Achieve femtoampere leakage in surface-mount op-amp layouts

Alfredo Saab - July 18, 2008

The input currents of CMOS operational amplifiers are low enough for use in electrometric circuits (Reference 1), but the leakage currents of IC packages and PC boards in such circuits make necessary the use of special materials and construction techniques. These techniques include the use of conformal coating, as well as Teflon or similar quality materials for the PC board and standoffs.

The rail-to-rail output range and sub-negative-supply input range of currently available low-cost op amps let you reduce the package and PCB-leakage currents by extending the use of well-known guarding and bootstrapping techniques. These techniques allow the use of standard materials and assembly methods for electrometric circuits. In comparison with standard-design circuits, the test circuits, built using standard FR4 PC boards without conformal coating, show input currents reduced from 500 fA to 40 fA. The remaining current is probably leakage from internal ESD-protection diodes at the inputs of the IC amplifier.

Most sensors act either as a voltage source or as a current/charge source. Each signal type places a different demand on the amplifier to which it is connected. Regardless of type, low noise and low thermal drift of the voltage offset are among the characteristics most desirable for sensor-signal amplifiers.
The input circuit of choice for use with voltage signals that originate from high source impedance is the voltage follower (Figure 1a). Its high input impedance and low output impedance make it ideal for use as a buffer for voltage-signal sources that cannot accept a load.

The op-amp transimpedance stage (Figure 1b) is useful for amplifying current signals. Its low input and output impedances suit it best as an input amplifier for current signals. Gain is the ratio of output (V) to input (A), so the amplifier gain has the dimensions of V/A (ohms).

High-impedance sensors require amplifiers with ultra-low input current. High input impedance and low input current are required to achieve the necessary bandwidth for applications like hydrophones and piezoelectric sensors. In other cases, excessive load on a sensor deteriorates the signal or the sensor itself, or both (such as with electrochemical sensors).

Electrometric amplifiers are defined (Reference 2) as those with input resistance greater than one teraohm (1 TΩ) and input currents less than 1 pA. These amplifier input currents are dominated by leakage that depends strongly on the temperature, environment, and time. Dependence on time and environmental conditions implies an uncertainty in the total input current over the operating range of temperature and humidity.

For a voltage follower, input current produces a drop across the signal source impedance that adds directly to the signal. For a transimpedance amplifier, input current is indistinguishable from signal current, and therefore adds an uncertainty to the value of total current. In both cases, input-current uncertainty translates directly to the amplifier output. It is desirable, therefore, to minimize input current and to desensitize the input current to the effects of time and environmental factors.

**Input-current reduction techniques**
Op-amp input current is the sum of transistor gate leakage and ESD input-protection leakage, plus package and PCB leakage (Figure 2). The gate leakage of a MOSFET transistor is quite small, because the gate oxide is an excellent insulator. Package leakage is caused by finite resistivity of the molding compound. PCB leakage is caused by leakage paths on the circuit board.

Gate and ESD leakage can be improved only by IC design and manufacturing. Leakage from other sources can be reduced by the use of adequate board layout and circuit design techniques, and by the use of special materials.

Standard PCB substrate materials such as FR4 and G10 are epoxy-glass composites that have electrical properties subject to manufacturing variations. Properties such as resistivity depend on the composition and grade of the original materials. These materials are also somewhat hygroscopic, they readily absorb moisture, which introduces a dependence on the circuit environment and PCB history as well. To solve these problems, electrometric circuits commonly employ materials such as Teflon, polyamide, high-grade ceramic/glass, and quartz, which maintain excellent insulating properties over a wide range of conditions.

Circuit-design methods can also reduce leakage currents. For example, test data on two amplifier circuits presented here demonstrate that a considerable reduction in input current and input capacitance can be achieved using a combination of off-the-shelf ICs and common PCB substrate materials such as FR4 and G10. Both circuits used a variation on the well-known techniques of bootstrapping and guarding. The circuits are implemented with a CMOS op amp chosen for its low noise, rail-to-rail output range and below-the-negative-supply input range, as well as good CMRR and PSRR.

Guarding the inputs of a modern op amp in its small package presents some difficulties. The traditional op-amp pinout places the terminal for negative supply voltage next to the sensitive positive input. It’s not always possible to guard amplifier inputs, because the soldering pads may be too close together to insert a metal line between them. To solve this problem, we propose a circuit technique that creates a guard ring around the input pins and bootstraps the op amp’s negative-
supply voltage line to the input voltage of the amplifier.

In a modified voltage follower (Figure 1c), the input amplifier (IC1) is powered by a 3V linear regulator (IC3), which in turn is powered from the +5V line. IC1’s V+ and V- terminals are connected across the output of IC3, between OUT and GND. As a result, IC1’s power supply is a regulated 3V source. The IC1 output drives the positive input of IC2 through a level-shifting network (D1 and R2), which provides headroom for IC1’s output voltage by setting its operating point one diode drop above the negative supply for IC1. IC2’s negative input connects to IC2’s output.

The IC2 output feeds back to the negative input of IC1, setting an overall gain of unity from circuit input to circuit output. The IC2 output also drives IC3’s GND terminal and IC1’s V- terminal, thereby bootstrapping IC1’s V- terminal. R1 and C1 provide dynamic stability, yet the low value of R1 has no effect on dc-gain accuracy. Since the voltage between V- and the IC1 inputs is always zero, the package leakage currents are minimized, as are PCB leakage currents from the circuit input to IC1’s negative supply terminal. IC2’s bipolar supply voltages (±2.5V) allow it to handle bipolar inputs and provide a bipolar output. For the component values shown, the operating voltage swing (input and output) is +1.5V to -2.4V. (Increasing the supply voltage to IC3 can raise the positive swing almost to the 2.5V rail of IC2.) Throughout this range, the output linearity is better than one part in 104.

The modified transimpedance stage (Figure 1d) is similar to the modified voltage follower, but doesn’t require a regulated bootstrapped source because the inputs of IC1 and the negative supply terminal are always at the same potential (circuit common). When compared with a standard version such as that of Figure 1b, the 95% reduction in input current is similar to that observed for the follower type. For this circuit, the output voltage swing is rail-to-rail with respect to the supply voltages used for the output stage.

**Circuit construction and test**

The test circuits were assembled on double-sided, 1oz. tinned, copper-clad 1/16-in. FR-4 PCB material, with an 8-pin op amp used in all circuits. The boards were built, cleaned, and then baked dry. To reduce noise and the influences of external wiring, ground loops, and air drafts, we performed the tests under battery power in a shielded test enclosure. The instrumentation was an HP3458A 8½-digit voltmeter and a precision dc-voltage calibrator.
Measurements on the standard voltage-follower amplifier (Figure 1a) and modified version (Figure 1c) used the setup of Figure 3, in which input current is measured by placing a 1-GΩ resistor in series with the input. To obtain the amplifier’s input current, output voltage is first measured with zero volts input and the 1-GΩ resistor short-circuited, and then measured again after removing the short across the 1-GΩ resistor. Since the amplifier is a highly accurate and very linear unity-gain follower, the output measured is a replica of the input voltage, but acquired at a low impedance point.

<table>
<thead>
<tr>
<th>Circuit type</th>
<th>Input Current (μA)</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Voltage Follower</td>
<td>480</td>
<td>92</td>
</tr>
<tr>
<td>Modified Voltage Follower</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Standard TIA</td>
<td>573</td>
<td>95</td>
</tr>
<tr>
<td>Modified TIA</td>
<td>28</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: A comparison of electrometer circuits.

The difference between the two measurements is the voltage drop across the 1-GΩ resistor caused by the input current, which is easily calculated. Input currents for the circuits of Figure 1b and Figure 1d were measured using similar procedures. To confirm results and allow for thermal time constants to settle, a large number of measurements were made for all circuits over a period of several days. The results show good repeatability (Table 1). Noise issues caused by the large value resistors were dealt with by using long voltmeter integration times and by averaging a large number of measurements for each reading.

**Input capacitance and temperature effects**

In Figure 1c, because pins adjacent to the amplifier input (and the amplifier structure itself) are bootstrapped to the input voltage, the input capacitance of this circuit is less than that of the Figure 1a circuit. For Figure 1a, the capacitance seen from the amplifier input consists of that of the IC package (amplifier input capacitance plus associated package capacitances), added to that between the input pins and PCB traces nearby. In the modified circuit (Figure 1c), careful PCB layout reduces capacitance external to the IC package, and bootstrapping minimizes all capacitances.
Input capacitance for the circuit of Figure 1c was determined by measuring the amplifier’s output rise time (Figure 4) when driven by a pulse from a source with 100-MΩ internal impedance. The rise time is 22 µsec. Since the relevant time constant is the 100-MΩ source-impedance times the input capacitance. A quick calculation shows a reduction to about 100 femtofarads. The input capacitance of the amplifier alone is about 10 pF. As an aside, the 100-MΩ resistor in series with the input introduces an observable amount of thermal noise, as expected.

At room temperature and 0V input voltage, the input current for the Figure 1c circuit is 38 fA. Evidence of what could be the dominant component of that current can be obtained by heating and cooling the PCB to observe the temperature dependence of that current. The experimental results approximate the constant ΔT doubling typical of silicon junctions, which points (indirectly) to the input ESD-protection as the most likely source of this leakage component.

References