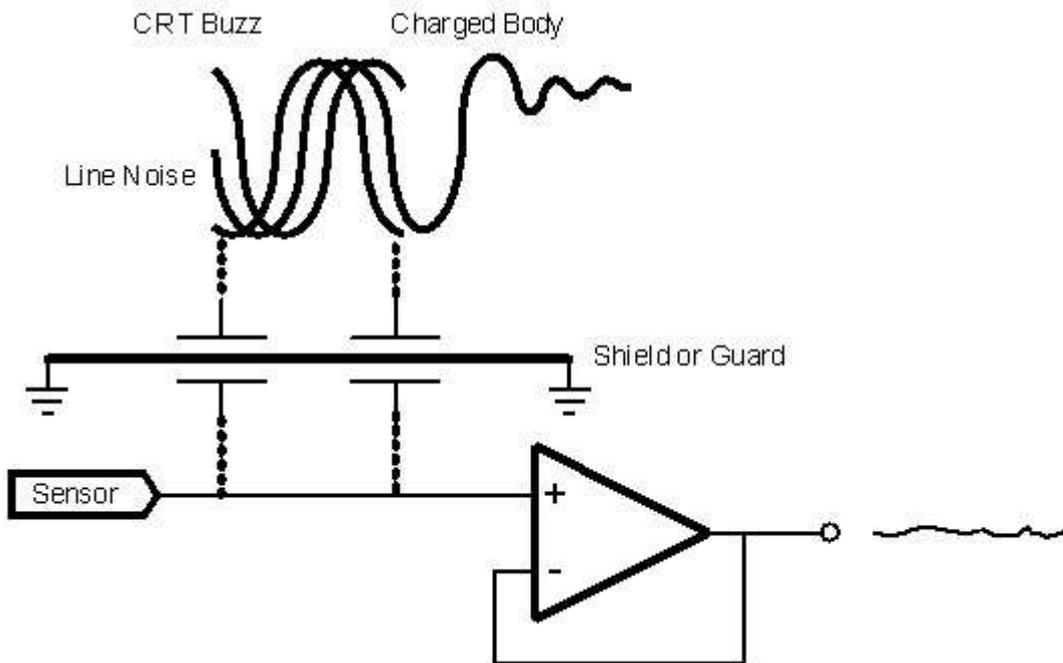


Figure 10. Solving Electrostatic Coupling

Surrounding the input stage in a conductive "cocoon" will eliminate most electrostatic coupling. The shield need not be ferrous, but at least conductive.

Another side effect of electrostatic coupling is input-to-output oscillations in high gain applications, where the input circuit can "see" the gained-up output signal conductor. The input can sense the output moving and creates positive feedback, similar to a PA system microphone feedback "howl". Input traces should always be shielded from the output signal lines.

One word of caution: If you use a large piece of thin aluminum or copper foil to shield your circuit, beware that you may be inadvertently creating an electrostatic microphone. The large, thin area can vibrate with sound waves or mechanical disturbances, and conversely modulate the stray capacitance (ΔC) as these surfaces vibrate. This "microphone" could be modulating low frequency noise like air conditioning rumble, handling noise and footsteps - even voices. Make sure any large surface areas are thick enough, stiffened, or dampened enough to minimize vibrations.

Electromagnetic coupling

Electromagnetic coupling

We are most familiar with electromagnetic coupling. This is the "transformer" effect where a magnetic field crossing a conductor creates a current across that conductor. This coupling can be in the form of "hum" from stray flux from a power transformer or RF transmitter. Switching power supplies can "spray" high-frequency flux into nearby conductors - even if they are electrically shielded. This is the most difficult effect to eliminate.

The most common effect is power line "hum" that is seemingly position sensitive, in that the amplitude of the hum changes as the circuit board is moved around. The common cure is to twist the input and return conductors together so that the induced currents cancel, but this may not be possible with coaxial or triaxial cables, or other single-ended unbalanced conductors.

Electromagnetic coupling is more difficult to eliminate and may require the use of special shielding materials (Steel, Mu-metal), or re-positioning the circuit perpendicular to the flux to minimize pickup.

Ground loops are even more sensitive

Ground loops become even more prevalent at low current levels. In most cases, a ground loop of only a few nA would not even raise any eyebrows. However, if the input common of a sensor is shared with the shielding or power ground, the ground currents can end up being superimposed on the measurement reference signal. The common or reference to the sensor should not be shared with any protective or power grounds.

Circuit voltage noise (amplifier) / amplifier selection

It is tempting to use the lowest noise Operational Amplifier for a sensitive circuit, but in the case of high-impedance circuits, this can be overkill, or even detrimental to circuit performance.

In most cases, the largest source of noise is the feedback resistor or sensor source impedance. Noise adds in the sum-of-the-squares fashion, so if you have a 400nV/Hz worth of source noise, a 6nV/Hz, or even a 50nV/Hz amplifier will not make much of a difference in the overall noise figure (400.04nV vs 403.11nV).

In order to make a JFET or CMOS device "low noise", the gate area of the input device must be increased by paralleling several devices. This increase in gate surface area will proportionally increase the input capacitance. A standard CMOS device, like the LMC662 (at 22nV/Hz), will have an input capacitance of 2-3pF, whereas a low noise CMOS device, like the LMV7715 (at 6nV/Hz), will have almost 15pF of input capacitance.

In inverting or transimpedance applications, this extra input capacitance in the inverting node can cause peaking, which will require feedback compensation, which eats into system bandwidth.

For non-inverting or buffer applications, the capacitance will add to the capacitive loading of the source, creating a RC pole with the source resistance, lowering the overall system bandwidth.

If bandwidth needs to be maximized, it may be necessary to use a noisier amplifier with less input capacitance.

Circuit current noise (amplifier, resistors)

Active devices also have noise currents. Noise Current can be thought of as the AC noise equivalent of DC bias current. At low impedances, current noise is generally not a problem. But at high impedances, this noise current can generate a noise voltage across input impedances, just like DC bias currents generate a voltage offset across input resistances.

Even if the DC bias current is cancelled out, a device with 0.1pA/Hz noise current will generate an additional 1000nV/Hz worth of noise voltage across a 10Megohm resistor. Current noise is uncorrelated and cannot be "cancelled out" with another resistor like the DC bias current.

Switches and switching

In some applications, input switching or multiplexing may be necessary. In the above picoamp world, electronic switching using JFET and MOSFET switches is common. However, in the sub-picoamp world, mechanical switches and relays still rule the roost.

While MOSFET and JFET switching can have relatively low leakages, they tend to suffer from charge injection, limited common mode range and stray capacitive effects. Reed relays dominate because of their compact size, fast operation, low leakage and ease of guarding.



Figure 11. A Typical Reed Relay with Electrostatic Guard Example

A reed relay consists of a pair of contacts enclosed within a long, hermetically sealed glass tube. A coil surrounds the reed to magnetically close the contacts when the coil is energized.

For low leakage applications, the reed can be placed inside a copper tube (inside the coil) to provide complete guarding of the entire reed assembly. With proper guarding, the relay is almost invisible to the circuit. The guard contact can be seen on the left side of figure 13.

One thing to be aware of with reed relays is the one-turn "transformer" effect. In the time between energizing the coil and the opening of the contacts, the reed acts as a one-turn secondary (with the coil as the primary). This can generate several millivolts across the relay contacts for a millisecond or two until they open. Be aware of this, particularly in integrator capacitor reset applications. Lower voltage relays will have less of this effect due to the lower number of turns in the coil.

Mechanical armature relays are generally not used due to their large size and difficulty to guard.

Power line noise

Power line noise

Powerline noise can manifest itself through many different ways. The obvious ways are the aforementioned ground loops, electrostatic and electromagnetic coupling, but there are some other avenues where line noise can infiltrate a high-impedance circuit.

For op-amps, instrumentation amps, CMOS switches and muxes, A/D's and other active devices with high impedance inputs, the input pins most likely have ESD protection or clamping structures on their input pins (as previously discussed). These structures have a direct connection to the power line, and also have inherent device capacitance across them. This small capacitance can couple noise directly into the high impedance input signal, bypassing any of the native Power Supply Rejection Ratio (PSRR) of the device. A few millivolts of "hum" or digital "hash" on the supply line can make its way through the protection diode capacitance and embed itself in the input signal.

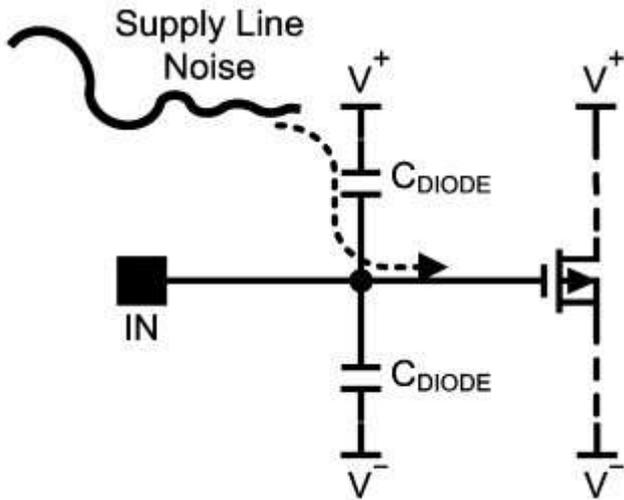


Figure 12. Supply Noise coupled through ESD diode capacitance

Another entry point is power supply derived bias voltages, which are usually obtained through a resistive divider. The typical $V_s/2$ divider has only 6dB of power supply rejection without any filtering. Adding a bypass capacitor to the tap may boost this up to 20-30dB or more at high frequencies, but at low frequencies, the capacitance may not be enough to completely eliminate power line frequencies (and their harmonics). If this bias line is used to provide a bias voltages for the sensor (before the gain stage), then the noise can "modulate" the sensor signal and be amplified along with the sensor signal.

Obviously, the rule here is to keep the supplies and bias voltages as clean as possible. Very sensitive stages should be supplied from a separate supply. In most cases, a simple R-C-L filter on the supply lines will suffice.

A word of warning: When bench testing, digitally controlled power supplies can have a combination of hum, switching noise and digital "hash" on them. Also, many DMMs have a lot of digital sampling transients on their inputs. The DMMs, when connected to an analog supply to monitor the voltage, can inject digital noise into the supply lines. If you see noise on your signal that correlates with the DMM's display update rate, then turn the DMM off and see if the noise goes away.

Ionizing Radiation

One interesting phenomenon that occurs down at the femtoamp levels is the detection of naturally occurring ionizing radiation³. The most common effect is a sudden "pop" or step change in a measurement.

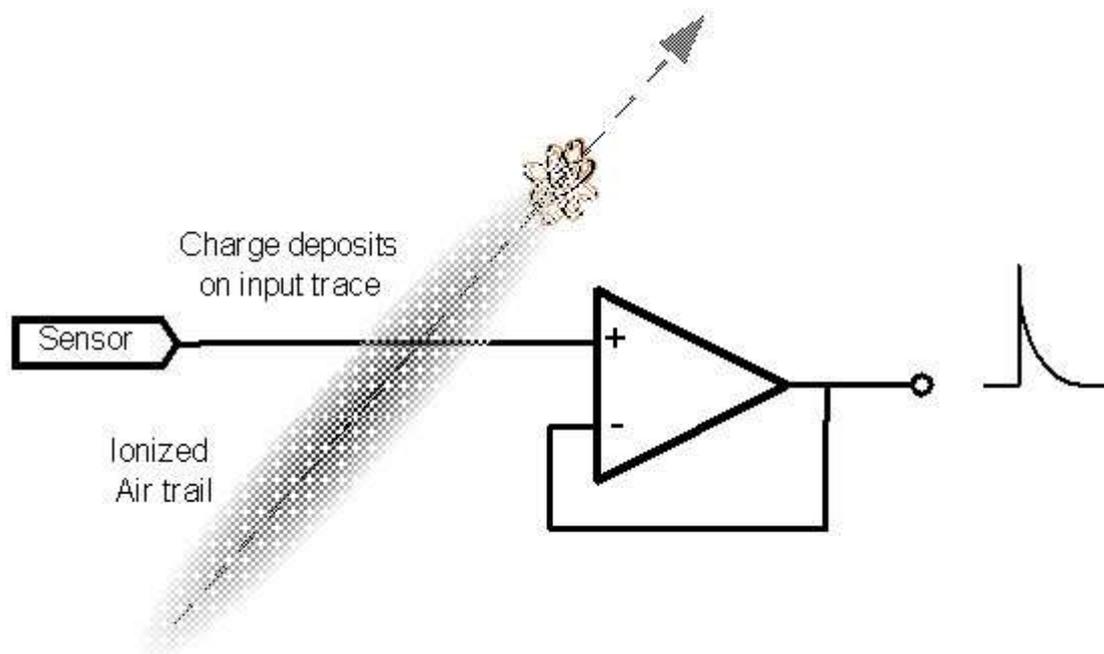


Figure 13. Ionizing Radiation deposits charge on circuitry.

As the particles fly by at the speed of light, they ionize the air in their wake. If the input conductors happen to be near by, they will accumulate some of this charge.

The radiation sources are both terrestrial, and extraterrestrial, and are all around us. The largest contributor is extraterrestrial. Energetic particles are generated from the sun, solar flares, exploding supernovae and other galactic sources. Those particles have come a long way to disturb your measurement! Terrestrial sources of radiation can include common materials such as ceramic, stone and granite. Radon can accumulate in enclosed underground areas.

Alpha and beta particles can be stopped with a few millimeters of aluminum, but the more energetic gamma and "X" rays (which can create the alpha and beta particles) are stopped by much more dense materials (centimeters of lead).

This phenomenon may occur once a week, or several times in one day, maybe once a year. The strikes are random in both time and amplitude, and frequency depends on circuit layout, sensitivity, altitude and construction materials.

With an integrator, this sudden accumulation of charge will look like a sharp step, but the slope of the line generally does not change. A transimpedance amplifier will show a sharp rising edge followed by an exponential decay.

The only way to minimize these events is to minimize the amount of air between the measurement nodes and the guard, as well as keeping the surface area of the input conductors to a minimum. Do not inadvertently create your own small-scale ion chamber!

Triboelectric effects

Triboelectric⁴ charge is when two different materials are rubbed together and a charge is created. This is the familiar "comb in hair" spark effect.

This effect is most evident in coaxial cables where the conductors rub against the plastic dielectric as the cable is flexed. These materials rub against each other and can create a charge between the outer shield and the inner conductor.

To see this effect yourself, connect one end of a coax cable to an oscilloscope and set the scope to it's lowest sensitivity, then wiggle or tap the cable. You will see that a voltage waveform is generated just by moving the cable. Special "Low Noise" coax cable designed for high impedances places a graphite powder around the dielectric to minimize the effect. Messy, but effective.

Many connectors, such as inexpensive BNC's or multi-line IDC headers and D-Sub connectors can also exhibit this effect as the plastic insulator rubs against the pins or housing. Special care should be exercised when selecting any connectors for low-level signals. Teflon (PTFE) insulated connectors are the recommended.

Piezoelectric effects

Another charge generator is the Piezoelectric⁵ property. Piezoelectric charge is where a single material self-generates a charge when stressed, impacted or flexed. The most familiar of these is the Piezo crystal, as found in Piezo speakers, BBQ lighters and "crystal" microphones. Many materials, including ceramics and glass have Piezo properties.

As the audio guys can tell you, ceramic capacitors are very microphonic, and will generate a tiny voltage when stressed or vibrated. At low current levels, this effect can be a significant source of "mechanical" noise, especially with surface mount devices where they are rigidly affixed to the board and can sense board flexing and vibrations. Care should be taken if ceramic capacitors are used so that they are not subjected to stress and vibrations.

Mechanical stress and vibrations

Mechanical stresses on the components or insulation materials can create charges that will interfere with the signals. Components that commonly tend to get repeatedly stressed are the PC board, controls and signal connectors to the outside.

The PC board itself can generate a charge if flexed or stressed. This can be an issue in portable, vehicular or other "ruggedized" operating environments. Multiple mounting points, board stiffeners and board supports may be needed. Switches, potentiometers, connectors and other external devices should be securely mounted to the panel and not rely on the PCB for mechanical support.

[Part 3](#) of this series provides detailed PCB-design techniques and shows a real-world example of a low-leakage design.

Author Information

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