8

Multiple plate systems

Capacitive sensors can be quite accurate, with accuracy determined by the precision of the mechanical system. But often some component cannot be precise. If, for example, the capacitive plates are mounted on a mechanical system with poor quality bearings, or the bearings are located at some distance from the transducer, accuracy may suffer as a result of uncompensated tilt or unguarded stray capacitance. When a simple analog approach is not accurate enough, a multiple plate design can be used. This technique applies equally well to linear and rotary arrays, and basically replicates a single-plate analog sensor many times with an added circuit to count plates.

8.1 CAPACITIVE MULTIPLE PLATE SYSTEMS

Multiplate sensors are of two types. Often, the simple three-plate pickup described in Chapter 5 does not have enough capacitance to produce a usable signal-to-noise ratio, or to overcome parasitic capacitance by enough margin for good stability. To remedy this, replicating the three-plate pattern many times and driving each replication identically will increase capacitance, as in the accelerometer described in Chapter 15. This produces a sensor with good resolution, to 5×10^{-12} mm, but poor range of motion, 0.1–1 mm. When the goal is good resolution combined with a long measurement range, often exceeding a meter, the best solution is to replicate a simple plate pattern many times and arrange the drive and pickup circuit so analog interpolation handles the fine position between plates and a digital plate counter adds coarse position information. Multiplate systems include Kosel's linear transducer described in Section 9.2, with a 4×10^{-9} mm resolution and a 3 cm range, and Zhu et al. from Section 9.3 with 1×10^{-6} mm resolution and a range of over a meter. The vernier caliper described in Chapter 18 has a resolution of 2×10^{-4} mm and a 6" range in a compact and inexpensive instrument.

8.1.1 Rotary encoders

Plate shapes

With either capacitive or optical rotary sensors, the normal technique for multiturn high resolution encoding is to build plate patterns (Figure 8.1) which generate sine and cosine waveforms, or triangular waveforms which are used similarly. This allows a rotary encoder to cover more than 360° without ambiguity, and allows a linear encoder to use multiple plates for greater accuracy.

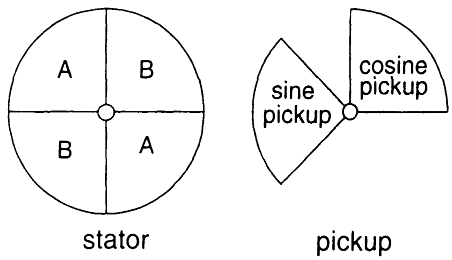

Figure 8.1 Sine/cosine rotary plate pattern

The pickup plates are positioned on top of the stator with small air spacing. This figure shows four stators at 90° and two pickups, but it can be extended to, say, 100 stators at 3.6° to increase resolution, and 50 pickup plates to increase area and thereby decrease noise. The multiple stator plates are connected directly, and two pickup amplifiers and two drive circuits are needed. Again, guard or shield around the pickup plates (not shown) reduces the effect of stray capacity.

With simple pie-shaped plates as shown above, the shape of the demodulated signals produced at a constant mechanical rotation is triangular. A true sine and cosine shape can be obtained by shaping the stator plate as shown in Figure 8.2 so that rotation produces sine waves instead of triangular waves. The shape is defined by setting the convolution of pickup plate and stator plate to the sine of the mechanical angle. If this is done, the mechanical angle is easily calculated as

$$\theta = \tan^{-1}\left(\frac{\text{sin pickup}}{\text{cos pickup}}\right)$$

where sin pickup is the demodulated sine plate and cos pickup is the demodulated cosine signal.

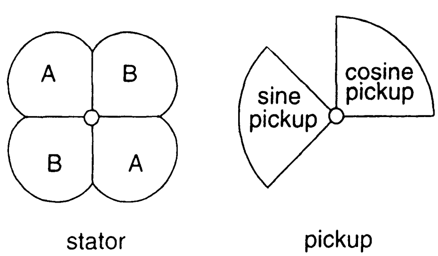

Figure 8.2 True sine and cosine shaping

Angle demodulation

With the pie-shaped plate pattern shown (Figure 8.1), two triangular outputs are produced, called tsin and tcos (Figure 8.3).

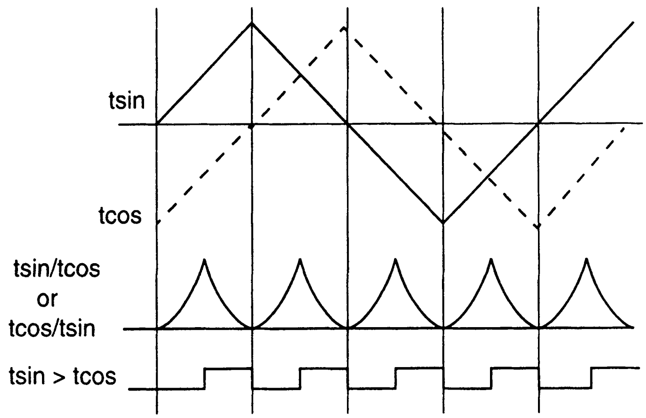

Figure 8.3 Triangular output waveform

tsin and tcos are the demodulated plate signals. The other waveforms are steps in the calculation of angle, as described below. A polar plot of tsin and tcos output signals vs. mechanical deflection angle with the sin and cos plots superimposed is shown in Figure 8.4.

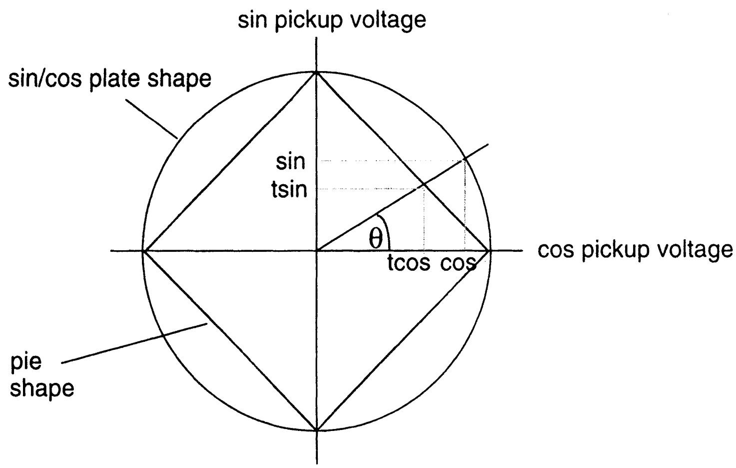

Figure 8.4 Triangular geometry

As the plates are rotated through mechanical angle θ, the true sin/cos (Figure 8.2) plate shape will produce a circular trajectory and the pie-shaped plates (Figure 8.1) will describe a diamond trajectory.

With true sine and cosine waveforms, conversion to angle is done with the inverse tangent calculation. For ease of computation, as the tangent function is infinite at some angles, its reciprocal is used when its value is above 1 to keep the number in bounds. A similar reasoning applies to the triangular equivalent, where the waveform labeled tsin/tcos or tcos/tsin (Figure 8.3) along with the result of the equality comparison tsin > tcos is used to convert to angle θ, using

$$\theta = \arctan\left(\frac{\text{tsin}}{\text{tcos}}\right) \quad \text{if tsin} < \text{tcos}$$

or

$$\theta = \pi/4 - \arctan\left(\frac{\text{tcos}}{\text{tsin}}\right) \quad \text{if tsin} > \text{tcos}$$

This method requires a little more computation than simply choosing either tsin or tcos based on which is in its linear range, but it is preferred as it is insensitive to absolute changes in amplitude if tsin and tcos are well matched in relative amplitude.

The arctan calculation may be done with a lookup table which also can compensate for any lingering nonlinearities like rounded corners on the triangular waves caused by excessive plate spacing. With two lookup tables, the sensitivity to mismatched relative amplitudes can be compensated.

Linear encoders

Linear multiplate encoders are identical to the rotary encoders described above, except with a linear pattern instead of rotary (Figure 8.5).

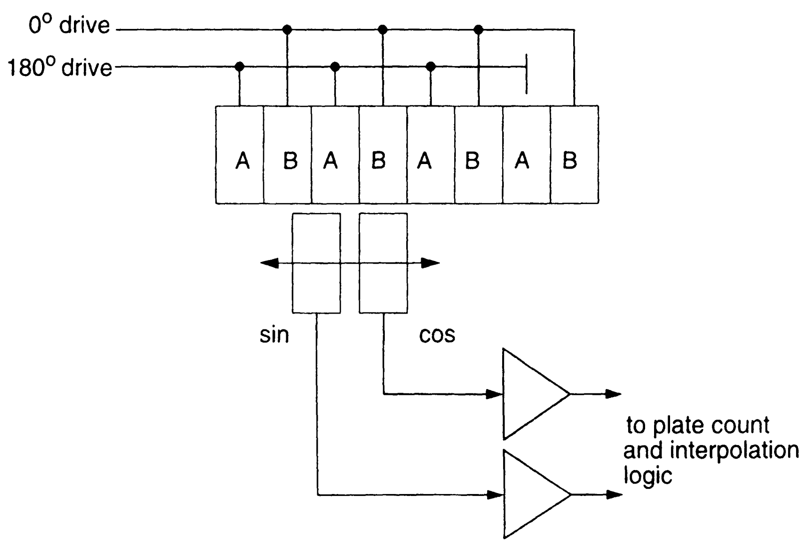

Figure 8.5 Linear multiplate encoder pattern

The electrode pattern above will produce a pair of triangular waveforms, displaced 90 mechanical degrees. These patterns, too, can be shaped to produce an accurate sine/cosine output waveform.

8.2 MULTIPLE PLATE COUNTING

For multiple plate design, after a plate geometry is chosen for either linear or rotary sin-cos signal generation, it is replicated many times in a linear or rotary array. A circuit which counts plates in an up-down counter establishes coarse position, and the arc tan calculation above adds fine position if needed. The plate counting logic is identical to circuits used for optical incremental stripe encoders. These encoders, called also quadrature encoders, have two optical stations mechanically spaced 90° apart, reading out a stripe wheel or grid. This produces two outputs, *A* and *B*, shown for a linear sensor (Figure 8.6).

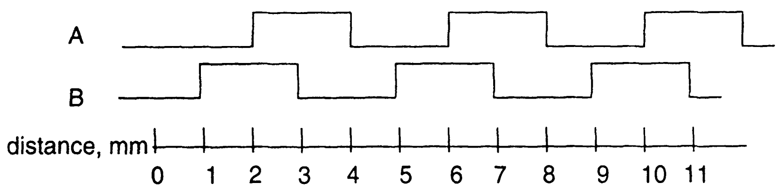

Figure 8.6 Encoder outputs

An up-down counter is used which would store the coarse position, representing 1 mm increments for the case above.

For more precise encoders, the final output position is the sum of the coarse plate count from the up-down counter and a fine analog measurement of the distance to the last plate. This technique is sometimes used for optical encoders, but light source aging, dust, and photodevice tolerances makes analog interpolation inaccurate. It works well for multiple plate capacitive sensors, however, as the analog outputs are quite stable.

A typical multiple plate capacitive sensor outputs 0° and 90° sinusoidal sin-cos or triangular tsin-tcos waveforms, generated by repeated rotary or linear patterns as in Figure 8.1. These waveforms feed both coarse and fine measurement systems (Figure 8.7).

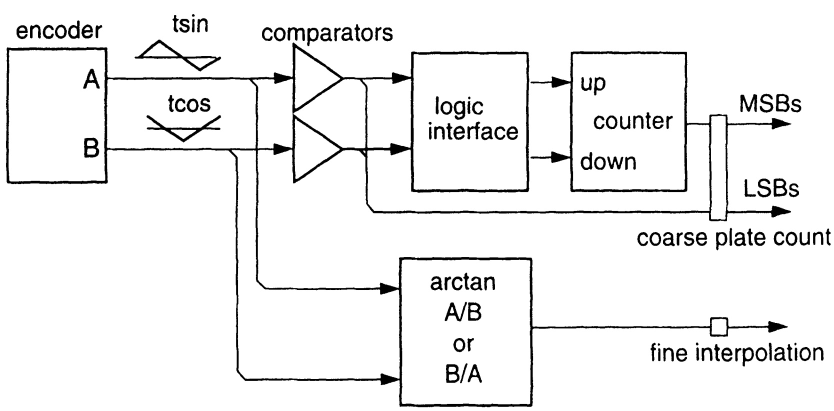

Figure 8.7 Encoder logic interface

The three outputs are added for the complete position determination, with the most significant bits (MSBs) added to the least significant bits (LSBs) to form the plate count, and the arctan calculation added to provide the interpolation fraction.

The logic interface between the quadrature signals A and B and the up-down counter must be carefully designed to avoid miscounts which can happen if noisy edges are present. See, for example, Kuzdrall [1992, pp. 81–87] or Berger [1982, p.128]. The quadrature signal pair at the comparator outputs can be considered as a 2 bit encoder output from an encoder with 90° resolution. Then its state diagram, which shows the relationship between the comparator outputs and the input mechanical angle θ, can be shown as in Figure 8.8.

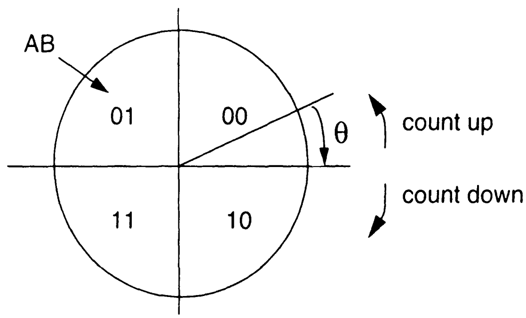

Figure 8.8 Quadrature polar plot

As the input mechanical angle varies from 0 to 360°, the output code successively becomes 00, 01, 11, 10 and repeats.

In an ideal world, the up-down counter could be incremented by the 1 to 0 transition of the A signal if $B = 0$, and decremented by the 0 to 1 transition of the A signal if $B = 0$. Then the A and B signals would be converted from Gray code to binary code and appended to the up-down counter's output as the least significant two bits.

8.3 DEBOUNCE

The debounce algorithm above runs into problems in the real world. With arbitrary mechanical input angles, the A signal may dither at some high frequency and cause continuous activity of the counter, causing excessive consumption in battery powered circuits or synchronization problems for microcomputers. Another more serious hazard: if the arctan calculation produces a fine angle measurement of 359° just as an edge noise glitch on the A signal increments the counter, a 360°, or one plate, error results. These errors can be eliminated by either:

1. Schmitt triggers on A and B signals instead of comparators
2. Logic interface design which produces a digital Schmitt trigger effect

Approach 1 will cause the coarse plate counts to lag the fine measurement by an amount proportional to the trigger threshold. Approach 2 is simpler and safer; a mechanical analog illustrates its operation (Figure 8.9).

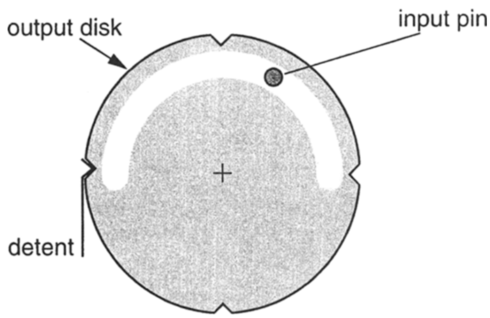

Figure 8.9 Mechanical encoder debounce

The input pin can assume any angle and may dither. The output disk is detented at 90° positions, and allows 180° of input dither before moving to a new position so that only 0°, 90°, 180°, and 270° orientations are asssumed. This analog can be represented by state table (see Figure 8.10), or logic.

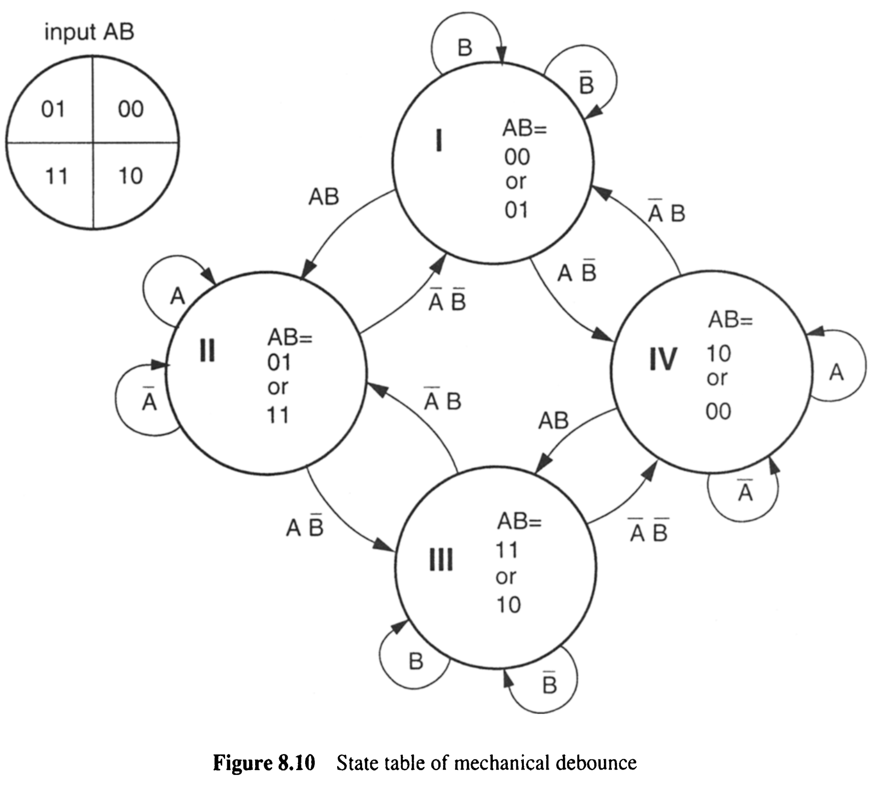

Figure 8.10 State table of mechanical debounce

The "input *AB*" figure shows that the input code is 00 in the first quadrant, 0° to 90°, 01 in the second quadrant, etc. The four output states **I** – **IV** respond to changes in the *AB* input as shown. This state machine can be implemented in logic (Figure 8.11) with the outputs active low. Debounce can also be implemented in logic (Figure 8.11).

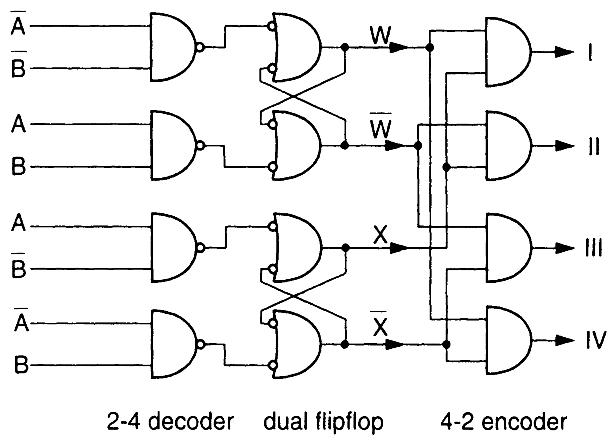

Figure 8.11 Logic diagram of encoder debounce

The noisy *A* and *B* signals produce the clean, debounced gray-coded versions, *W* and *X*, which are recoded into the four debounced quadrant states, **I – IV**. This approach sacrifices 90° of resolution if the fine plate measurement is not used, when compared to an undebounced approach. When the fine plate measurement is used, the output is unambiguous and resolution is not lost. The fine plate measurement provides the fraction of 360° measurement, while the coarse plate count is derived from the debounced signals.

8.4 TRACKING CIRCUITS

Another way to keep track of position in a multiplate system is by use of tracking logic. A number of tracking algorithms are possible. Here, in Figure 8.12, one pickup and amplifier are used instead of two, and three different sets of plates are driven.

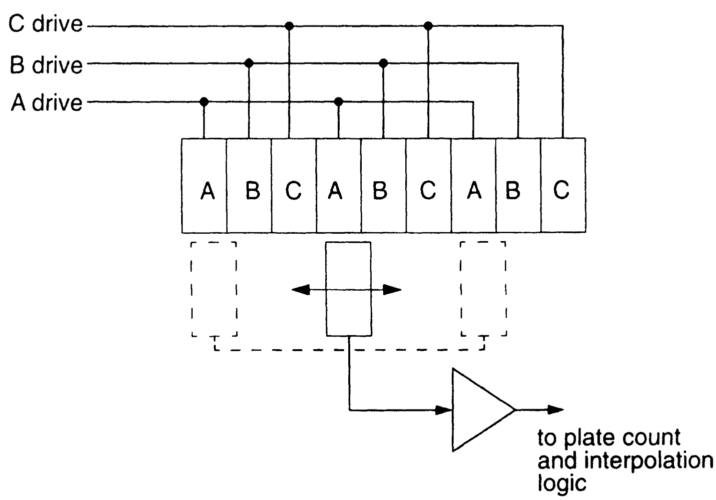

Figure 8.12 An example of tracking logic

8.4.1 Tracking algorithms

A simple tracking algorithm first does an acquisition sweep to see which driven plates are opposite the pickup. In the figure above, plates *A* and *B* would be chosen. Then the ratio and the sign of the voltage on *A* and *B* are varied until the pickup output is zero. In the figure, that would happen with about four times the voltage on *B* as on *A*, and with opposite signs. This ratio is adjusted as needed to null the pickup output to track plate motion; if the plate moves to the right, the voltage on *A* increases while *B* decreases until the plate crossed over *B*, then *A* drops to zero and *C*'s voltage increases. Generating the tracking signal involves changing the voltage linearly on the three drivers.

8.4.2 Three-phase drive

A second option, properly called a three-phase drive rather than a tracking algorithm, would be to drive the plates with 0°, 120°, and 240° sine waves or square waves and detect position as the phase angle of the fundamental at the pickup output. No acquisition sweep is needed.

The tracking system has an advantage in that only one pickup amplifier is needed, which saves power in portable applications. Multiple pickup plates as shown in dotted line can be used in either the sin-cos or the tracking system for more output. The disadvantages of tracking systems are the slightly greater complexity of the drive circuit and the extra computation which may limit maximum tracking speed.

PLATE CONSTRUCTION

Capacitive plates are normally fabricated as a conducting pattern on a dielectric substrate. For additional mechanical or thermal stability, the dielectric is bonded to a more stable material such as stainless steel or Invar. In any case, the critical parameters of plate construction are accuracy, stability, and resistance to environmental factors such as temperature, humidity, and corrosion.

8.5.1 Printed circuit board techniques

The simplest and most convenient way to construct the capacitor plates is often by use of standard printed circuit (PC) technology. The final plate accuracy using this approach will depend on the processes used to fabricate the board as listed below.

Photoplotting

The standard process exposes sensitized polyester film with either a raster-scanned laser or an *x-y* [Gerber] plotter. Raster-scanned plotters digitize the entire plot and scan the film one line at a time with a small light spot. The older and slower (but no less accurate) vector plotters move a larger, shaped light aperture in vector coordinates. Either method is normally calibrated to an accuracy of 0.0002–0.0008 in over the 22–25 in plotting area, with a minimum pixel size of 0.0001–0.0005 in.

Flatbed plotters and drum types are available. Flatbed plotters are used for glass substrates, but the maximum speed is 1–2 Mpixels/s as compared to the drum plotter's 10–100 Mpixels/s speed.

The speed of the laser plotter allows production of 1× artwork with multiple step-and-repeat patterns directly from the plotter instead of using an intermediate photographic step, thereby improving accuracy.

Phototool

The phototool is the imaged film used for production, and in the case of the laser plotter, it is usually the plotter output directly.

The plotter output is sometimes transferred to Diazo film by contact printing. Diazo film is used as it is convenient and rugged, but exposing Diazo adds an extra photographic step and slightly compromises accuracy. Directly imaged polyester film is the most commonly used medium; 4 mil and 7 mil stock is available with 4 mil stock the most popular, but 7 mil stock is slightly more dimensionally stable.

Polyester is a reasonably stable base, with low humidity-induced creep of 9–14 ppm/°C, a reasonable temperature coefficient of expansion of 15 ppm/°C and excellent mechanical strength. Storage as well as exposure of polyester media should be in controlled temperature and RH conditions; the temperature profile between storage and imaging is important, as polyester has a hysteresis curve for rising and falling humidity. Total imaging tolerances can be about 1 mil in 24 in.

Glass is less sensitive to temperature (about 5 ppm/°C) than polyester and is insensitive to humidity. Glass is used for very accurate substrates, but it is not normally available from a PC house. Some specialized optical shops can generate glass-substrate images. Diamond is still better (1–4 ppm/°C), but its cost renders it unattractive for most nonjewelry applications.

Exposure

The exposure step attempts to exactly replicate the phototool image as a chemical change in the resist coating of the substrate.

The polyester phototool should be exposed to the photosensitive layer of the PC board at the same temperature and humidity as the original exposure. If not, an error of 50–100 ppm is induced by a 10°C temperature change or a 10% change in relative humidity.

Quality PC houses use carefully collimated light to do the exposure, so the accuracy of alignment of the image to the surface of the board is not particularly critical. A vacuum is used to guarantee close contact. Projection exposure is also used, and needs no vacuum system as close contact is not important. The phototool is imaged at 1× magnification with a low *f*-number reflective lensing system.

The photosensitive layer of the PC board, the photoresist, must first accept an optical image as a chemical change, then, after development with a solvent wash which removes unexposed areas for a negative-working resist, it becomes an etch blocking layer. Liquid and dry film resist types are available. Liquid resists are capable of good performance, but are more difficult to use repeatably; most PC board houses use dry film resist.

Etching

The etching step flows liquid or vapor etchant over the board which etches away the copper in areas where the resist has been removed. Etching requires close control for good accuracy, with the amount of undercut carefully controlled so the image neither grows nor shrinks. Fineline PC board techniques have been developed which allow high yield production of trace widths down to 0.003 in.

PC board substrate accuracy

Once the PC board has been exposed, developed, and etched, some moderate change in substrate dimension may result from chemical absorption. Absorbed solvents can be baked out in drying ovens.

8.5.2 Other techniques

Printed circuit board construction is easy and inexpensive, but other approaches may be needed for unusual applications requiring, for example,

- extreme stability
- extreme tolerance to relative humidity changes
- transparency
- nonplanar shapes
- large size
- very small size

Thin films

Vacuum deposition of a variety of conductive materials to thicknesses between 0.05 and 25 μm can be used to produce capacitive sensor plates. Accurate plate patterns can be defined by sputtering a metal or a compound through a mask onto a suitable substrate, or by coating the insulating substrate with a resist as in PC board fabrication, exposing through a phototool, and developing with solvent wash and etching. The mask is more convenient but less accurate; submicron accuracy is available with resist and phototools using technology developed for integrated circuit fabrication.

Transparent thin films are used in capacitive touch screens for touch-sensitive input application over computer monitors. Many normally opaque metals become transparent in very thin layers; tin oxide and indium-tin oxide are transparent conductors in thicker films and are easier to deposit with good linearity.

Thick films

Thick films are used in producing hybrid circuits and microwave devices. Thick film devices such as conductors and resistors are screen printed onto a smooth substrate, usually alumina ceramic, and fired at 850–1000°C. Film thicknesses are 25–250 μm. The 5–10 mil line definition is not as good as photoetched processes, and no transparent conductors are available, but the process is simple and reasonably inexpensive.

Conductive films

Table 8.1 [Burger, 1972, p. 450] lists conductive films produced by both thin (above the line) and thick film methods.

Table 8.1 Conductive films

Material	Process	Pattern	Thickness μm	Sheet resistance Ω/□
Aluminum	evaporation	mask, resist	0.5–1	0.03–0.06
Titanium	evaporation	mask, resist	0.5	0.1
Silver-chromium	evaporation	reverse metal	0.5	0.1
Gold-chromium	evaporation	reverse metal	0.5	0.1
Copper-chromium	evaporation	mask, resist	0.8	0.02
Platinum-gold-cermet	screen	screen	25	0.08
Silver-cermet	screen	screen	25	0.005
Palladium-gold-cermet	screen	screen	25	0.04

The notation of sheet resistance in Ω/□, ohms per square, reminds us that sheet resistance is the resistance measured across two opposite faces of a square test pattern and is independent of the dimension of the square.

Resistive thin films

Resistive thin films with capacitive pickup have some applications. See, for example, "Graphic input tablet" in Chapter 19. Producing an accurate high value resistance by vacuum evaporation or thin film sputtering of a conductor is difficult, as the resistivity is a nonlinear function of film thickness with the curve becoming very steep as molecular thicknesses are approached. Most metals have bulk resistivity in the 1–10 μΩ-cm range and would need a very unstable molecular-dimension film thickness to produce an easy-to-drive 1000 Ω resistance. Higher resistivities are available with nickel/chromium alloys or tantalum nitride at 100 Ω-cm [Harper and Sampson, p. 8.28]; these materials produce sheet resistivity of 100–300 Ω/□. Still higher resistivities can be provided by cermet, a metal/metal oxide composition. Cermets can be thin-film vacuum deposited or screened and fired for thick films, and are most often used for sheet resistivity in the range of 1000–3000 Ω/□ [Harper and Sampson, p. 8.44].

Resistive thick films

Resistive thick films are often useful in capacitive sensors. The technology of producing resistive thick films is mature and is used in manufacturing very precise potentiometers as well as fixed resistors for application to many different substrates. Many different formulations can be chosen to optimize a particular application.

Potentiometers which use resistive film have an intrinsic sliding noise component due the small contact area of the metal brush and the microscopic surface roughness of the resistive material. This noise component and the added friction and wear of the brush are avoided if a capacitive readout replaces the brush.

A partial list of resistive materials [Burger, 1972, p. 452] appears in Table 8.2.

Table 8.2 Resistive films

Material	Deposition process	Thickness µm	Masking	Sheet resistance Ω/□	Temp. coeff. ppm/°C
Nichrome	evaporation	0.02	reverse metal, KPR	20–800	+/–100
Tantalum	sputtering	0.05–0.5	reverse metal	10K–20K	+50 to –300
Tin oxide	pyrolysis	0.001–0.5	reverse metal	10–5K	–1500 to +250
Palladium-silver-cermet	screen and fire	25	screen print	1–20K	<200
Rhenium	evaporation	~1000	stencil mask	10–4K	+/–500

Evaporation heats the material in a vacuum chamber until evaporation launches particles which are deposited on a target. Sputtering uses a plasma beam, often argon ions, to blast molecules from a target in a vacuum. Coatings produced in a vacuum chamber are called thin film irrespective of film thickness, and coatings produced by screen printing are called thick film.

Tin oxide is very popular as it is not only a semiconductor, but it is transparent. It is often doped with indium to produce indium tin oxide, ITO, with better physical characteristics than tin oxide. Other deposition methods may be used which do not require vacuum, such as pyrolysis, which exposes a target heated to 300–360°C to gas produced by bubbling nitrogen through indium tin chloride liquid. The gas reacts with oxygen from the air, catalyzed by the hot surface, to form a 1–10 µm layer of indium tin oxide. The accuracy of the resistance can reach 5% with careful process control.

Thick film deposition is discussed by IHSM, the International Society of Hybrid Manufacturers, and thin film by the American Vacuum Society and the Electrochemical Society. Many independent coating laboratories such as Optical Coating Labs in California can handle contract deposition of resistive films.

Metal-filled paint

Several methods are used to coat plastic molded parts with a conductive surface to attenuate RF radiation. One is painting or screen printing the surface with a metal- or carbon-filled polymer with air-drying solvent. Silver is most often used. It is difficult to produce accurate high value resistances with metal-filled paint, and the conductivity is often not adequate for good RF shielding. This method is not useful for very accurate capacitor plate definition, as the limits of screen printing tolerance are on the order of 0.2 mm, but it is convenient and easy to set up. A manufacturer of electrically conductive paint which can cure at low (50°C) temperatures and bonds well to tin oxide or indium tin oxide surfaces as well as to Kapton and glass is Creative Materials Inc., 141 Middlesex Rd., Tyngsboro, MA 01879.

Plastic plating

A variety of metals, including chrome, can be plated onto the surface of plastic parts with good (10–20 lb/in) peel strength. Plating followed by photoimage and etch produces accurate, complex-geometry capacitive electrodes. One company that specializes in molded, selectively plated plastics for electronic interconnection is Mitsui-Pathtek, Rochester, NY, (716)272-3126.

8.6 DIELECTRIC SUBSTRATE

Normal FR-4 glass-epoxy PC substrate works reasonably well as a dielectric for capacitive sensor electrodes. It has the characteristics shown in Table 8.3.

Table 8.3 1/16 in FR-4 PC board characteristics[a]

Dielectric constant @60 Hz	5.0
Dielectric constant @1 MHz	4.6
Dielectric strength, V/mil	360
Volume resistivity, Ω-cm	3.8×10^{15}
Surface resistivity, min., MΩ / ❑[b]	10^4
Specific gravity	1.8
Water absorption, %/24 h	0.2
Heat softening temperature, °C	105–125
Tensile strength, lb/in^2	30,000
Coefficient of thermal expansion, ppm/ °C	15–18
Thickness tolerance, mil	+/– 7.5[c]
Maximum acceptable bow and twist, %	0.6 – 2.0[d]

[a] [C. Harper and R. Sampson, *Electronics Materials Processes Handbook*, © 1970, the McGraw-Hill Companies. Reprinted with permission of the publisher]

[b] NEMA minimum; typical values are much higher

[c] For grade A. IPC-L-115 calls out grade B at +/–5 and grade C at +/– 2 mils

[d] Two-sided level C material is 0.8%; level A is 2.0% as measured by IPC-TM-650

Improved performance PC laminates are available from suppliers such as Rogers Corporation, 100 S. Roosevelt Ave., Chandler, AZ 85226, (602)961-1382. Laminates such as Rogers' RO3000 feature very low dissipation factor, <0.0013 @ 10 GHz, 10^{12} Ω/cm volume resistivity, 10^{13} Ω/❑ surface resistivity, and a dielectric constant of 3.0 ± 0.04 with a temperature-induced change of less than 0.5% between –100°C and +250°C.

PC boards can be specified with 1/2, 1 or 2 oz/sq ft copper foil, and 0.1 oz is available at extra cost from specialty suppliers. The thinner foil etches more accurately so undercut during etch is minimized and it is recommended for sensor applications. The thickness of 1 oz foil is 0.00137 in.

In some applications needing excellent stability or extended temperature range operation, PC laminates are available from sources such as Rogers Corporation with superior temperature and physical properties (Table 8.4).

Table 8.4 Properties of some PC board plastics[a]

	E-glass (FR-4)	S-glass	Quartz	Aramid	PTFE[b]
Specific gravity, g/cm^3	2.54	2.49	2.20	1.40	2.2
Tensile strength, kg/cm	350	475	200	400	210
Young's modulus, kg/cm^2	7400	8600	7450	13,000	3500
Maximum elongation, %	4.8	5.5	5.0	4.5	150
Specific heat, cal/g°C	0.197	0.175	0.230	0.260	
Thermal conductivity, W/m–°C	0.89	0.9	1.1	0.5	
Coef. of temp. expansion, ppm/ °C	5.0	2.8	0.54	–5.0[c]	99
Softening point, °C	840	975	1420	300	
Dielectric constant at 1 MHz	5.8	4.52	3.5	4.0	2.0
Dissipation factor at 1 MHz	0.0011	0.0026	0.0002	0.001	<0.0002

[a] [Senese, 1990]

[b] [Data from C. Harper and R. Sampson, *Electronic Materials Processes Handbook*, © 1970, the McGraw-Hill Companies. Used with permission of the publisher]

[c] Along fiber axis

E-glass

This is the normal G-10 or FR-4 substrate used for 95% of PC boards. It is made from woven continuous-fiber borosilicate glass in an epoxy binder. Specifications are listed in IPC-EG-140, from the Institute for Interconnecting and Packaging Electronic Circuits.

S-glass

This is a similar glass except with a considerably better performance at high temperatures. It is more expensive. Specifications are in IPC-SG-141.

Quartz

Quartz (fused silica) glass is more expensive, more stable, and more abrasive, making PC drilling more difficult. Specifications are in IPC-QF-143.

Aramid

Aramid fiber, also known under DuPont's trade name of Kevlar, has a negative temperature coefficient which, when combined with epoxy's positive coefficient, can produce very low total temperature coefficient. It is expensive and difficult to drill in conventional PC boards, although it is used extensively in flexible thin-substrate circuits.

The dielectric constant of PC boards will increase after water absorption. Several different types of thermoset resins of the type used for PC board laminates were conditioned by boiling in water for 24 h, and exhibited increases in dielectric constant of 10–30% [Shimp, 1990]. This reference also tested different resins for dielectric constant stability with temperature, and found the dielectric constant of normal epoxy laminate within 2% from 0–100°C but increasing by 15% at 200°C. Newer resin types such as AroCyB cyanate ester homopolymer have a dielectric constant which is flat to 1.5% over 0–200°C.

1/16 in glass-epoxy PC boards are normally specified to have a curvature of less than about 0.01 cm/cm. Thicker stock is used for designs needing better flatness than this, or the PC material can be bonded to a metal backing.

Table 8.5 Properties of various dielectric substrate materials[a]

Material	Dielectric constant	Volume resistivity Ω-cm	Surface resistivity Ω/❑	Dielectric strength, V/mil
Air	1	--	--	--
ABS	2.9–3.3	10^{15}–10^{17}	--	300–450
Alumina	8–9	10^{14}–10^{15}	--	250–400
FR-4 PC board	4.6	3.8×10^{15}	--	--
Glass (common)	8	10^{15}–10^{17}	10^{12}	--
Glass (fused silica)	3.78	$>10^{19}$	2×10^{14}	1500
Glass-epoxy	5–7	--	--	--
Nylon	6.0	10^{14}–10^{15}	--	300–400
Polyethylene, med. density	2.2–2.3	10^{15}–10^{18}	--	450–1000
Polyimide	3.5	10^{16}–10^{17}	--	400
Polystyrene	2.4–2.7	10^{17}–10^{21}	--	300–3000
PTFE	2.1	$>10^{18}$	--	480
Solder mask, dry film	3.6	$>3 \times 10^{14}$	$> 7 \times 10^{13}$	--
Titanium dioxide	14–110	--	--	--
Water	80	--	--	--

[a][Harper and Sampson, 1970, pp. 1.20, 3.4–3.11]; *Reference Data for Engineers*, pp. 4–20

PTFE

Polytetraflouroethylene (Teflon™) is used for specialized microwave PC boards because of its low dielectric constant, 2.1. It also has a low dissipation factor, 0.8×10^{-4}, excellent volume and surface resistivity, and low friction, and it is one of just a few plastics with zero water absorption. These properties are valuable for capacitive sensors if the additional cost of PTFE stock is acceptable.

Dielectric layers

A dielectric layer is sometimes used in variable capacitors to increase capacity by virtue of its dielectric constant and to allow close spacing without danger of shorting. Also, the dielectric layer acts to stabilize the plate structure against mechanical resonances.

Dielectric layers are also useful for capacitive sensors for the same reasons. The increase in capacity causes a beneficial increase in signal strength. The ideal dielectric would have a large and stable constant, low friction, and good resistance to wear. Unfortunately, the lowest friction material, PTFE, also has the lowest dielectric coefficient and is difficult to manufacture in thin gages, although Teflon/anodize coating is available for aluminum in thin layers. (See Table 8.5.) For more detail on the physical characteristics of glass, see Harper and Sampson [1970, Chapter 3.]