VII. Passive Elements

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The previous sections of this chapter have described the active elements used in MMICs, and although they are critical for circuit performance and reliability, it is the passive elements that determine the circuit's bandwidth, center frequency, and other electrical characteristics. Besides connecting the various active elements together, passive elements are used to set the bias point for the circuit and impedance match the active devices to themselves and the input and output connections of the MMIC. Passive elements are composed of lumped elements such as resistors, capacitors, and inductors and distributed elements such as transmission lines. In general, distributed elements are physically large enough that transmission line characteristics play a significant role in their function. Distributed elements have inductive, capacitive, and resistive aspects, all of which are taken into account by the transmission line analysis. The rule of thumb is that an element must be considered as a distributed element if it has dimensions greater than $\lambda/10$, where λ is the wavelength. Lumped elements on the other hand are small enough that transmission line effects do not play a significant role in their function. Nevertheless, even lumped elements are not purely inductive, resistive, or capacitive, but have aspects of all three due to parasitics. Because of these parasitic effects, lumped elements will resonate at some frequency. Failure to account for this complexity may lead to significant errors in circuit design. CAD programs such as SuperCompact and HP-EEsoF's Libra and Touchstone that are used in MMIC design contain models for most passive elements. Unfortunately, circuit designs do not always meet the modeled electrical performance goals because of unaccounted-for electromagnetic coupling effects and limitations of the models themselves.

The ability to fabricate MMICs and realize the advantages of size, ruggedness, reproducibility, and cost require that methods exist to fabricate the required passive components. Economic considerations require the MMIC chip size to be minimized as much as possible to maximize the number of chips on a wafer. Unfortunately, the passive components, especially inductive elements, tend to be large. In addition, the elements must be separated from each other to minimize electromagnetic coupling between the elements. The result is that the active elements occupy only a small portion of the MMIC area. Lastly, all passive components must be fabricated on the semi-insulating GaAs substrate.

The following is a brief description of passive elements, methods of fabrication, and the associated reliability concerns.

A. Resistors

Resistors are used for feedback circuits, setting the bias point of active devices, isolation, and terminations in power combiners and couplers. Two types of resistors are used in MMIC fabrication: thin films of lossy metals and lightly doped GaAs active layers. Figure 3-23 shows schematics of each of these two types of resistors. The resistance for both types of resistors may be given by

$$R = \frac{\rho_s L}{A}$$

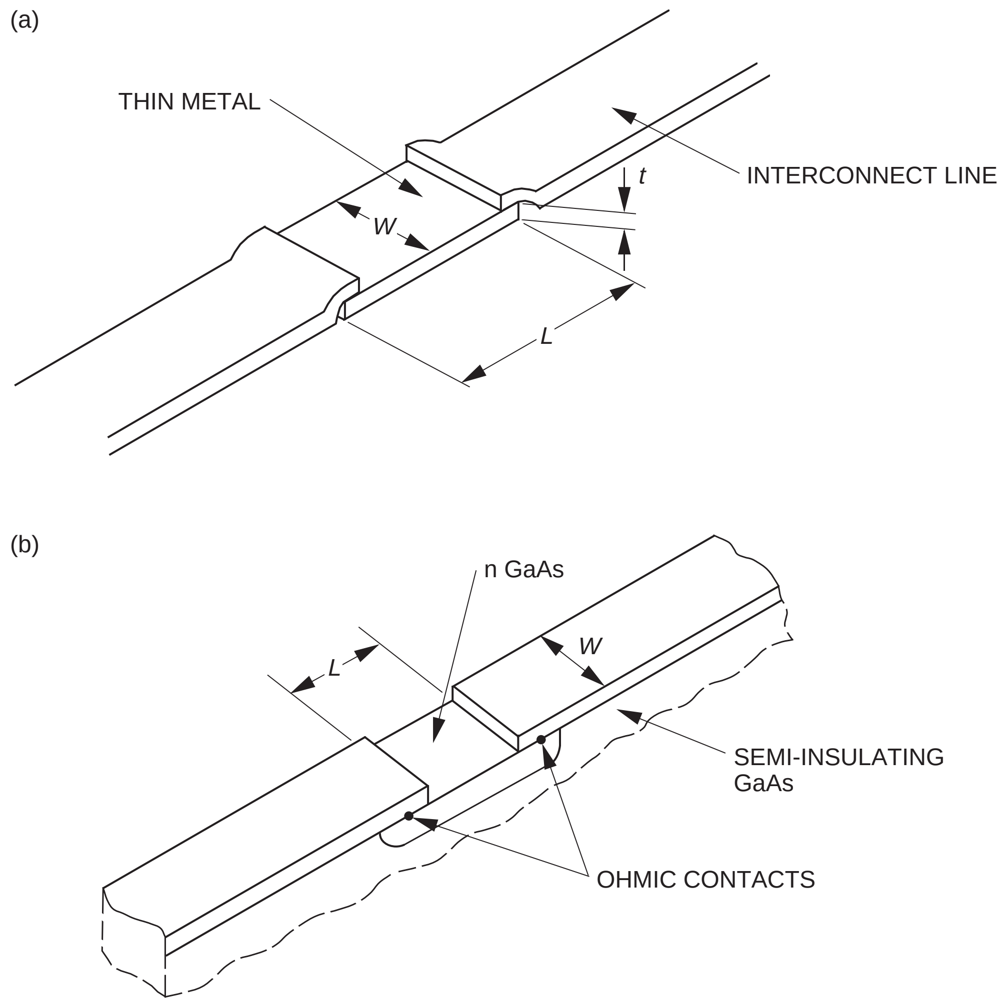

Figure 3-23. Two resistor types in MMIC fabrication: (a) thin film and (b) GaAs-based resistor incorporating an n GaAs channel and ohmic contacts.

where ρ_s is the sheet resistivity, $A = W*t$ is the cross-sectional area of the resistor, t is the resistor thickness, W is the width of the resistor, and L is the length. The efficiency of the resistor as determined by the resistance per unit length is a function of ρ_s. For metal thin-film resistors, ρ_s is a function of the metal. For GaAs based resistors, ρ_s is a function of the doping concentration.

Metal thin-film resistors are used for accurate, low-resistance applications. They are usually fabricated from TaN and NiCr, although Cr, Ti, Ta, Ta_2N, and AuGeNi alloys have also been used. Some of the advantages of thin-film resistors are a low Temperature Coefficient of Resistance (TCR), tight tolerances, small parasitics, and low sheet resistivity. The major disadvantage of thin film resistors is the added processing steps required to fabricate them, although thermal dissipation difficulties and electromigration failures are also a concern. Short resistors or those made from materials with a large resistivity have fewer parasitics, but they have a higher thermal load to dissipate. When resistors must dissipate large amounts of power, they can have the highest temperature on the MMIC and limit the MMIC reliability. Sidegating or the flow of current around the perimeter of the resistor is usually eliminated by depositing the resistor on top of an insulating film such as Si_3N_4. Electromigration failures result from the large current densities that can flow through the thin metal films. Tantalum resistors have exhibited this problem for thin, 0.006-μm layers, with currents of 0.06 mA/μm of line width. Lastly, NiCr resistors are susceptible to degradation due to moisture. Therefore, these resistors must be passivated.

GaAs-based resistors are implemented by the use of an FET channel and ohmic contacts that are already available in the MMIC fabrication process. The total resistance of these elements is the sum of the resistance of the GaAs channel itself and the two ohmic contacts. The advantage of GaAs-based resistors is the wide range of resistivities available through changes in the doping level. GaAs-based resistors have several potential problems, however: current saturation, Gunn domain formation, and a high TCR. Above a critical electric field, the current in GaAs will saturate and the device loses its linearity. In practice, this is not a severe limitation since the length of the resistor is usually sufficient to prevent the electric field from reaching its critical value. Gunn domain formation, the initiation of microwave oscillations due to an applied static electric field, also occurs only if large electric fields are present. A more serious problem is the large positive TCR (+3000 ppm/°C). This can result in significant resistance changes over temperature. Fortunately, modeling techniques can be used to determine the resistance change that is tolerable for a given circuit and application.

The issues of current handling capacity, thermal dissipation, and distributed effects also play a role in the design and operation of GaAs based resistors. The resistor, especially one in the dc source or drain circuit, must be able to handle the current passing through it without reaching saturation. GaAs is a relatively poor thermal conductor and will not be able to remove heat rapidly enough if too much power is dissipated in too small an area. Physically large resistors on the other hand will become distributed elements and act as lossy transmission lines. In general, GaAs-based resistors may be thought of as a gateless FET. If the resistor is properly designed to operate below the current handling limit and the critical electric field limit, thermal heating should not be a problem.

B. Capacitors

Capacitance may be included in MMIC circuits in any of four basic configurations: an open-circuit transmission line, coupled lines or interdigitated capacitors, Schottky diodes, and metal-insulator-metal (MIM) capacitors. Coupled lines and open-circuit transmission lines can be used to provide fairly low capacitance values. For these two capacitor types, the capacitance is dependent on the electrical length of the transmission lines. Therefore, the capacitance is highly frequency dependent. The advantage of these capacitors is that they are easy to fabricate since they require only a single metal layer.

The most popular type of capacitor for MMICs has become the MIM capacitor because of the high capacitance per unit area that can be obtained. Therefore, smaller and less costly circuits are possible. A schematic of an MIM capacitor is shown in Figure 3-24. This thin-film capacitor is composed of two metal plates separated by a dielectric material. Typically, the dielectric material overlaps the first metal layer and the upper metal layer has a smaller area than the lower metal layer. This configuration helps to minimize fringing fields to ground and shorts between the upper and lower capacitor plates. Although the air bridge shown on Figure 3-24 is not required, it is often included to further minimize parasitic capacitance. The dielectric is typically silicon nitride (Si_3N_4, 0.1 to 0.4 μm thick) since it is already used in the MMIC fabrication process for circuit encapsulation, although SiO_2 and Ta_2O_5 are also used. Since the dielectric layer is substantially thinner than the substrate thickness, MIM capacitors exhibit significant

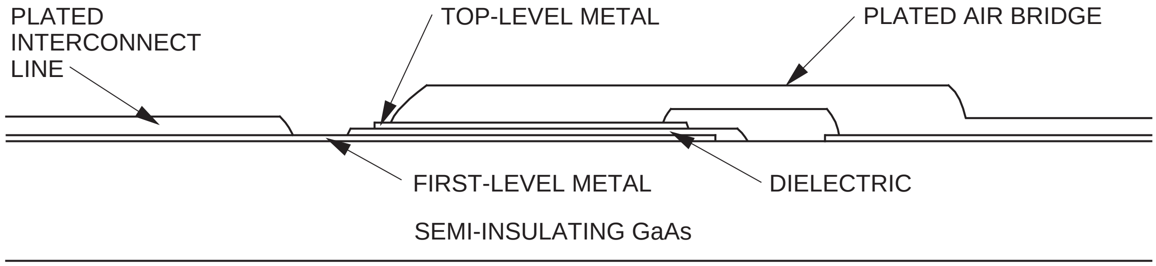

Figure 3-24. MIM capacitor using an air bridge for top-level interconnect.

fringing effects, which are a function of the perimeter. Careful experimentation to determine the magnitude of this effect for specific process parameters, such as dielectric type and thickness, is essential for any stable process. Test capacitors should also be included on the wafer for in-process verification.

The yield of MIM capacitors on a wafer plays a major role in determining the total yield for the wafer. One pinhole that ruins one capacitor also ruins the entire chip. The problem can be illustrated by considering a complex MMIC chip with ten capacitors and a capacitor yield of 95%. This case would produce a chip yield of only 60% on capacitor defects alone. The major yield limiting factor for MIM capacitors is shorts caused by pinholes in the dielectric or sharp points on the metal plates. Pinholes are very difficult to eliminate completely, but they can be minimized by good cleaning and deposition processes. Again, trade-offs require an engineering judgment based on the experimental results and the realized yields for a particular process. In addition to pinholes, the circuit design must assure that the electric field across the capacitor does not exceed the dielectric breakdown field .

C. Inductors

Inductors are necessary elements in MMICs where they function as tuning elements and RF chokes in dc bias circuits. Inductors are one of the easiest passive elements to fabricate. As a distributed element, they are realized by a section of high-impedance transmission line. These inductors are limited to inductance values below 2 to 3 nH because of the high losses associated with the long lengths of high-impedance transmission line. Lumped element inductors can be used to provide inductance up to 20 nH.

Lumped inductors are typically comprised of a transmission line in a spiral shape. A typical spiral inductor is shown in Figure 3-25. The total inductance is a result of the self-inductance of the high-impedance transmission line and the mutual inductance created by the electromagnetic coupling between the closely spaced lines. An air bridge is required to connect to the center tap of the spiral inductor. Although the spiral inductor is easy to fabricate, it is one of the most difficult devices to theoretically model because of the coupling between lines. Therefore, experimental characterization is usually required. Removable air bridges are often used in the first iteration to characterize an inductor with a different number of turns. In actual MMIC circuit designs, a model of these parts based on the measured data is used in the CAD programs.

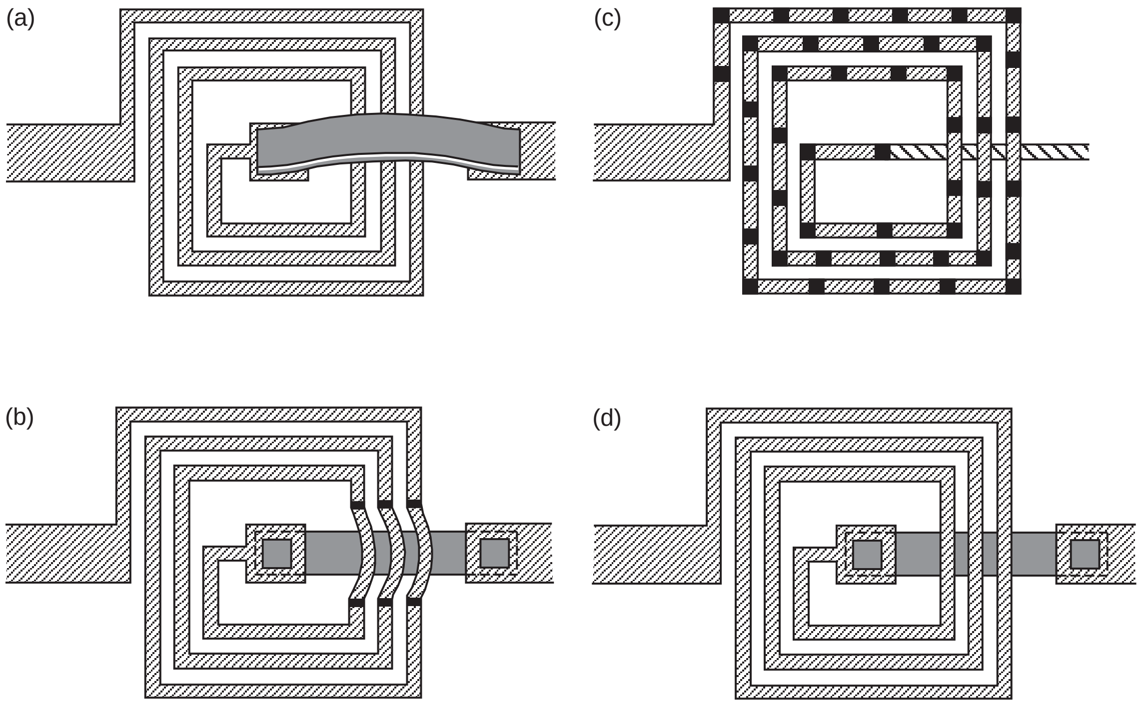

Figure 3-25. Spiral inductors: (a) as a single air bridge, (b) as air bridges over an underpass, (c) formed entirely of air bridges, and (d) using two metal levels for an underpass. (From [1].)

From a reliability point of view, the spiral inductor is a combination of transmission lines and air bridges. There are no special reliability issues associated with spiral inductors other than the air bridges and electromigration.

D. Transmission Lines

The dielectric constant of GaAs, coupled with the 100-µm-thick substrate commonly used in MMICs to facilitate heat removal, results in compact, narrow transmission lines. The critical transmission line parameters are the characteristic impedance of the line, the attenuation, and the frequency dependence of the phase velocity and impedance. The physics of transmission lines on dielectric substrates is rather complex, especially considering the realities of composite metallizations of finite thickness, discontinuities, radiation effects, and current distribution. The details of this topic are beyond the scope of this text, but adequate consideration should be given by the MMIC designer and the process engineer to understand the topic. CAD programs can provide ample support in obtaining reasonable analytical approximations, which can be used in the design stage to model the desired characteristics.

For MMIC purposes, the transmission lines are almost always microstrip, although coplanar waveguide transmission lines have been used. Both of these transmission lines are shown in Figure 3-26. The characteristic impedance of microstrip is inversely proportional to the ratio of the conductor width to the substrate thickness and also to the dielectric constant of the substrate. The conductor thickness also has a minor effect on the characteristic impedance. For GaAs substrates, the width-to-height ratio for a 50-Ω characteristic impedance is approximately 0.7. Therefore, for the typical 100-µm-thick substrate, the microstrip line width is 70 µm for a 50-Ω impedance. High-impedance lines have a smaller line width although lines thinner than 10 µm are rarely

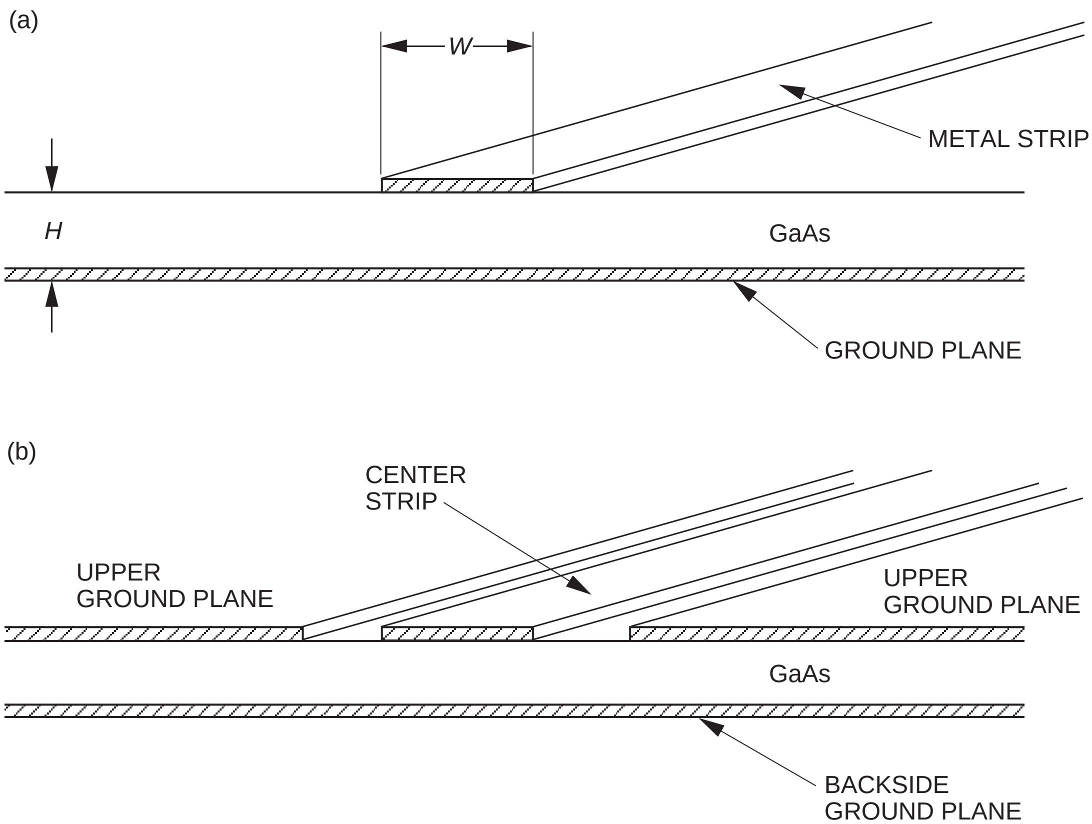

Figure 3-26. Transmission lines: (a) microstrip and (b) backside of grounded coplanar waveguide.

used because of the high conductor loss associated with the thin lines. Obviously, these are very large line dimensions compared to the gate widths discussed in Section 3-III. Electromagnetic coupling between transmission lines can be significant. Since the theoretical analysis of the coupling is difficult to perform, the transmission lines are normally separated by two to three line widths to minimize the coupling. The backside grounded coplanar waveguide has additional problems due to the excitation of parasitic modes that severely degrade circuit performance. Specifically, a slotline type of mode can propagate if the two ground planes are not held at the same potential and a parallel plate waveguide mode can propagate if the upper and lower ground planes are not held at the same potential. To accomplish these two requirements, air bridges and via holes are required.

The only reliability issues associated with transmission lines are electromigration and adhesion of metal on the substrate. Electromigration typically is a concern for the high impedance lines used in the dc bias circuit.

E. Via Holes

Both microstrip and backside grounded coplanar waveguide require via holes to either provide microstrip short circuits or to tie the upper and lower ground planes of the coplanar waveguide together. Via holes are etched through the GaAs substrate, usually from the backside of the substrate to minimize the top-side element area. This wet or dry etching process is followed by a gold sputtering step and finally a gold plating step to fill the hole with gold. A schematic of a filled via hole is shown in Figure 3-27.

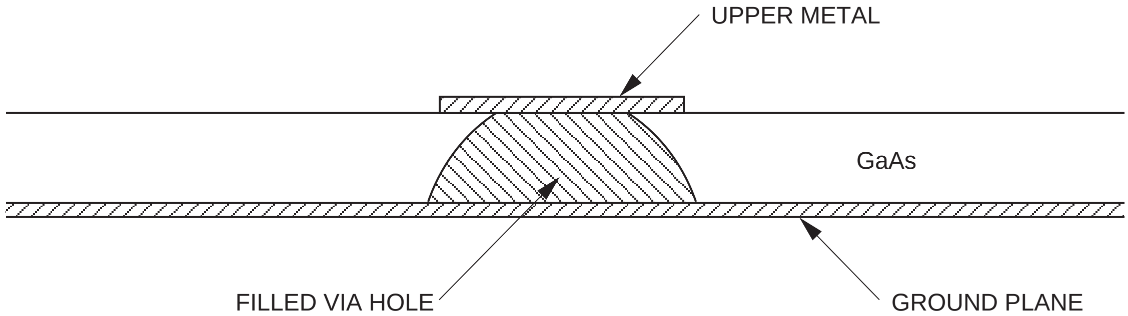

Figure 3-27. Ideal via hole in GaAs.

Several reliability issues arise from via holes. First, vias, if completely filled with gold, may cause cracking of the GaAs due to Au and GaAs thermal expansion mismatch. However, vias must contain enough gold to provide an acceptable thermal path. Since via holes are often used under the source contacts of field-effect transistors, an increase in thermal resistance may result in an increase in the junction temperature and a resulting degradation in the device reliability. Second, when via holes are placed directly under MIM capacitors, the capacitance yield is degraded because of the nonplanar via hole surface.

F. Air Bridges

Air bridges or crossovers are required for most MMIC layouts comprised of microstrip and absolutely necessary for coplanar waveguide circuits. In addition, air bridges are often incorporated into power transistors to connect the source leads of the parallel gates. An air bridge is simply a metallic bridge that permits two transmission lines to cross over each other without forming an electrical short circuit. A typical air bridge is shown in Figure 3-28. It is fabricated by depositing the first-level metal to form the transmission lines. Photoresist is then spun onto the wafer and holes opened where the bridge connections or posts are to be made. Then a second photoresist pattern is developed that defines the bridges. A gold layer is sputtered onto the wafer and the bridge interconnect metal is plated to the proper thickness.

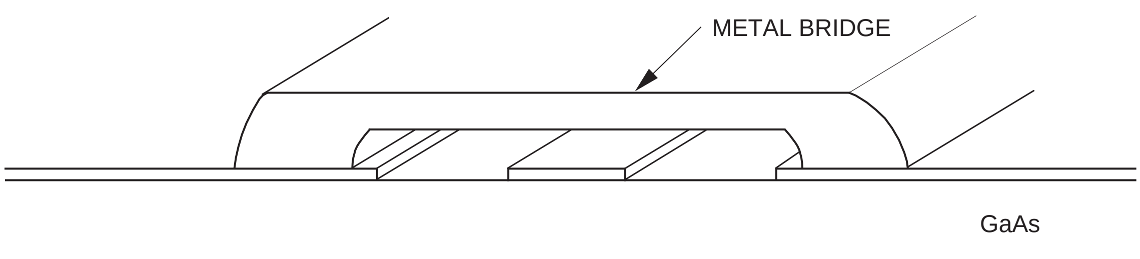

Figure 3-28. Air bridge connecting coplanar waveguide ground planes.

The reliability of air bridges depends on the bridge-metal thickness, the contact or post size, the bridge height, the interconnect metal used, and the bridge length. The primary concern is that the air bridge will sag and create a short circuit. Proper choice of the metal and the bridge length-to-width ratio and the application of dielectric coatings under the air bridge can often minimize this effect. In addition, the bridge height and shape can be altered by simple changes in the photoresist processing steps. Typically, air bridges are on the order of several microns and ideally have an arched shape for strength. Once these factors have been established and followed as part of the design rules, the major failure modes are electromigration and cracking of the interconnect metal.

Reference

[1] M. Gillick and I.D. Robertson, "Passive Components," *MMIC Design*, I. D. Robertson, Editor, The Institution of Electrical Engineers, United Kingdom, 1995.

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