Design femtoampere circuits with low leakage, part one

Paul Grohe, Texas Instruments - November 17, 2011

Circuits that carry femtoamperes of current have many subtleties that you wouldn't normally consider in the design and layout of conventional circuitry. If you overlook these subtleties, the circuit loses low-end resolution and exhibits drift due to the components, materials, and circuit layout. Knowing the circuit's limitations and leakages and providing ways to minimize or eliminate them will lead to improved circuit performance.

The world below a picoampere is unique and plays by a different set of rules. In this world, even the mechanical parts of the circuit can become parts of the electrical circuit. Designing for operation at subpicoamp and femtoamp levels requires special techniques and compromises that normal current levels don't generally require (**Reference 1**). Unfamiliarity with or neglecting these precautions can result in endless headaches for designers. Electrical engineers will find themselves playing double roles as mechanical engineers.

This three-part article guides you through the tricky and unconventional design techniques you need to create successful low-current circuits. This first part defines and describes the designs that carry these low currents. It explains the problems that arise when you design these circuits and examines the application of shielding and guarding methods. Part two will examine how your component selection affects the performance of your low-leakage circuits and discuss how noise creeps into low-leakage designs. Part three will provide detailed PCB-design techniques and show a real-world example of a low-leakage design. It will also describe how to verify the performance of your low-leakage-design techniques.

Low-current applications

To put things into perspective, 1A equals 6,241,500,000,000,000,000, or 6.24^{18} electrons/sec; 1 pA, or 1^{-12}A, equals 6.24 million electrons/sec; and 1 fA equals 1^{-15}A, or 6240 electrons/sec. In the subpicoamp world, there are three common enemies: current leakages, noise sources, and stray capacitance. A good low-current design must minimize the effects of these common enemies and strike a balance between optimal performance and product manufacturability. You will need special techniques and materials that may be incompatible with conventional production flows.

These high-impedance circuits often go directly into an amplifier input with no parallel-resistive connections. Examples of these circuits include pH probes, gas-sensor amplifiers, medical sensors, sample-and-hold circuits, and three-amplifier instrumentation amplifiers. The circuits can have input impedances into the teraohm range. A transimpedance amplifier, or current-to-voltage converter, is often used at these low current levels. You see this circuit configuration in noninverting amplifiers, photodetector amplifiers, current-to-voltage converters, and photomultiplier circuits. The amplifier's inverting input node and its feedback elements are critical nodes. The current leakage in this node determines the ultimate accuracy of the device.

Higher-current circuits, such as low-frequency filters and logarithmic amplifiers, also benefit from low-leakage-design techniques. They will have extended dynamic range, with improved low-end accuracy and lower drift than nonoptimized designs. **Causes of disturbance**

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Dirty PCB traces can cause leakage at low currents. The dirt between the traces or across insulating materials—not the trace or wire itself—causes the leakage, serving as a conductive medium between two conductors. Dry dirt in itself may not cause a problem. A combination of dirt with moisture, salts, and oil, however, becomes conductive. The concept here is simple: Keep things clean.

Moisture is the instigator of most leakage problems. When moisture combines with environmental salts and other contaminants, its conductivity increases. Insulation, PCBs, and other hydroscopic materials absorb the moisture, decreasing the electrical resistance of the materials and leading to increased leakage between the conductors.

Contamination between conductors can also create a galvanic reaction in the presence of the right combination of materials and moisture. Moist and salty dirt between a copper trace and a zinc-plated screw or an aluminum case will generate a current between the materials. This current is detrimental to your measurement and causes corrosion of the materials. Because the moisture level varies over the course of the day, season, and geographical location, it creates a moving baseline leakage that is difficult to remove. These leakages change hourly, weekly, or yearly, depending on the environment and the season.

The particles and moisture in air as it moves over a conductor generate a small charge, so you should protect the input circuit from moving air currents. Make sure that fan-cooling airflow does not blow directly over sensitive nodes. Airflow can also cause dust and moisture to accumulate on the conductors and components.

You must take into account the properties of insulating materials in your design. These materials come into direct contact with low-level signals, usually through the connectors, the supports, or the PCB. In the electronics industry, the most common insulators are fiberglass, glass, ceramic, PVC (polyvinyl chloride), epoxy, and Teflon. Each material has its own weaknesses and strengths. Dry air is a good insulator. Keeping conductors in the air can provide the lowest-leakage results. Air does have a low breakdown voltage, however, which limits this technique in high-voltage applications.

PTFE (polytetrafluoroethylene) and FEP (fluorinated-ethylene propylene), more commonly known as Teflon, have the best leakage and high-voltage characteristics of common insulating materials, but they are expensive, soft, and difficult to machine. Teflon PCBs are expensive because of the material and the extra steps the fabrication process requires.

Ceramic, although a good insulator, tends to be piezoelectric. Ceramic self-generates charge when it is subjected to stress or impact. It also readily absorbs moisture if it is not sealed or glazed. Although glass is a good insulator, it displays some of the piezoelectric properties of ceramics. IC packages use a molded glass-epoxy compound that allows for currents lower than 1 fA. Epoxy is an excellent, low-cost insulator; however, it is hydroscopic and can absorb moisture over time. Many components, connectors, and wire insulation use PVC, which can generate charge if flexed or rubbed against another conductor, just as combing your hair can generate current. For this reason, PVC insulation in and around the input circuit should be avoided.

It might seem logical to build the ultimate low-leakage layout entirely on a slab of Teflon. This can be a bad idea, however. Because Teflon is a good insulator, any charge deposited on its surface will slowly dissipate. If a sensitive node is nearby, the accumulated charge will lead to slow settling or drift. A better approach is to cover a large surface area with a guarded conductive plane. Although this approach seems counterintuitive to the desire for low leakage, you should minimize the use of insulators. Insulation must provide isolation, but using too much of it provides a surface to accumulate extra charge.

For low-voltage circuits, an aluminum standoff topped with a small piece of Teflon insulation works better and is less expensive than using an entire standoff made of Teflon. If the circuit will be handling high voltages, you need a Teflon standoff for its better insulating properties. For ac circuits, the narrow insulator has higher stray capacitance that may cause other problems. As in all analog design, you must consider many trade-offs. PCBs have a large influence on low-leakage design because the PCB material is in intimate contact with all of the circuit nodes.

The performance of your circuit is only as good as the performance of the PCB material. As with RF circuits that operate at gigahertz speeds, you should consider the PCB as an active component. Most PCBs' material characteristics and development focus on high-frequency RF designs. Manufacturers gear PCB specifications toward circuits that operate at these speeds. They give a nod to low-current requirements by specifying a volume resistivity. The manufacturer's specifications are for the fresh laminate material before processing—not the finished product. That product comprises a sandwich of laminates, bonding glues, fillers, solder masks, and silk-screen that make up a PCB.

The most common PCB material is FR4 (flame-resistant 4), which comprises epoxy-impregnated fiberglass cloth. Manufacturers compress this epoxy under high pressure to form a solid board. FR4 has good electrical properties, but it is not the most desirable material for low-current circuits. You can improve the performance of FR4 using special layout and circuit techniques.

When performance is more important than cost, you can use exotic Teflon or ceramic hybrids, such as Rogers Corp's Duroid hybrid substrate materials, targeting use in microwave and ultra-hig--speed digital circuits. The materials' excellent controlled dielectric properties can result in two- to three-times-lower stray capacitance and leakage than those of FR4, but at a cost two- to five-times higher.

The boards also require special PCB-fabrication processes and etching, which some PCB-fabrication houses may be unable to accommodate. The Rogers soft, bendable 3003 material, which is ceramic-reinforced PTFE, requires backing for mechanical stability. Rogers 5880, a glass-reinforced PTFE, gives the best low current and stray capacitance, but it is brittle and cracks easily. It is possible to create a hybrid board, with advanced materials for the critical layers and FR4 for noncritical layers and mechanical stability. This approach is expensive and requires using an advanced board house, however.

Use caution with solder-mask placement. Although solder masks generally help reduce moisture infiltration into the PCB material, surface-charge problems might arise with large areas of Teflon. A better approach uses a bare-copper guard-plane area around sensitive nodes. To prevent oxidation, either solder-level or plate the bare-copper guard area with gold or tin.

Shield, guard, enclose
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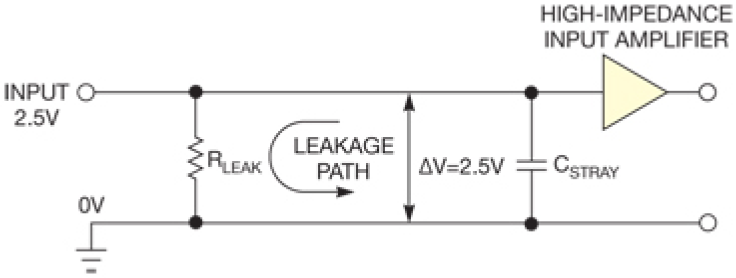

Figure 1 Current leakage and stray capacitance can cause problems in your low-current circuits.

You wire a metallic shield, case, or enclosure to a ground or a common potential. At high impedances, however, these shields create problems with stray capacitance and leakages. Examine, for example, a circuit with a 2.5V input voltage and with 2.5V across the stray-capacitance and leakage paths (**Figure 1**). The 2.5V across the leakage resistance creates a leakage current, and the 2.5V source voltage charges or discharges the stray capacitance, which takes some time to get through the high source impedance and affects the measurement's settling time.

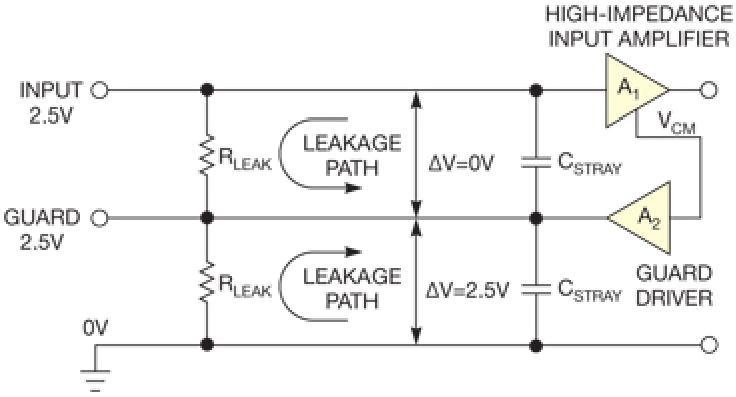

Figure 2 Adding a guard ring between the input node and ground will reduce leakage and capacitive-loading effects.

Guards are important in subpicoamp designs because they can cancel the input-leakage currents and most of the fixture capacitance. You drive the guard to a potential equal to the input-signal level. You apply a buffered output derived from the measurement amplifier. This guard acts as a subshield, surrounding and protecting the input-signal lines. External leakages now flow into the low-impedance guard instead of the input traces (**Figure 2**). This approach yields only a few millivolts of potential difference instead of 2.5V across and smaller current flows through leakage resistor R_{LEAK} and stray-capacitance capacitor C_{STRAY}. As a bonus, guards also reduce the input capacitance through a bootstrapping effect. Performed correctly, this approach can cancel out fixture and cable capacitance. Unfortunately, you cannot cancel out the amplifier's input-stage capacitance.

Locate the input traces and all of the sensitive feedback components on your PCB within the perimeter of the thick copper-guard traces (**Figure 3**). Then, remove the solder mask from this area to reduce surface charges. Buffer amplifier A_2 drives the guard ring. In the inverting and transimpedance designs, you drive the guard to the same potential as the noninverting input's node and feed the potential on the noninverting pin to the guard buffer. The noninverting node is low-impedance, and the buffer does not affect the circuit's operation. The guard should cover the entire input section, the inverting node, and the feedback resistor. Extend it as far into the sensor circuit as possible without affecting sensor operation.

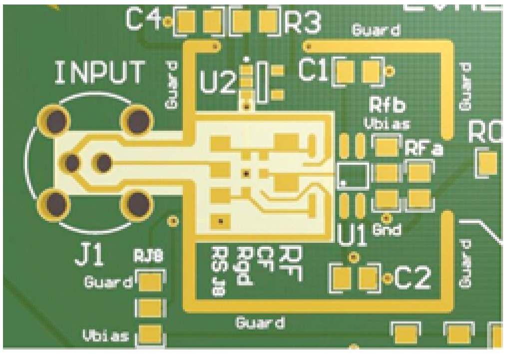

Figure 3 The thick copper trace on this PCB acts as a guard ring. The goldplated traces prevent corrosion. Remove the solder mask in the guarded area to reduce leakage.

When designing in the noninverting mode, drive the guard to the same potential as the inverting input node through a buffer. This node follows the input signal through the feedback action of the amplifier. Take care that the capacitance of the buffer's input does not cause peaking due to capacitive loading of the inverting node. The guard-driver amplifier should be unity-gain-capable and protected from short circuits and external overvoltages. The bandwidth of the buffer should be slightly wider than the main circuit's bandwidth to reduce phase-lag errors. Avoid a peaking response in the guard buffer to prevent system instability. A grounded shield protects the circuit from external noise and EMI by shunting the noise to ground. Because the grounded shield generally does not follow the input voltage, it does not cancel the capacitance caused by the guard.

In the previous examples, you buffer the guard line from a circuit node using a separate amplifier, providing a low impedance to drive the shields and coaxial-cable guards. If you need to guard a small location, you can derive a local guard from the opposite input terminal. Keep in mind that the local guard also adds capacitance to the node to which it connects. This capacitance can lead to peaking in noninverting-amplifier configurations. If the opposite node is high-impedance, the guard can introduce external noise into the summing node unless you shield the guard itself. Do not use an unbuffered guard to drive external circuitry. Use it only for the immediate area surrounding the device.

Keep in mind that the guard is not ground, and ground is generally not a guard. The guard lines should not carry any currents other than the leakages, and you should treat them as signal lines. For effective designs, use guards and grounds together. The guard surrounds the input trace, and the grounded shields protect the guards from external interference. When you lay out a PCB, place a guard plane or guard traces below the sensitive traces. Be careful not to break up the power or ground layer too much. Surround the input circuit in a guarded cocoon using metallic shields on visible component sides and guard traces on layers below the sensitive nodes.

You should enclose your low-current circuits in a sealed environment. If possible, include a desiccant pack to absorb any traces of moisture. The wiring and control shaft entry and exit points should be airtight. You can use triaxial cables and connectors for low-current measurements. The cable contains both an outer grounding shield and an inner guard shield around the center conductor, extending the guard out to the measurement point. Commercial test equipment often uses Trompeter 70-series triaxial BNCs. Agilent prefers the three-lug style, while Keithley prefers the two-lug style.

Part 2 examines how your component selection affects the performance of your low-leakage circuits and discusses how noise creeps into low-leakage designs.

Reference

1. Low Level Measurements Handbook, Sixth Edition, Keithley Instruments, 2004.

Author's biography

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For More Information			
Agilent Technologies	Keithley Instruments	Rogers Corp	Trompeter