Chapter

11 Microwave Integrated Circuits

11.0 INTRODUCTION

With the development of electric technology in general and microwave solid state devices in particular, there has been a thrust on miniaturization and integration of devices, circuits, components, etc., in microwave engineering. This has led to the evolution of microwave integrated circuits (MIC) which have low weight, low volume, reliable and insensitive to mechanical shock (specially for defence and space applications). *MIC is an assembly in planar geometry that combines different circuit functions through microstrip/striplines*. The integration in the circuit may be small (<100), medium (<1000), large (LSI; up to 10^5), very large (VSLI; $>10^6$) or ultra large-scale (ULSI) on a single chip. The advantages of MICs over conventional or discrete circuits are better performance, higher reliability, reproducibility, low cost, and small size and weight. The following is a list of factors behind the boost in MIC technology:

1. Rapid growth of material processing technology such as epitaxy, ion implantation sputtering, etc.
2. Development of low noise MESFETs and power MESFETs.
3. Development of substrates with desired properties such as Si, GaAs, GaN, etc., having high $\varepsilon_r \sim 13$ and low-loss tangent, $\tan \delta = 5 \times 10^{-4}$.
4. Growth of CAD techniques par excellence.
5. Ability of fabricating various devices both active and passive simultaneously using the same process, e.g., MESFETs, Schottky diodes, switches, tank circuits, etc.
6. Realization of multilayer processing.

11.1 HYBRID AND MONOLITHIC MICROWAVE INTEGRATED CIRCUITS

Microwave integrated circuits now in common use are of two types: (i) hybrid microwave integrated circuits (HMICs) and (ii) monolithic microwave integrated circuits (MMICs). In HMICs, *the transmission lines and matching networks are realized as microstrip circuit elements on a suitable substrate material. The discrete components like transistors and passive components such as chip capacitors, inductors, resistors, etc. are connected by soldering or wire bounding techniques.* A typical HMIC is shown in Figure 11.1(a) along with the electric circuit to be realized in Figure 11.1(b).

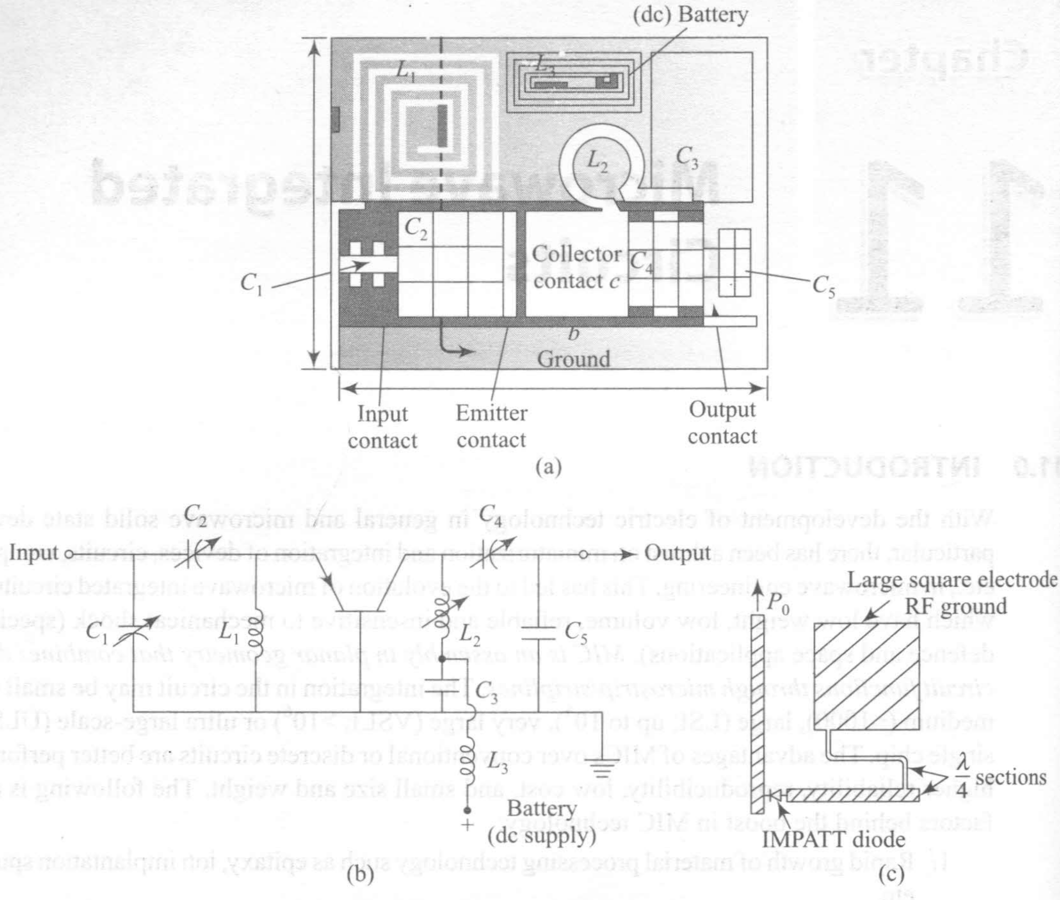

Figure 11.1 Hybrid microwave integrated circuit of a transistor amplifier: (a) HMIC with discrete element transistors, chip capacitors, and inductors are bonded to the substrate in single-layer metallization, (b) corresponding to electric circuit of transistor amplifier, and (c) miniaturized hybrid MIC IMPATT diode oscillator

In MMICs, *all active and passive components and sections of the transmission line are formed on the surface of the semiconductor substrate or into the bulk by some deposition scheme such as ion beam implantation, diffusion, epitaxy, sputtering, and/or evaporation.* A typical MMIC is shown in Figure 11.2. Table 11.1 compares an HMIC with an MMIC. The later features: small size, weight, circuit flexibility, and their performance may be enhanced with a little additional cost. Also, these are broadband because of quite less parasitic reactances. MMICs have some disadvantages too. They waste large areas of expensive semiconductor substrate. The required tolerances of components are critical. Debugging, tuning, and trimming of these devices are almost impossible. This makes their utility for moderate power and low Q.

For high Q and high power HMICs are more suitable. To meet the high power and high Q requirements *miniaturized hybrid MICs* have been designed, where passive elements such as inductors, capacitors, resistors, transmission lines, etc. are batch deposited on the substrate and active devices like transistors, diodes, etc., are wire bonded on to the substrate. These circuits are smaller in size and weight than HMICs but bigger than MMICs. A typical such miniaturized hybrid MIC of an IMPATT oscillator is shown in Figure 11.1(c).

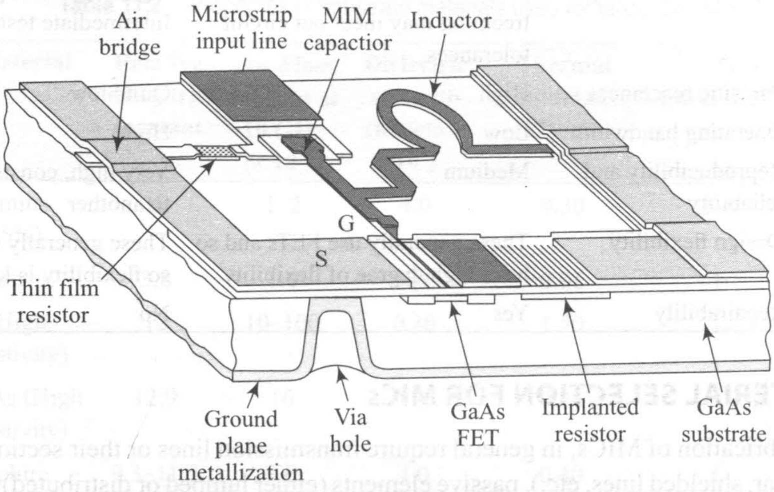

Figure 11.2 Structure of a monolithic microwave integrated circuit

Table 11.1 Comparison of HMIC and MMIC

S. No.	Property/ Specification	Hybrid microwave integrated circuit (HMIC)	Monolithic microwave integrated circuit (MMIC)
1.	Description	Transmission lines and matching networks are realized as microstrip circuit elements. The discrete components (resistors, capacitors, inductors, transistors, etc., are soldered or wire-bonded	All the active and passive components and sections of transmission lines are formed on the surface or into the bulk of semiconductor substrate by some deposition scheme
2.	Number of layers	Generally there are two layers: one for the transmission lines and matching networks and another for discrete components	There are several layers of metal, semiconductor (active devices) dielectric, and resistive films. There may be one layer for each circuit
3.	Substrate used	Generally dielectric or semi-insulator (SiO_2, SiO, Al_2O_3, etc.)	Generally semiconductor (GaAs, GaN recent)
4.	Cost	Labor cost high	No labor cost, cheap when produced in bulk (>200)
5.	Substrate area utilized	To the maximum	Low
6.	Debugging, tuning, and trimming after design	Possible, and is generally done (increases labor cost)	Not possible
7.	Size and weight	Large	Small
8.	Design tool CAD	Generally used	It is a must

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9.	Processing, steps, and intermediate testing	Processing steps not critical intermediate testing possible treeming may meet out circuit tolerances	Circuit tolerances to be meet out during design. Design steps are critical. Intermediate testing not possible
10.	Parasitic reactances	High	Quite low
11.	Operating bandwidth	Low	High
12.	Reproducibility and reliability	Medium	Very high, consistent from one chip to another
13.	Design flexibility	These generally use FETs and so have high degree of flexibility	These generally use GaAs MESFETs, so flexibility is less but still good
14.	Repairability	Yes	No

11.2 MATERIAL SELECTION FOR MICs

The fabrication of MICs, in general require transmission lines or their sections (microstrip, strip, coplanar, shielded lines, etc.), passive elements (either lumped or distributed) and active solid state devices (FETs, BJTs diodes, MESFETs, MOSFETs, etc.). For this we need five classes of materials:

1. Substrate material
2. Conductor material
3. Dielectric material
4. Resistive films
5. Ferromagnetic materials (for using ferrite devices)

Material selection for any MIC involves the evaluation of a number of properties like electric conductivity, dielectric constant, loss tangent, thermal conductivity mechanical strength, manufacturing capabilities, adhesion to substrate, etc.

11.2.1 Substrate Material

The selection of substrate material is most important because this is the substance on which the device is implemented. The selection of the material depends on the type of MIC and the device to be implemented. Table 11.2 lists some materials being currently used.

The substrate material should normally have (i) high dielectric constant with low-loss tangent, (ii) high purity, (iii) uniform thickness and fine surface finish, (iv) high resistivity, and (v) high thermal conductivity and high dielectric breakdown strength.

For hybrid MICs, alumina is commonly used at low frequencies. At high frequencies quartz is preferred.

For MMICs the substrate *must* be a semiconductor. The choice of the semiconductor depends on the type of active device and the frequency range of operation desired. For example, Si for the bipolar transistor and silicon on sapphire for MESFETs can be used up to several GHz. GaAs FETs are used up to 60 GHz. GaAs is a versatile circuit element and frequently used to design low-noise amplifiers, high-gain amplifiers, broadband amplifiers, mixers, oscillators, phase shifters, switches, etc. However, it cannot be used for high power requirements.

Table 11.2 Properties of substrate materials used for fabricating MICs[a]

S. No.	Material	Relative dielectric constant	tan δ loss tangent at 10 GHz ($\times 10^{-4}$)	Dielectric strength (kV/cm $\times 10^3$)	Thermal conductance (kW/cm)	Surface finish (μm)	Applications in MIC
1.	Alumina (99.5%)	10	1–2	4.0	0.30	2–8	Microstrip lines
2.	Quartz	3.8	1.0	10.0	0.01	1	Microstrips
3.	Si (High resistivity)	12	10–100	0.30	1.50	1	MMICs
4.	GaAs (High resistivity)	12.9	16	0.35	0.46	1	MMICs microstrips
5.	Sapphire	9.3–11.7	1.0	4.0	0.40	1	Microstrip lumped elements
6.	Glass	5	4.0	—	0.01	1	Lumped elements
7.	Beryllia (99%)	6.1	1.0	—	2.50	2–50	Compound substrate

[a] M. Caulton. *Proc. IEEE, 59*, 1481 (1971).

Table 11.3 Comparison of properties of Si, GaAs, and GaN

S. No.	Material	ε_r	Band gap (eV)	Breakdown *E* field (MV/cm)	Mobility (cm^2/Vs)	Saturated velocity 10^7 (cm/s)	Thermal conductance (W/cm/K)
1.	Si	12	1.1	0.3	1300	1.0	1.5
2.	GaAs	12.9	1.4	0.4	6000	1.3	0.5
3.	Ga N	9.0	3.4	3.0	1500	2.7	1.5

The material satisfying higher power requirement should have higher breakdown voltage and higher band gap. These requirements are met by a new material, GaN. Table 11.3 compares its properties with the frequently used Si and GaAs. Higher voltage and higher saturation velocity allows the designed amplifiers to produce more power in less space, i.e., higher power densities. However, GaN lags behind GaAs in mobility by a factor of 4, this limits its use at higher frequencies. Of course about twice the saturation velocity partially offsets the mobility disadvantage. Yet GaN technology is under development at a fast pace.

Other materials knocking in the future are carbon nano tubes (CNT) and graphines. Design of carbon nano tube antenna in planar structure provides tremendous potential for novel devices and systems.

11.2.2 Conductor Material

In MICs conducting materials are used both for generating conductor patterns and the ground plane. The desirable properties of conductors are as follows:

1. High conductivity
2. Good adhesion to substrate
3. Easily deposited, soldered, electroplated, and etched
4. Low temperature coefficient of resistance

Table 11.4 summarizes the properties of some commonly used conducting materials along with their deposition technique. It is seen that conductors having very good conductivity (category A) have poor adhesion to the substrate and relatively poor conductors have good adhesion to the substrate (category B). The obvious process is thus to deposit a thin layer of conductor from category B on the substrate and then deposit over it a layer of conductors from category A. The thickness of the later layer should exceed 4 to 5 skin depths so as to confine most of the current and provide low resistivity. The choice of material depends on compatibility with other materials used in the fabrication of the MIC. Typical combinations used are Cr–Au, Cr–Cu, Cr–Cu–Au, Ti–Au, Ti–Pd–Au, Ti–Pt–Au, etc. To mention, the frequently used gold top surface is excellent for ultrasonic bonding but copper requires for soldering. Materials of category D are generally used to provide the potential barrier needed for active devices. It may be mentioned that Al is a good conductor and has fair adhesion to substrate and so its use does not require intermediate layer of materials from category B.

Table 11.4 Conductor materials commonly used in the design of MICs[a]

Category	Material	Surface resistivity (ohm/sq × $10^{-7}\sqrt{f}$)	Normalized skin depth $\delta\sqrt{f(\mathrm{GHz})}$ $\mu\mathrm{m}\cdot\sqrt{(\mathrm{GHz})}$	Coefficient of thermal expansion (α/°C × 10^6)	Adherence to substrate	Deposition technique
Very good electric conductors	Au	2.5	2.49	15	Very poor	Evaporation electroplating
A	Cu	2.6	2.09	18	Very poor	Evaporation electroplating
	Ag	3.0	2.03	21	Poor	Evaporation
	Al	3.3	2.61	26	Fair	Evaporation electroplating
Good electric conductors	Cr	4.7	5.75	8.5	Good	Evaporation electroplating

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B	Ta	4.2	6.26	6.6	Very good	Electron beam evaporation sputtering
	Ti	7.2	11.00	9.0	Good	Evaporation sputtering
Moderate electric conductors	M_0	4.7	3.8	4.6	Fair/good	Electron beam evaporation sputtering
C	W	4.7	3.76	6.0	Fair/good	Sputtering chemical vapor deposition Electron beam evaporation
Barrier conductors	Pt	12.5	5.2	9.0	—	Electron beam Evaporation sputtering
D	Pd	12.6	5.2	11.0	—	Evaporation sputtering

[a] Peter Russer, Nima Routhi, and Mircea Dragoman *et al. IEEE Microwave Mag., 11* (7) (Dec 2010) pp. 58, 72, and 81 respectively (and references therein).

11.2.3 Dielectric Material for MICs

Insulating dielectric film is needed in MICs to provide insulation for capacitors, overlying lines and active/passive elements, and to block dc. The desirable properties of the dielectric materials are as follows:

1. High dielectric constant compatible to the circuit required
2. Low dielectric loss (tan δ) or high Q
3. High breakdown electric field
4. Reproducibility
5. Processability so that it develops least pin holes during processing

Commonly used dielectric materials are listed in Table 11.5 along with their properties. SiO_2 film is obtained by growing pyrolitic deposition and densifying by heat treatment to obtain high Q film for capacitors of capacity 0.02–0.05 μF/sq mil. $Si_3 N_4$ and $Ta_2 O_5$ are another frequently used dielectrics having higher dielectric strength (10^7 V/m) and so used in high power microwave integrated circuits.

Table 11.5 Dielectric thin film materials[a] used in MICs along with their properties and method of deposition

S. No.	Dielectric material	Relative dielectric constant (ε_r)	Microwave (Q)	Dielectric strength (breakdown E-field) (V/m) $\times 10^7$	Method of deposition
1.	SiO_2	4	100–1000	1.0	Deposition
2.	SiO	6–8	30	0.04	Evaporation
3.	$Si_3 N_4$	7.6	—	1.0	Vapor phase sputtering
4.	Ta_2O_5	22–25	100	0.60	Sputtering, anodization
5.	$Al_2 O_3$	7 to 10	—	0.40	Evaporation, anodization

[a] Reference 1 of Bibliography.

11.2.4 Resistive Films for MICs

Resistive films are used in MICs to provide bias to the networks, attenuations, and terminations. The desirable properties of resistive films are as follows::

1. Good stability
2. Low temperature coefficient of resistivity (TCR)
3. Sheet resistivity as high as 10–1000 Ω/sq.

Good dissipation capacity properties of typical film materials commonly used are summarized in Table 11.6.

Table 11.6 Commonly used material for resistive films in MICs along with their properties and method of deposition

S. No.	Resistive film material	Resistivity (Ω/square)	Temperature coefficient of resistance (% °C)	Stability	Method of deposition
1.	Ni–Cr	40–400	+ 0.002 to + 0.1	Good	Evaporation
2.	Ta	5–100	– 0.01 to 0.01	Excellent	Sputtering
3.	Cr–SiO	≤600	– 0.005 to – 0.02	Fair	Evaporation cermet
4.	Ti	5–2000	– 0.1 to 0.1	Fair	Evaporation
5.	Cr	10–1000	– 0.1 to 0.1	Poor	Evaporation

Evaporated Ni–Cr and Ta nitride are most frequently used. The conditions of film formation determines its TCR. The film thickness is chosen to be more than a skin depth to have better dissipation.

11.2.5 Ferrimagnetic Materials for MICs

Many times MICs require the fabrication of non-reciprocal ferrite devices such as circulators (frequently used with negative resistance solid state devices), isolators, switches, etc. The desirable properties are as follows:

1. High dielectric constant
2. Low-loss tangent ($\sim 10^{-4}$)
3. High saturation magnetization
4. Appropriate resonance line width

Commonly used ferrite materials are listed in Table 11.7 along with their properties. The selection depends on the circuit to be designed. As seen from Table 11.7, Mg–Mn and Ni–Zn are suitable for resonant devices. YIGs are of course most frequently used. There are two processes in use: (a) A ferrite disk or pluck is cemented into the non-ferromagnetic substrate, and (b) using ferrimagnetic substrate to implement the ferrite components. The devices are magnetized by miniature permanent magnets.

Table 11.7 Commonly used ferrite material and their properties[a]

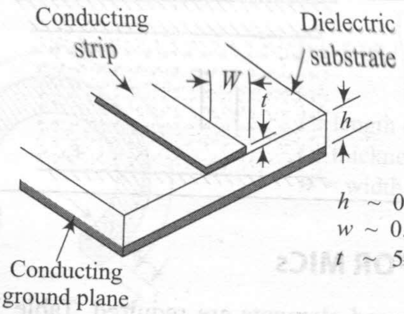
S. No.	Ferrite material	Dielectric constant	Loss tangent (tan δ) $\times 10^4$	Saturation magnetization (Gauss)	Resonant line width ΔH (Oe)
1.	YIG	16	5	1780	40
2.	YIG (Al)	14–15.5	5	200–1325	40
3.	YIG (Gd)	16	5	1250	70
4.	Mg–Mn	13	5	2100	500
5.	Ni–Zn	9.4	10	3800	110
6	Al_2O_3 (99.5%)	9.4	2	—	—
7	Mg Ti	16	2	—	—

[a] G.R Harrison *et al. IEEE Trans., MTT-19*, 577 (1971).

11.3 TRANSMISSION LINES USED FOR MICs

The commonly used transmission lines for MICs are striplines, microstrip lines, suspended substrate transmission lines, slot lines and coplanar lines, coupled lines etc. These have been discussed in Chapter 9. For ready reference these are shown in Table 11.8 with practical dimensions and uses. The characteristic impedance of these lines range from 35 to 75 Ω.

Table 11.8 Lines used in the design of MIC

S. No.	Line	Layout diagram with dimensions	Use
1.	Microstrip line	 $h \sim 0.12 - 1.25$ mm $w \sim 0.12$–1.25 mm $t \sim 5$–10 μm	Transmission line Tuning circuit Distributed elements Inter-connect lines

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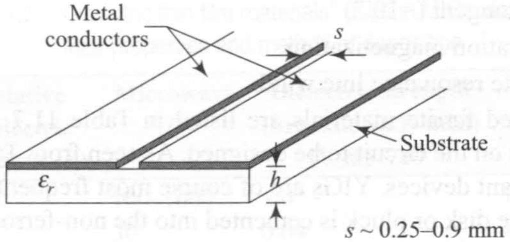
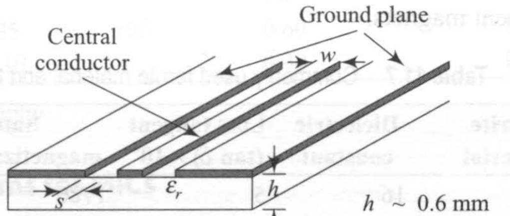
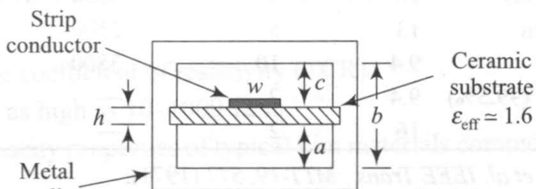
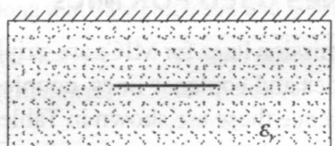
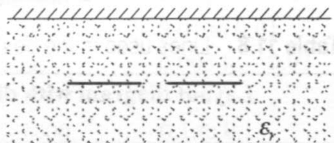
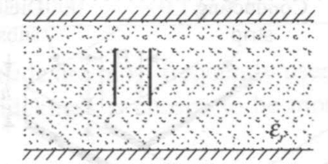
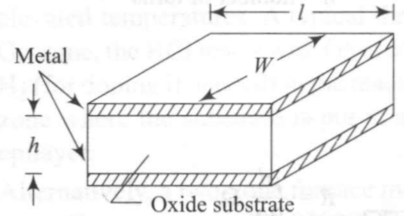
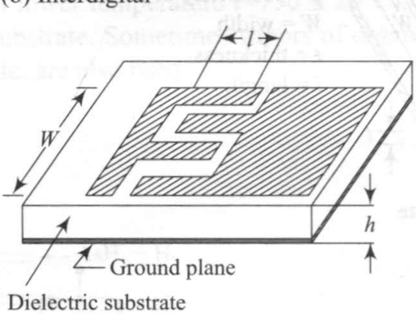
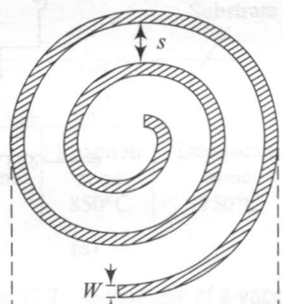
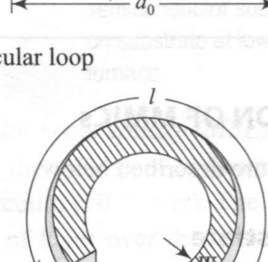
(*Contd.*)

2.	Slot line	 $s \sim 0.25–0.9$ mm $h \sim 3$ mm	Antenna lumped element, shunt connecting lines
3.	Coplanar line	 $h \sim 0.6$ mm $w \sim 0.25$ mm $s \sim 0.25$ mm	Lumped elements active device circuitry
4.	Suspended substrate line	 $h \sim 0.6$ mm $b \sim 3$ mm $w \sim 2.5$ mm	Radiation-less transmission line
5.	Enclosed stripline		Transmission line passive elements
6.	Coupled lines (a) Weakly coupled		Couplers, filters, dividers
	(b) Strong coupled		

11.4 LUMPED ELEMENTS FOR MICs

To design hybrid MICs, lumped elements are required. Table 11.9 shows the various lumped elements along with their design formulae.

Table 11.9 Planar monolithic circuit elements

<table>
<tr><th>Element</th><th>Configuration</th><th>Formula</th></tr>
<tr><td>1. Capacitor</td><td>(a) Planar
</td><td>$C = \varepsilon_0 \varepsilon_r \frac{W}{h}$ F/cm
W = width of metal
ε_r = dielectric constant of oxide substrate
$\varepsilon_0 = 8.854 \times 10^{-12}$ F/m</td></tr>
<tr><td></td><td>(b) Interdigital
</td><td>For $h >> W$
$C = \frac{\varepsilon_r + 1}{W} [0.089 (N - 3) + 0.10]$ pF/cm
N = number of fingers
l = finger length (cm)
W = figure-base width (cm)</td></tr>
<tr><td>2. Inductors</td><td>(a) Circular–spiral
</td><td>$L = 0.03125\, n^2 d_0$ nH/mil
n = number of turns
d_0 = spiral width</td></tr>
<tr><td></td><td>(b) Circular loop
</td><td>$L = 5.08\, l \left[\ln \left(\frac{t}{W + t} \right) - 1.76 \right] \times 10^{-3}$ mH/mil
l = length of ribon (mils)
t = thickness of strip (mils)
W = width of strip (mils)</td></tr>
</table>

(Contd.)

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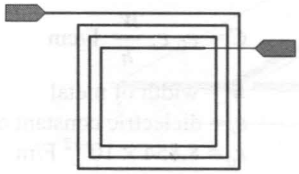
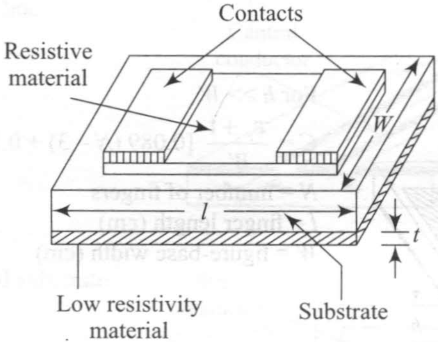
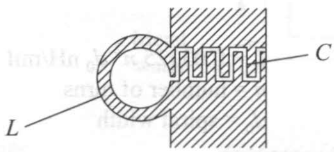
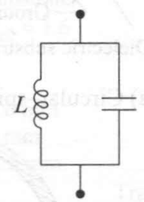
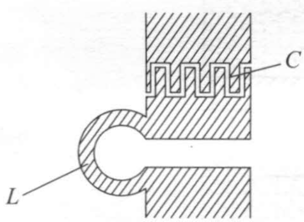
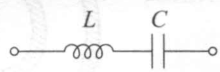
	(c) Square spiral 	$L = 8.5\,A^{1/2}\,n^{5/3}$ nH A = surface area in cm^2 n = number of turns	Circuit element
3. Resistors		$R = \dfrac{\rho l}{Wt}\ \Omega$ ρ = resistivity of material W = width t = thickness l = length	Circuit element
4. LC circuits	(a) Parallel 		Antiresonant circuit
	(b) Series 		Resonant circuit

11.5 PROCESSES USED IN THE FABRICATION OF MMICs

The processes used in the fabrication of MMICs are described below.

11.5.1 Growth of Epitaxy Layer on Substrate

For MMICs a layer of semiconductor is grown on a single crystal lattice-matched substrate. This process is known as expitaxy technology. Three processes are commonly used.

1. *Liquid phase epitaxy (LPE):* In this process, polycrystalline GaAs is melted and the reactor furnace has arrangement for tilting it so that the substrate is covered with the saturated