13 Hazards

Several hazards, unsuspected by practitioners of mainstream electronic engineering, await the unwary designer of capacitive sensors.

13.1 LEAKAGE

With small capacitive plate areas, electrode capacity is often a fraction of a pF. The silicon-based accelerometer of Chapter 15, for example, has a sensor capacitance of 0.1 pF. Low power circuit design requires a low excitation frequency, so the measured impedance of the capacitive sensor can often be many megohms, and measuring this impedance with good precision may require amplifier input impedance and printed circuit board and component leakage impedance to be many hundreds of megohms.

Leakage paths on the printed circuit board are usually a surface effect, not a bulk effect, and can be caused by:

- Rosin residue or lubricant acting as an attractant for dirt and dust
- Incompatible PC board rosin and cleaning fluids which chemically react to produce a conductive residue
- Conductive paint. Some black pigments are heavily carbon-particle loaded, and the paint will dry to a high-resistance conductor
- High humidity

13.1.1 Guarding against leakage

Surface leakage can be combatted by guarding. A typical high impedance guarded amplifier is shown in Figure 13.1.

The op amp input bias current may be as low as 10 fA. If a board leakage resistance path of $10^{15}\ \Omega$ connects the input to a +10 V rail in the circuit above, the leakage current I_L will equal the op amp bias current and it will cause excess noise as well as shifts in the

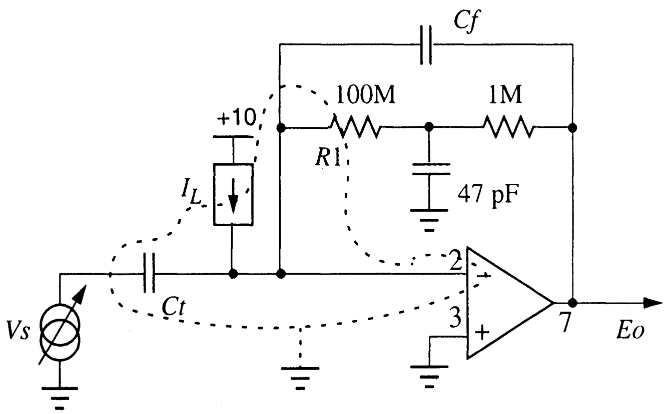

Figure 13.1 Guarding leakage paths, low-Z amplifier

bias point. It is very difficult to achieve this level of resistance on an unguarded PC board surface; very clean Teflon surfaces and long paths would be needed.

Surface leakage guarding

Luckily, surface guarding is a very effective technique to interrupt leakage paths. If a grounded printed circuit trace is added which surrounds the high impedance node, shown above as a dotted line, the leakage currents are interrupted. For surface mount construction, the guard trace must be on the same side of the PC board as the components; through-hole construction requires guards on both top and bottom surfaces. To guard pin 2 of the amplifier from leakage to pins 1 and 3, the trace should pass between pins 2 and 1 and also 2 and 3. For a low-Z or feedback amplifier as shown in Figure 13.1, the guard is grounded; for a high impedance amplifier the guard is connected to the amplifier output. Solder mask which covers the guard trace would produce a path which conducts surface currents over the guard, so solder mask should be relieved over the guard foil.

If *R*1 is a surface mount part, it can trap conductive residues under its body, or it can collect a conductive residue on its insulating body. One repair is to provide a solder-mask-relieved spot of grounded copper under the body of the part, but this method is unpopular with production personnel and also provides only a 90% solution, as surface currents can flow on the top surface of the part. For very high impedances or problem environments, somewhat better performance is available: *R*1 can be split into two series 50M resistors, with a guard surrounding the node where they connect (Figure 13.2). Capacitor leakage current is usually not a serious problem, as the DC potential across the components is generally near zero. For example, in the circuit shown in Figure 13.2, all the circuit's capacitors will have zero DC potential if the excitation *Vs* is centered on ground.

Bulk leakage guarding

Bulk PC board leakage currents in fiber reinforced boards can flow along impurities on the surface of the fibers. This is more of a problem for through-hole construction than surface mount. These currents can be interrupted by stitching small-diameter plated-through holes through the board in a way that will intersect all fibers, and connecting them to ground or guard voltage (Figure 13.3).

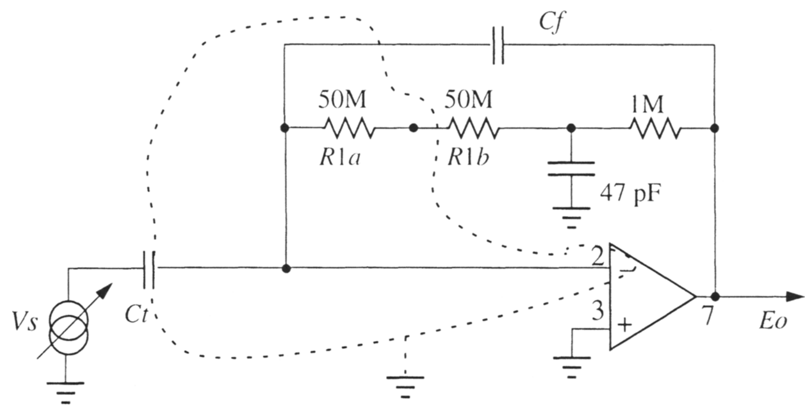

Figure 13.2 Guarding leakage paths, low-Z amplifier

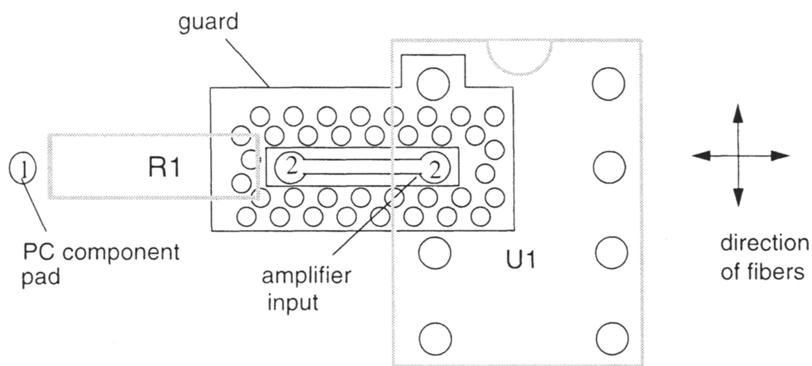

Figure 13.3 Guarding bulk PC leakage

Here, the sensitive node between a through-hole operational amplifier input, $U1$-2, and a high-value resistor, $R1$-2, has been guarded with etch, shown shaded, on both top and bottom sides. Many small via holes are stitched through the guard to interrupt bulk leakage current along the glass fibers. As the fibers are at 90° angles, the pattern shown is sufficient to interrupt all fiber-surface conduction.

Printed circuit board test patterns

Test coupons for measuring surface leakage can be used. These are interdigitated combs, specified by the Institute of Printed Circuits (IPC). The recommended minimum resistance is 10 MΩ. With normal PC board production techniques, the resistance should be many hundreds of megohms.

Some water-based fluxing processes may leave a white residue which has hundreds of ohms of surface resistance if incompletely cleaned. Keeping the board clean is also important, as surface impurities can be conductive, or can become conductive with high relative humidity. Nonconductive conformal coating can be used in extreme cases.

13.2 STATIC DISCHARGE

In position-measuring applications, capacitive sensors often have one moving plate. If the plate is coated with a dielectric such as solder mask, it can accumulate static charge by triboelectric charging. This is the familiar rub-the-comb-on-the-silk-shirt effect. When the accumulated charges reach a threshold voltage, the Paschen voltage (679 V in air at 1 atm), they can discharge in a small spark which can cause a large if mercifully brief transient in the nearby high impedance amplifier.

Paschen's law

Air breakdown at normal pressure happens when a free electron, propelled by a strong electric field within a narrow gap, dislodges enough other electrons in collisions with air molecules to produce a chain reaction. The final breakdown is a stream of positive ions which proceeds from anode to cathode [Javitz, 1972, p. 337].

Paschen's law can be shown, at large spacing, in Figure 13.4. A magnified view for low spacing or low pressure is shown in Figure 13.5.

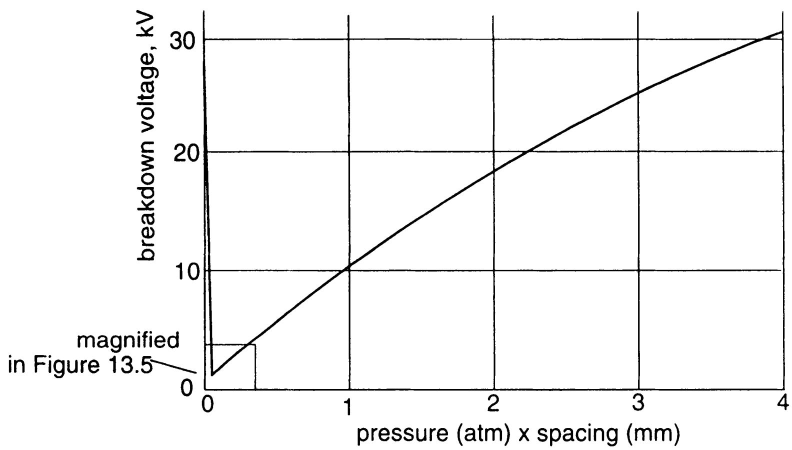

Figure 13.4 Paschen's law in air [Modified by permission from material in *Durchbruchsfeldstärke* by W.O. Schumann, pp. 51, 114, 1923. Berlin, Germany: Springer-Verlag GmbH & Co.]

At small spacing and low pressure, the mean free path of an electron at 10^{-4} mm is not long enough to produce many electrons by collision, and the breakdown voltage increases even though the field strength goes up. The population of free electrons to initiate the chain reaction is dependent on background ionizing radiation such as light and cosmic radiation and is invariant with field strength; no electrons are emitted from a conductor except at very high field strengths.

13.2.1 To combat static discharge

Raise the humidity

The surface leakage resistance of almost all insulators is is a strong function of humidity. At reasonable values of relative humidity, say 20% and higher, triboelectric discharge is not hazardous.

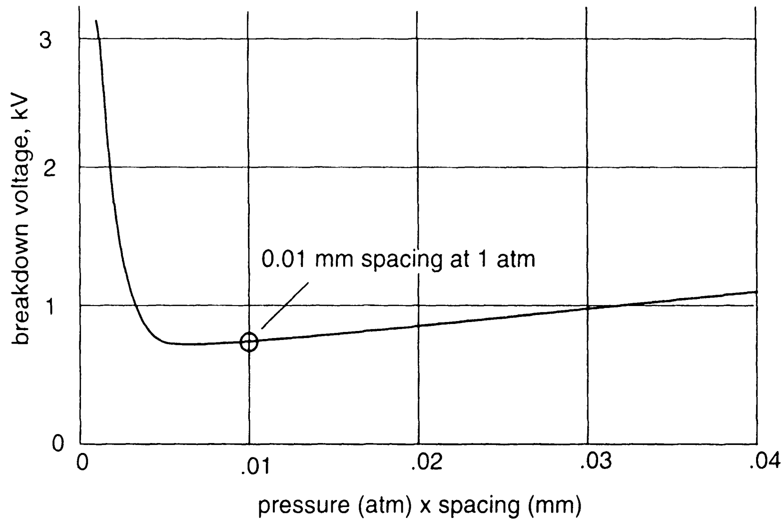

Figure 13.5 Paschen's law, detail

Use a static dissipation treatment

Many of these treatments are deliquescent and should be tested since a harmful conductive water deposit may form. Also, since most work by absorbing water vapor, the conductivity can vary by factors of 1000:1 when relative humidity changes from 5% to 95%.

Redesign the circuit to be zap-resistant

As an example of a zap-sensitive circuit, a plate counting circuit which keeps track of multiplate coarse position can pick up an extraneous count pulse during a static discharge, causing a large unrecoverable position error. The counter can be redesigned as shown in Figure 18.6 so that a single measurement which is different from its neighbors is assumed to be a discharge and is discarded.

Use bare metal plates without a dielectric coating

Bare metal will not have triboelectric-effect static discharge problems. Corrosion of bare copper is minimized by use of a corrosion-resistant metal plating such as nickel or gold over nickel.

Use similar materials

The triboelectric series listed in any physics reference shows which materials produce the strongest triboelectric charge when rubbed. The best case is to use identical materials, which have no triboelectric effect.

Ionize the air

Alpha particles generated by low-level radioactive materials produce charged ions by collision with air molecules, and static charge is dissipated by the slightly conductive air. Another technique is to excite a sharp point with high AC voltage, causing a corona discharge at the tip and launching a cloud of positive and negative ions into the air. One company that specializes in air ionization equipment is NRD, Inc., P.O. Box 310, Grand Island, NY 14072-0310.

13.3 STATIC CHARGE

Low level static charge can build up from the effects above. At levels where it is too low in voltage to spark, it may still cause problems. A static DC voltage on capacitive plates which are measuring an AC signal can turn into an AC voltage by $V = Q/C$. As Q is constant, a mechanical vibration which changes spacing and hence capacitance will produce an AC voltage V. If the system has mechanical resonances, this voltage will respond to a mechanical excitation impulse with a damped sinusoid voltage transient which can be many times larger than the signal being measured. Some fixes are listed below.

Use the methods listed above

All of the techniques for static discharge will also fix static charge problems.

Use a higher frequency carrier

Mechanical vibrations and resonances are usually in a low frequency range, say below 10 kHz. Use a 100 kHz carrier and a demodulator which includes a highpass filter to eliminate mechanical resonance and static charge effects.

Use adequate headroom in amplifiers

Even if the carrier frequency is well above the frequency of mechanical vibration, if the vibration is strong enough, the static-charge-induced voltage may exceed the linear range of the amplifier. Make sure adequate linear range is provided, or use a passive highpass filter which precedes the active amplifier.

13.4 CROSSTALK IN SILICON CIRCUITS

Silicon implementations of capacitive sensor circuits have different signal integrity problems than discrete implementations. All components on a silicon chip are capacitively coupled to the common substrate through either a silicon dioxide layer or a reverse-biased p-n junction. In addition, the p-n junction's capacitance is nonlinear, and temperature-dependent diode leakage current is added. The substrate voltage will not be the same as the reference voltage of the PC board the chip is soldered to, due to ground return currents, so care must be taken to bring the chip's signal ground reference out to sensitive input circuits through a dedicated pin which is not shared by load current or power return currents.

Other unwanted crosstalk is caused by parasitic capacitances between close-spaced signal and clock lines. Capacitively coupled clock frequency signals near the excitation frequency of a sensor will alias down to a harmful DC or low frequency signal at the demodulator output. The very high impedance nodes and connection wires of capacitive sensors can be shielded from adjacent clock interconnects with an interposed dummy grounded line or a guard ring as in PC board practice, and a low-impedance polysilicon plate or diffusion well can be layered underneath [Hosticka, 1990, p. 1348].

The use of differential paths and differential circuits for signal conduction and generation offers an improvement over traditional single-ended design. With careful symmetric layout, differential paths reject crosstalk, improve power supply coupling, and increase dynamic range by doubling signal level while keeping noise constant. Moving the differential partition back to the sensors, if possible, can first-order compensate for several types of sensor inaccuracy and environmental dependence.