CHAPTER

5

CIRCUIT FABRICATION

5.1 SUBSTRATE SELECTION

There are basically two major type of substrate material being used in the microwave integrated circuits today. At the low dielectric constant side is the plastic substrate, represented by Teflon (usually PTFE). At the high dielectric constant side is the ceramic substrate, represented by Alumina (Al_2O_3). The following Table compares the major characteristics of these two types of substrates.

Table 5.1 Characteristics of PTFE and Alumina substrates.

Substrate Material	PTFE	Alumina (Al_2O_3)
Relative dielectric constant e_r	2.1 ~ 2.5	8 ~ 10
Loss tangent: $10^4 \times \tan d$ (@ 10 GHz)	3 ~ 15	1 ~ 15
Dielectric strength in KV/cm	~ 20	~ 90
Dielectric constant temperature coefficient: $\Delta e_r / e_r \cdot \Delta T \left(\mathrm{ppm}/{}^{o}\mathrm{C}\right)$	~ 400	~ 140
Thermal conductivity in $\mathrm{W} / \mathrm{cm} \cdot {}^{o}\mathrm{C}$	0.002 ~ 0.003	0.2 ~ 0.3
Thermal expansion $\Delta\lambda / \lambda \cdot \Delta T$ in $\left(\mathrm{ppm}/{}^{o}\mathrm{C}\right)$	6 ~ 100	~ 6

Teflon is a relatively soft material, therefore its mechanical stability is not as good as the ceramic, e.g. it does not hold its shape very well. Therefore, glass fiber is regularly added to the Teflon to reinforce the mechanical stability of the substrate. This process increases the dielectric constant somewhat, depending on the amount of fiber added, but generally not a significant change. However, adding glass fiber does increase the loss tangent more and the substrate becomes anisotropic. Anisotropy is most obvious in woven glass fiber reinforced Teflon substrate. Some manufacture add randomly arranged tiny glass fiber segments to the Teflon, such as Roger's RT-Duroid, to reduce this effect.

Alumina is formed by tiny grains of Al_2O_3, crystal which in monocrystalline form is called sapphire. Although sapphire itself is anisotropic, the radom arrangement of the tiny grains of crystal in Alumina generally form isotropic substrate, unless the manufacturing process causes the grains to arranged in certain preferred orientation. The purity of the Alumina plays an important role in the dielectric constant, as well as other characteristics, of the substrate. As the purity increases, the relative dielectric constant increase. The most commonly used Alumina substrate is 99.5% pure and has a relative dielectric constant of 9.8.

The plastic substrate usually comes in discrete thickness from 5 mils to 100 mils and above. It also almost always comes with conductor lamination, usually copper, on one or both sides of the substrate. Unwanted metal while forming electrical circuits on the soft substrate must be removed by chemical or mechanical means. Alumina substrate also comes in many different thickness with the most common one to be 25 mils thick. However, it usually does not have any conductor on either side of the substrate. Circuit conductors must be formed on the surface of the substrate by either the thin-film or the thick-film process.

The advantage of a high dielectric constant substrate is in the size reduction factor. Comparing two substrates of the same height, the wavelength of the microwave signal in Alumina is about one half the size of the wavelength in PTFE at the same frequency. Thus, microstrip circuit elements built on a Alumina substrate is about half the size of the same circuit on a PTFE board. Therefore, to increase the dielectric constant of their product, soft substrate manufacturer mix various amount, as well as different kind, of ceramic powder into the plastic to form new substrate material. As a result, ceramic filled PTFE substrates come in a wide spectrum of relative dielectric constant from 3 up to 10 and above.

From Table 5.1, it is obvious that ceramic substrates are better suited for high power application from either the dielectric strength or the thermal conductivity. The thermal expansion coefficient of the substrate are important for both the adhesion of the conductor and mounting of the substrate to circuit housing. The temperature dependency of the dielectric constant is especially important for high Q circuit. Other properties to consider when choosing a substrate are homogeneity of dielectric constant through out the substrate, small dielectric constant and dimensional variation between lots, uniformity of substrate thickness, and substrate surface flatness and smoothness. Of course, cost is always one of the most important considerations of the substrate selection process. However, the final cost of producing a microwave integrated circuit may be more on the circuit fabrication process than on the substrate itself depending what type of substrate and process is used.

5.2 CIRCUIT REALIZATION

As described in the previous section, circuit realization on soft substrate usually involves metal removal process and in hard substrate metal formation process. In all cases, photomask and etching are commonly used at one time or the other. For this reason, we'll discuss the circuit fabrication process of soft substrate first, which is mainly photomask and etching.

Microwave circuit fabrication on soft substrate is essentially the same as the process of regular PC board. First, circuit layout is converted to a certain format for generating photomasks. Gerber is one of the formats that is commonly used in PC board fabrication. It contains a series of photo plotter control commands in ASCII code. The photo plotter itself consists of an aperture wheel and an XY table. The aperture wheel is setup according to the apertures specified during the conversion from layout to Gerber. A positive or negative mask is then produced by flashing and/or shining lights through the aperture and moving the film on the XY table. Modern photo plotter use synthesized aperture and do away with the mechanical aperture wheel. While the photomask is being plotted, the surface of the soft substrate is treated according to the manufacture's recommendation and a thin layer of photoresist is applied on the surface. Depending on the type of the photoresist, either the positive or negative photomask is pressed against the substrate and exposed under a light. Then, the photoresist over where no circuit elements exist are washed away. Subsequently, the exposed metal is etched away by chemical process and finally the remaining photoresist is remove.

Circuit dimension accuracy is important for microwave circuit, which may not be as important in ordinary PC board process. Therefore to ensure good dimensional accuracy, a couple of issues in the photomask and etching process are discussed here. First, the emulsion of the photomask must be on the side that's touching the substrate when the photoresist is exposed to the light source. Otherwise, the light can shine under the mask and causing the width of the microstrip line to come out reduced. During the etching process, undercut or overcut of the conductor with respect to the mask could occur depending on how well the etching chemical and etching duration is controlled. The under or over etching problem can become severe as the operating frequency of the circuit goes up, i.e. the size of the circuit goes down. This can be overcome somewhat by choosing a substrate with thinner conductor cladding when the design frequency is high. Or, compensation factor can be incorporated in the photomask, if etching process is stable. For instance, the circuit can be made larger on the photomask when the amount of over etching is kept the same between lots.

Thin film and thick film process both need to heat the substrate with temperatures above $400^{o}C$. Since Teflon can only withstand temperature below $260^{o}C$, thus these two process can only be used in the fabrication of ceramic substrate circuits. In thin film process, very thin layer of metal is first deposited on the substrate by vapor deposition or sputtering. Then, the conductor is thickened by electroplating followed by the photomask and etching process to form the circuit. In thick film process, photomask and etching process is done on a fine mesh screen to form circuit patterns. Then, a uniform layer of conductor paste is squeezed through the screen and onto the substrate surface similar to a screen-printing process. Finally, the whole substrate is dried and heated up so the conductor in the paste can settle and adhere to the substrate.

Both the vapor deposition and sputtering requires high vacuum environment, which means costly fabrication equipment for producing thin film circuit. Thick film process is relatively cheap and suitable for mass production. But, because of the size of the mesh and the mechanical printing process, the circuit resolution is limited and the circuit alignment is not as good as the photo process. However, both film fabrication technique can produce on substrate resistors and capacitors by repeating the process with layers of resistive conductors, dielectric materials, and conductors.

The machining of soft substrate is relatively easy. No special tooling is required for cutting and drilling. The through hole contact, i.e. via holes, is produced by drilling and electroplating the hole wall. Via holes can also be quickly made in prototyping by using metal eyelets. On the other hand, ceramic substrate require special cutting and drilling tools such as diamond saw, diamond drill, laser cutting and drilling equipment, and etc. Via holes on the ceramic substrate is drill on the unplated substrate, and then the hole wall is coated with metal during the deposition and electroplating process.

Ceramic substrate is suitable for many different kinds of assembling method, such as soldering, epoxy bonding, ultrasonic wire bonding, and thermocompression wire bonding. Wire bonding on soft substrate is possible but difficult. Therefore, soldering and epoxy bonding are the most common assembling method utilized on soft substrate.

5.3 SUBSTRATE PARAMETER VERIFICATION

Substrate manufacturer use various kinds of cavity resonance method to measure the substrate characteristics parameters for production control. These methods usually require special plating of the substrate or special fixtures for measurement, thus are not suitable for substrate verification by a circuit designer. However substrate verification is very important, especially when the circuit performance comes out different than the expectation. Therefore a circuit structure that can be produced on the substrate using the standard fabrication process is needed. Printed resonators, either in the shape of a ring or just a straight piece of transmission line are ideal for this purpose. They are shown in Figure 5.1.

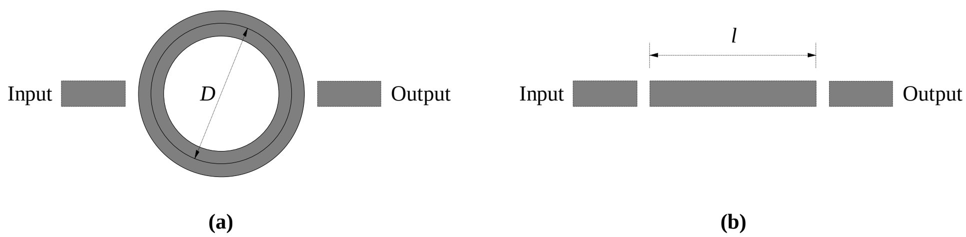

Figure 5.1 **(a)** Ring resonator **(b)** Straight resonator.

The resonance frequency of the resonator can be found by measuring transmission characteristics using a signal source connected to the input and a power meter at the output, or any similar setup. The connector discontinuity is not important here. The resonance occurs when the perimeter of the ring is a whole number multiple of wavelengths of the Quasi-TEM mode wave in the substrate, i.e.

$$e_{r,\mathrm{eff}}(f_R) = \left(\frac{n \cdot c}{p \cdot f_R \cdot D} \right)^2 \tag{5.1}$$

where c is the speed of light in vacuum, f_R is the resonance frequency, and n is a whole number. In the straight resonator case, the resonance occurs when the length of the resonator is a whole number multiple of half the wavelengths of the wave. Therefore,

$$e_{r,\mathrm{eff}}(f_R) = \left(\frac{n \cdot c}{2 \cdot f_R \cdot l} \right)^2 \tag{5.2}$$

