Microwave Engineering
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Lecture No. 33
Lumped Elements

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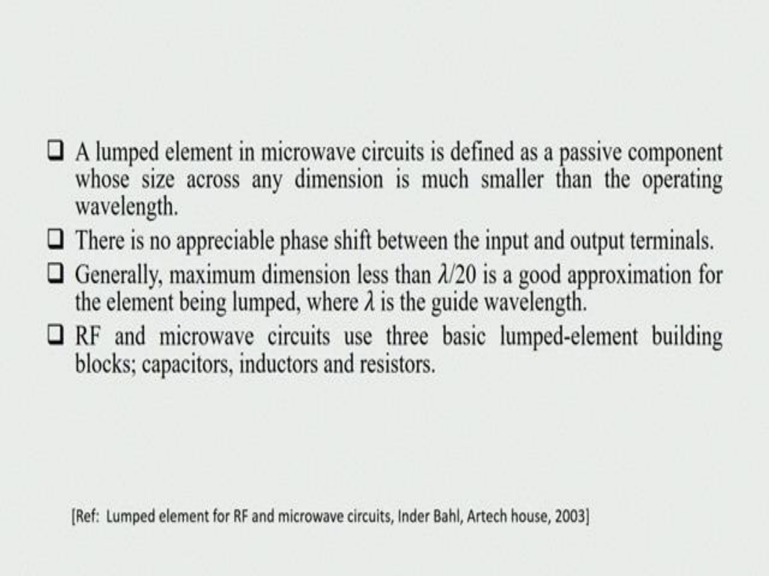

- ☐ A lumped element in microwave circuits is defined as a passive component whose size across any dimension is much smaller than the operating wavelength.
- ☐ There is no appreciable phase shift between the input and output terminals.
- ☐ Generally, maximum dimension less than $\lambda/20$ is a good approximation for the element being lumped, where λ is the guide wavelength.
- ☐ RF and microwave circuits use three basic lumped-element building blocks; capacitors, inductors and resistors.

[Ref: Lumped element for RF and microwave circuits, Inder Bahl, Artech house, 2003]

We start a new topic, lumped elements. A lumped element in microwave circuits is defined as a passive component, whose size across any dimension is much smaller than the operating wavelength. There is no appreciable phase shift between the input and output terminals of this type of lumped elements because of their small size. And generally, maximum dimension less than lambda by 20 is considered as a good approximation for the element being lumped, where lambda is the guide wavelength.

So, here, we will discuss the basics of lumped elements. We will keep our discussion brief and regarding lumped elements the reference that we will follow is lumped element for RF and microwave circuits, author is Inder Bahl, Artech house, 2003 publication. So, this will be our reference. Now, RF and microwave circuits use three basic lumped element building blocks; these are capacitors, inductors, and resistors.

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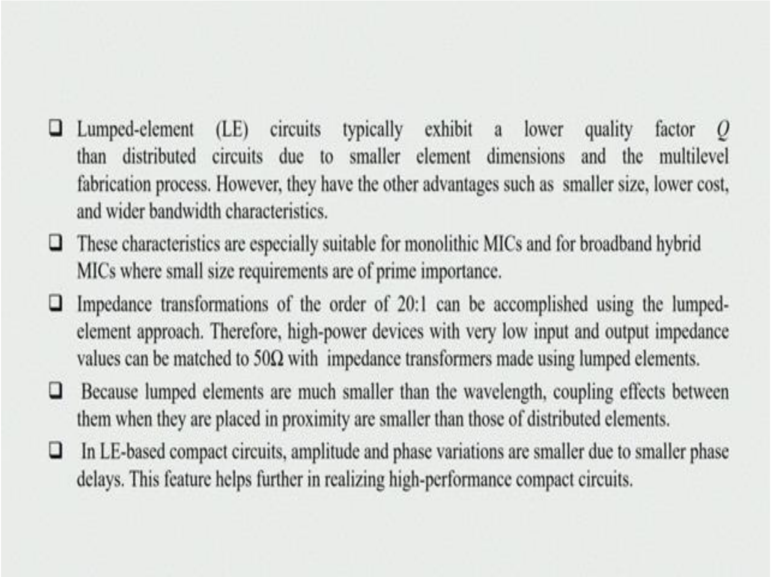

- Lumped-element (LE) circuits typically exhibit a lower quality factor *Q* than distributed circuits due to smaller element dimensions and the multilevel fabrication process. However, they have the other advantages such as smaller size, lower cost, and wider bandwidth characteristics.
- These characteristics are especially suitable for monolithic MICs and for broadband hybrid MICs where small size requirements are of prime importance.
- Impedance transformations of the order of 20:1 can be accomplished using the lumped-element approach. Therefore, high-power devices with very low input and output impedance values can be matched to 50Ω with impedance transformers made using lumped elements.
- Because lumped elements are much smaller than the wavelength, coupling effects between them when they are placed in proximity are smaller than those of distributed elements.
- In LE-based compact circuits, amplitude and phase variations are smaller due to smaller phase delays. This feature helps further in realizing high-performance compact circuits.

The lumped element which is abbreviated as LE. So, lumped element circuits typically exhibit a lower quality factor Q than distributed circuits due to smaller element dimensions and a multilevel fabrication process. However, they have other advantages such as smaller size, lower cost, and wider bandwidth characteristics. So, these characteristics offered by the lumped elements are suitable for monolithic MICs and for broadband hybrid MICs where small size requirements are of prime importance.

These lumped element circuits can provide impedance transformation of the order of 20 is to 1, and therefore high-power devices with very low input or output impedance can be matched to 50 Ohm with impedance transformers made using lumped elements. Because lumped elements are much smaller than the wavelength, coupling effects between them when they are placed in proximity are smaller than those of distributed elements. And in LE-based compact circuits, amplitude and phase variations are smaller due to the smaller phase delays. This feature helps further in realizing high-performance compact circuits.

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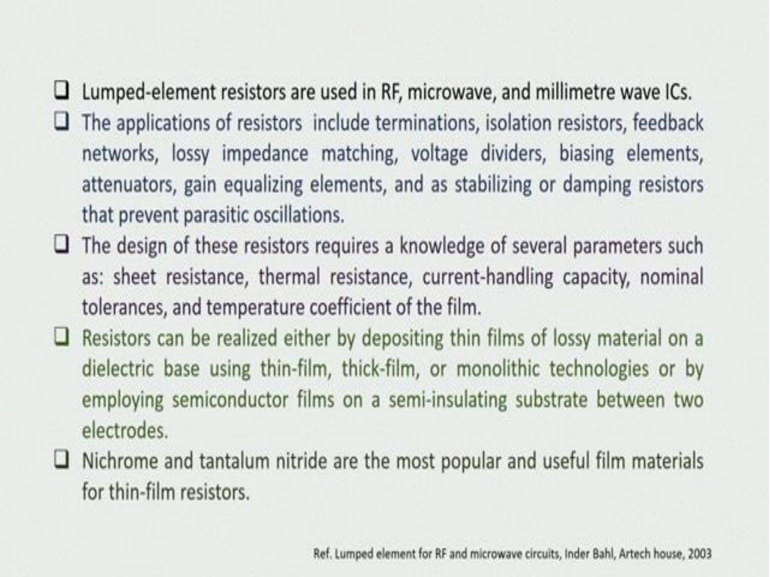
Resistors



- Lumped-element resistors are used in RF, microwave, and millimetre wave ICs.
- The applications of resistors include terminations, isolation resistors, feedback networks, lossy impedance matching, voltage dividers, biasing elements, attenuators, gain equalizing elements, and as stabilizing or damping resistors that prevent parasitic oscillations.
- The design of these resistors requires a knowledge of several parameters such as: sheet resistance, thermal resistance, current-handling capacity, nominal tolerances, and temperature coefficient of the film.
- Resistors can be realized either by depositing thin films of lossy material on a dielectric base using thin-film, thick-film, or monolithic technologies or by employing semiconductor films on a semi-insulating substrate between two electrodes.
- Nichrome and tantalum nitride are the most popular and useful film materials for thin-film resistors.

Ref. Lumped element for RF and microwave circuits, Inder Bahl, Artech house, 2003

We start our discussions with resistors. Lumped element resistors are used in RF microwave and millimeter-wave ICs. Now, resistors are used for a variety of applications, which include termination, as isolation resistor, in feedback network, lossy impedance matching, voltage divider, biasing element, attenuator, gain equalizing element, and also as stabilizing or damping resistor that prevents parasitic oscillations.

So, we can see that a wide variety of circuits require resistance, and when this circuit is to be a part of an integrated circuit, we go for lumped-element resistors. And the design of these resistors requires knowledge of several parameters such as sheet resistance, thermal resistance, current handling capacity, nominal tolerances, temperature coefficient of the film. Films are used for realizing resistors and since the purpose of the resistor is to dissipate power. So, the temperature of the films rises, and therefore it is important to know about the temperature coefficient of the films.

Resistors can be realized either by depositing thin films of lossy material on a dielectric base, either using thin-film, thick-film or monolithic technologies or by employing semiconductor films on a semi-insulating substrate between two electrodes. So, these are the different ways we can realize resistors. Nichrome and tantalum nitride are the most popular and useful film materials for thin-film resistors.

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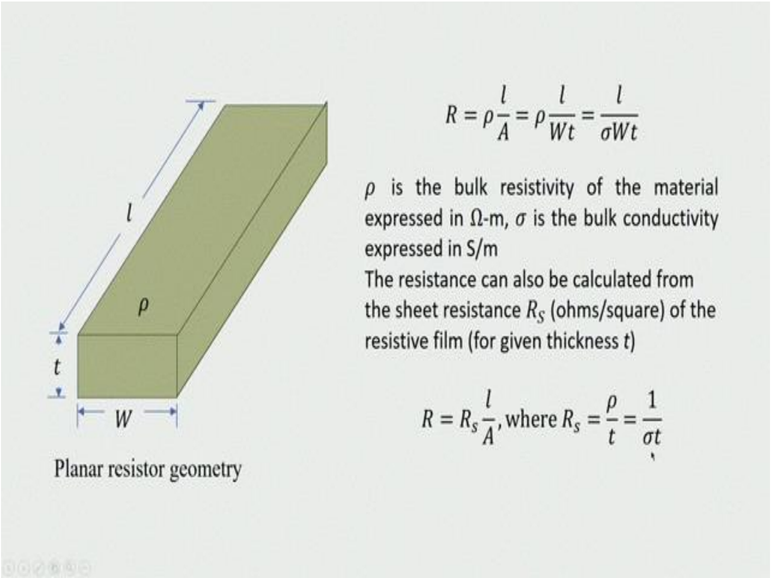
$$R = \rho \frac{l}{A} = \rho \frac{l}{W_t} = \frac{l}{\sigma W_t}$$

$$R = R_s \frac{l}{A}, \text{ where } R_s = \frac{\rho}{t} = \frac{1}{\sigma t}$$



Planar resistor geometry

$$R = \rho \frac{l}{A} = \rho \frac{l}{Wt} = \frac{l}{\sigma Wt}$$

ρ is the bulk resistivity of the material expressed in Ω-m, σ is the bulk conductivity expressed in S/m

The resistance can also be calculated from the sheet resistance R_S (ohms/square) of the resistive film (for given thickness t)

$$R = R_s \frac{l}{A}, \text{where } R_s = \frac{\rho}{t} = \frac{1}{\sigma t}$$

So, here we show planar resistor geometry, where the material has a bulk resistivity of rho it has width W, thickness T and length L. So, the resistance is given by rho L by A. Now, this area A is WT and therefore we can also write it to be L by Sigma WT, where Sigma which is equal to 1 by rho is the conductivity.

Resistance can also be calculated from the sheet resistance RS, which is measured in ohms per square of the resistive film. And for a given thickness of the film T, we can write R equal to RS L by A, where RS is related to rho S, RS is equal to rho by T, which is equal to 1 by Sigma T.

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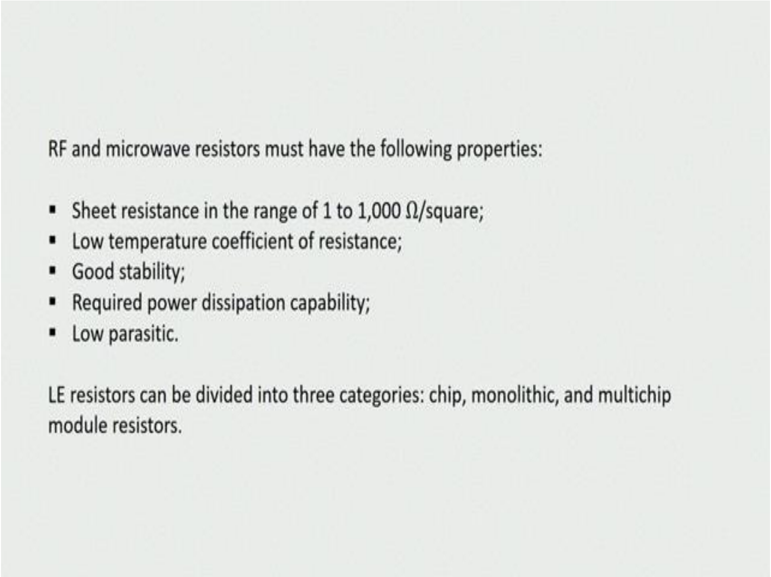

RF and microwave resistors must have the following properties:

- Sheet resistance in the range of 1 to 1,000 Ω/square;
- Low temperature coefficient of resistance;
- Good stability;
- Required power dissipation capability;
- Low parasitic.

LE resistors can be divided into three categories: chip, monolithic, and multichip module resistors.

Now, we discuss some of the desirable properties of RF and microwave resistors. Sheet resistance in the range of 1 to 1000 ohm per square. Low-temperature coefficient of resistance as already mentioned that a register would dissipate power and in that process, it will get heated up. Now, if it has high-temperature coefficients of resistance then the value of the resistance will change, and the actual value of the resistance will be different after usage of some time from the nominal or the design value of the resistance.

Good stability. Required power dissipation capability. And low parasitic. Lumped element resistors can be divided into mostly three categories. One is the chip resistor, another is monolithic, and multichip module resistors.

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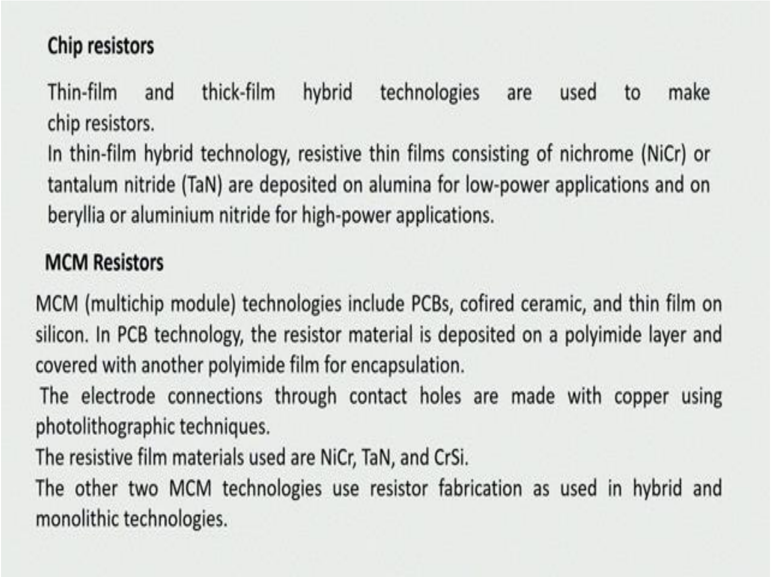

Chip resistors

Thin-film and thick-film hybrid technologies are used to make chip resistors.
In thin-film hybrid technology, resistive thin films consisting of nichrome (NiCr) or tantalum nitride (TaN) are deposited on alumina for low-power applications and on beryllia or aluminium nitride for high-power applications.

MCM Resistors

MCM (multichip module) technologies include PCBs, cofired ceramic, and thin film on silicon. In PCB technology, the resistor material is deposited on a polyimide layer and covered with another polyimide film for encapsulation.
The electrode connections through contact holes are made with copper using photolithographic techniques.
The resistive film materials used are NiCr, TaN, and CrSi.
The other two MCM technologies use resistor fabrication as used in hybrid and monolithic technologies.

Now, these chip resistors are made using thick-film or thin-film hybrid technologies. In thin-film hybrid technology, resistive thin-film consisting of nichrome or tantalum nitride are deposited on alumina substrate for low-power applications and on beryllia or aluminum nitride for high-power applications.

MCM resistors or multichip module based resistors, they include MCM, or multichip module technologies include PCBs, cofired ceramic, and thin film on silicon. In PCB technology, the resistor material is deposited on a polyimide layer and covered with another polyimide film for encapsulations. So, polyimide is a polymer of amide.

The electrode connections through contact holes are made with copper using photolithographic techniques. So, we have in the PCB technology, the resistor material is deposited, and then we have this encapsulating material, and the connection is made using contact holes, and copper is used for making these electrode connections or contact.

The resistive film materials used, as we have already mentioned nichrome or nickel-chromium or tantalum nitride or TaN and chromium silicon. The other two MCM technologies use resistor fabrication as used in hybrid and monolithic technologies.

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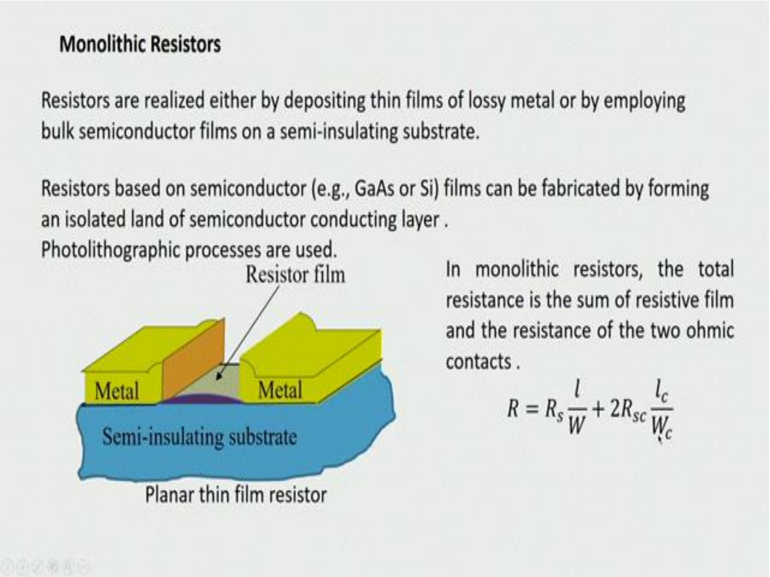
$$R = R_s \frac{l}{W} + 2R_{sc}\frac{l_c}{W_c}$$



Monolithic Resistors

Resistors are realized either by depositing thin films of lossy metal or by employing bulk semiconductor films on a semi-insulating substrate.

Resistors based on semiconductor (e.g., GaAs or Si) films can be fabricated by forming an isolated land of semiconductor conducting layer .
Photolithographic processes are used.

Planar thin film resistor

In monolithic resistors, the total resistance is the sum of resistive film and the resistance of the two ohmic contacts .

$$R = R_s \frac{l}{W} + 2R_{sc}\frac{l_c}{W_c}$$

Let us now move on to monolithic resistors. The resistors are realized either by depositing thin films of lossy material or by employing bulk semiconductor films on a semi-insulating substrate. Resistor based on semiconductor either gallium arsenide or silicon films can be fabricated by forming an isolated land of semiconductor conducting layer. And photolithographic process is used.

So, here we have metallization, here we have a semi-insulating substrate, and then we have the resistor film. So, this is the planar thin-film resistor. In monolithic resistors, the total resistance is the sum of resistive film and the resistance of the two ohmic contacts provided by these metals. And therefore R will be equal to RS L by W, L is the length of the filling, W is the width plus 2 times the resistance because of this ohmic contact. So, RSC LC divided by WC.

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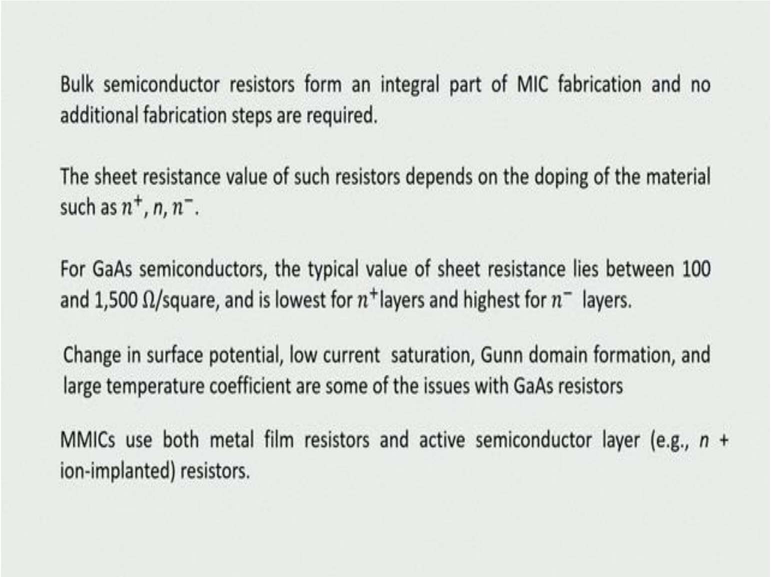

Bulk semiconductor resistors form an integral part of MIC fabrication and no additional fabrication steps are required.

The sheet resistance value of such resistors depends on the doping of the material such as n^+, n, n^-.

For GaAs semiconductors, the typical value of sheet resistance lies between 100 and 1,500 Ω/square, and is lowest for n^+layers and highest for n^- layers.

Change in surface potential, low current saturation, Gunn domain formation, and large temperature coefficient are some of the issues with GaAs resistors

MMICs use both metal film resistors and active semiconductor layer (e.g., n + ion-implanted) resistors.

Bulk semiconductor resistors form an integral part of microwave integrated circuit fabrication, and no additional fabrication steps are required. The sheet resistance value of such resistors depends on the doping of the materials such as N plus, N, or N minus. N plus is highly doped, N is moderately doped, and N minus is the lightly doped.

For gallium arsenide semiconductors, the typical value of sheet resistance lies between 100 Ohm to 1500 ohm per square and is lowest for N plus layers because it becomes highly conductive and highest for N minus layers. Now, gallium arsenide resistors have some issues, and these are change of surface potential, then low current saturation, Gunn domain formation, and large temperature coefficient.

So, in gallium arsenide, the saturation level of the current is low, and also if the voltage becomes very high we know that Gunn diode formation can take place. The temperature coefficient is higher in gallium arsenide. MMICs use both metal film resistors and active semiconductor layer. For example, N plus ion-implanted resistors.

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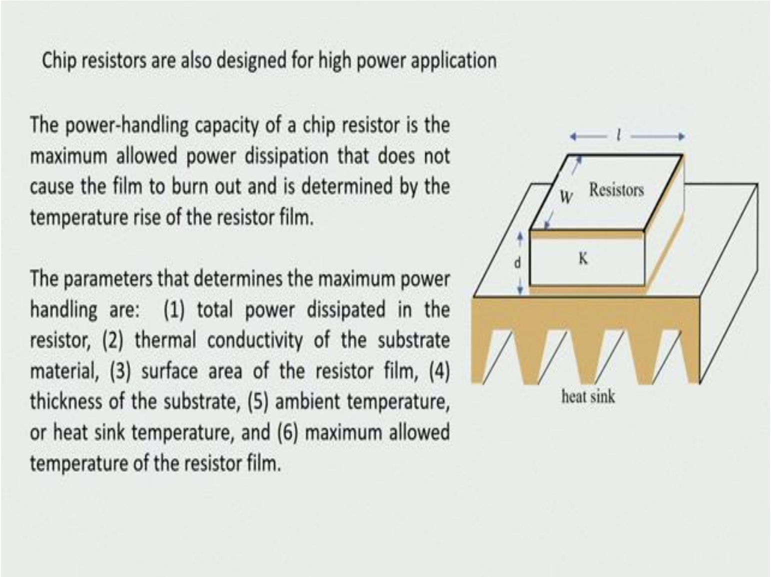

Chip resistors are also designed for high power application

The power-handling capacity of a chip resistor is the maximum allowed power dissipation that does not cause the film to burn out and is determined by the temperature rise of the resistor film.

The parameters that determines the maximum power handling are: (1) total power dissipated in the resistor, (2) thermal conductivity of the substrate material, (3) surface area of the resistor film, (4) thickness of the substrate, (5) ambient temperature, or heat sink temperature, and (6) maximum allowed temperature of the resistor film.

Chip resistors are also designed for the high-power applications. And power handling capacity of a chip resistor is the maximum allowed power dissipation that does not cause the film to burn out and determined by the temperature rise in the resistor film.

Now, parameters that determine the maximum power handling of these type of chip resistors are total power dissipated in the resistor, the thermal conductivity of the substrate material, surface area of the resistor film, thickness of the substrate, ambient temperature or the heat sink temperature and maximum allowed temperature of the resistor film. So, these are the parameters that actually determine the power handling capacity of the chip resistor, and in figure a chip resistor mounted on a heat sink has been shown.

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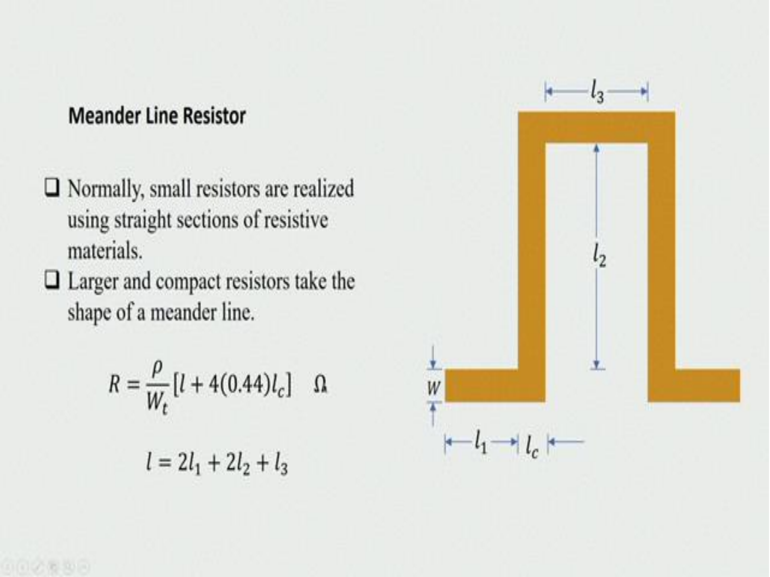
$$R = \frac{\rho}{W_t}[l + 4(0.44)l_c] \quad \Omega$$

$$l = 2l_1 + 2l_2 + l_3$$



Meander Line Resistor

- ☐ Normally, small resistors are realized using straight sections of resistive materials.
- ☐ Larger and compact resistors take the shape of a meander line.

$$R = \frac{\rho}{W_t}[l + 4(0.44)l_c] \quad \Omega$$

$$l = 2l_1 + 2l_2 + l_3$$

Another form of the resistor is meander line resistor. Normally, small resistors are realized using straight sections of resistive materials. But when it comes to the design of large and compact resistors meandered line is used and meandered line section is shown here. For this type of meander line section, resistance R is given by rho divided by W into T into L plus 4 into 0.44 LC ohm. Where this L is equal to 2 times L1 plus 2 times L2 plus L3 and LC it gives the width of the line, and it is taken care, its contribution because we have 4 corners here, 1, 2, 3, 4. So, it has been accounted here.

So, with this, we conclude our basic discussion on lumped element resistors. We have seen different types of resistors that are used. It may be based on PCB technology, thin or thick film, it may be on semiconductor and may be realized using photolithographic techniques. And we have also mentioned different circuits where this type of resistance finds applications.

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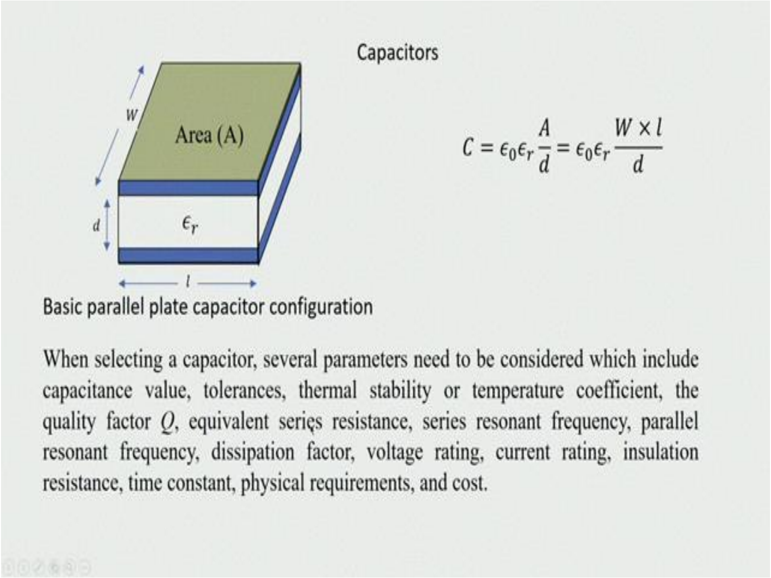
$$C = \epsilon_0 \epsilon_r \frac{A}{d} = \epsilon_0 \epsilon_r \frac{W \times l}{d}$$



Capacitors

$$C = \epsilon_0 \epsilon_r \frac{A}{d} = \epsilon_0 \epsilon_r \frac{W \times l}{d}$$

Basic parallel plate capacitor configuration

When selecting a capacitor, several parameters need to be considered which include capacitance value, tolerances, thermal stability or temperature coefficient, the quality factor Q, equivalent series resistance, series resonant frequency, parallel resonant frequency, dissipation factor, voltage rating, current rating, insulation resistance, time constant, physical requirements, and cost.

Let us now move into another topic the lumped element capacitor. So, we are showing a basic parallel plate geometry, where we have two metallic plates of area A. They are separated by a distance, and in between this metallic plates, we have a dielectric of relative permittivity epsilon R., And therefore the capacitance is given by epsilon naught, epsilon R A by D, which can be written as epsilon naught, epsilon R WL, width and length of the plate divided by D.

When we select a capacitor, several parameters need to be considered, which include, first of all, of course, is the value of the capacitor, the capacitance value we need. Then the tolerances, thermal stability, and temperature coefficient.

The quality factor capacitor is to stores charge, and the quality factor will determine how much energy is stored and how much power is dissipated. Equivalent series resistance, series resonant frequency, parallel resonant frequency, dissipation factor, voltage rating. What is the maximum voltage, it can withstand, current rating, insulation resistance, time constant and physical requirement and of course cost. So, many parameters are needed to be considered while choosing a particular form of capacitor for MIC application. We will discuss some of these parameters.

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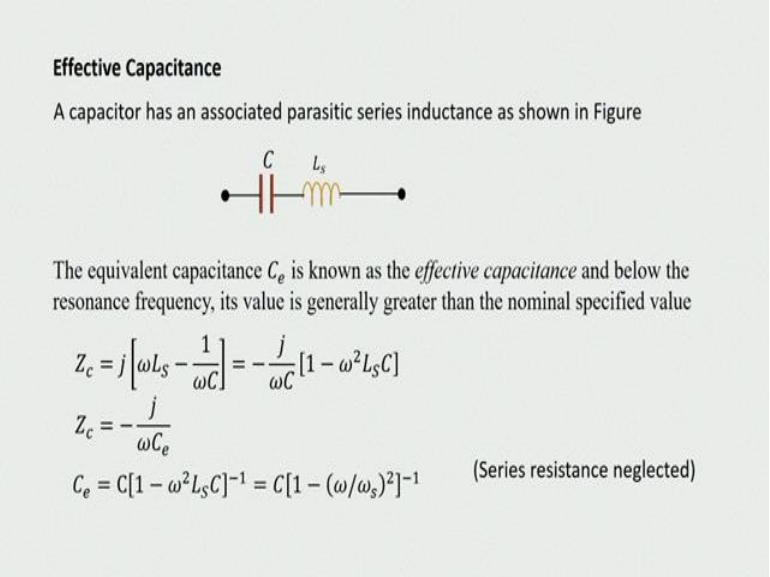
$$Z_c = j\left[\omega L_S - \frac{1}{\omega C}\right] = -\frac{j}{\omega C}\left[1 - \omega^2 L_S C\right]$$

$$Z_c = -\frac{j}{\omega C_e}$$

$$C_e = \mathrm{C}[1 - \omega^2 L_S C]^{-1} = C[1 - (\omega/\omega_s)^2]^{-1}$$



Effective Capacitance

A capacitor has an associated parasitic series inductance as shown in Figure

The equivalent capacitance C_e is known as the *effective capacitance* and below the resonance frequency, its value is generally greater than the nominal specified value

$$Z_c = j\left[\omega L_S - \frac{1}{\omega C}\right] = -\frac{j}{\omega C}[1 - \omega^2 L_S C]$$

$$Z_c = -\frac{j}{\omega C_e}$$

$$C_e = \mathrm{C}[1 - \omega^2 L_S C]^{-1} = C[1 - (\omega/\omega_s)^2]^{-1}$$

(Series resistance neglected)

So, we start with effective capacitance. A capacitor has an associated parasitic series inductance, which is shown in the figure. It will also have a resistance which we are neglecting for the time being. Now, once this capacitor is in series with LS, the equivalent capacitance CE, the effective capacitance CE can be calculated as shown, we have ZC as a series combination of C and LS, and it can be written as J omega LS minus 1 by omega LC.

And this can be written as J by omega C into 1 minus omega square LS into C and essentially ZC can be written as minus J by omega CE, where this CE is C divided by 1 minus omega square LS into C, and LS C can be written as 1 by omega S square, where omega S is the resonant frequency. And therefore C can be written as C into 1 minus omega by omega S square raise to the power minus 1.

Now, here we see that when omega is less than omega S, this bracketed term will be less than 1, and therefore C will be effectively divided by this term because of this power of minus 1. And therefore we will have C effective greater than C. So, we see that because of this parasitic inductance present, we have a capacitance value, which is actually more than the capacitance value which we want.

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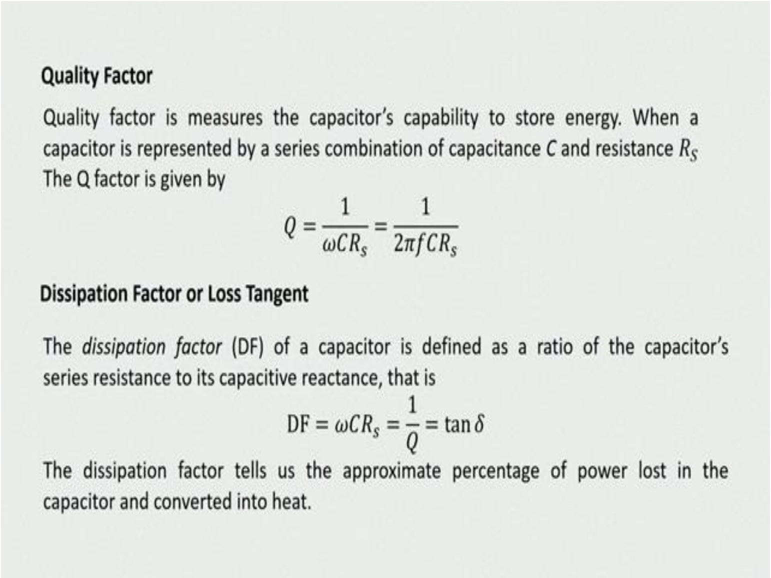
$$Q = \frac{1}{\omega C R_s} = \frac{1}{2\pi f C R_s}$$

$$\mathrm{DF} = \omega C R_s = \frac{1}{Q} = \tan\delta$$



Quality Factor

Quality factor is measures the capacitor's capability to store energy. When a capacitor is represented by a series combination of capacitance C and resistance R_S The Q factor is given by

$$Q = \frac{1}{\omega C R_s} = \frac{1}{2\pi f C R_s}$$

Dissipation Factor or Loss Tangent

The *dissipation factor* (DF) of a capacitor is defined as a ratio of the capacitor's series resistance to its capacitive reactance, that is

$$\mathrm{DF} = \omega C R_s = \frac{1}{Q} = \tan\delta$$

The dissipation factor tells us the approximate percentage of power lost in the capacitor and converted into heat.

The quality factor, as already mentioned, is a measure of capacitor's capability to store energy. And when a capacitor is represented by a series combination of C, capacitance C, and a series resistance RS, we can write the quality factor Q to be equal to 1 by 2 pi F CRS. So, smaller the value of capacitance higher will be the value of Q, and higher will be the capacitors, capacity to store energy.

The dissipation factor or loss tangent of a capacitor is defined as the ratio of the capacitors series resistance to its capacitive reactance, and this is given by RS divided by 1 by omega C that means omega CRS which is 1 by Q, and that is equal to tan delta. So, this factor actually tells us the approximate percentage of power loss in the capacitor and converted to heat. We want to minimize this loss.

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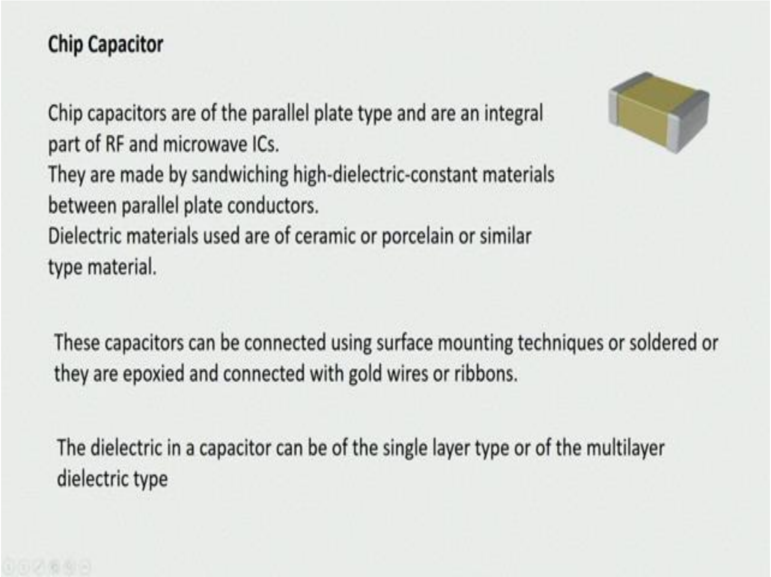

Chip Capacitor

Chip capacitors are of the parallel plate type and are an integral part of RF and microwave ICs.
They are made by sandwiching high-dielectric-constant materials between parallel plate conductors.
Dielectric materials used are of ceramic or porcelain or similar type material.

These capacitors can be connected using surface mounting techniques or soldered or they are epoxied and connected with gold wires or ribbons.

The dielectric in a capacitor can be of the single layer type or of the multilayer dielectric type

Chip capacitor these are actually parallel plate type and are an integral part of RF and microwave integrated circuits. They are made by sandwiching high dielectric constant materials between parallel plate conductors. Dielectric materials used are ceramic or porcelain or similar other types of material.

These capacitors can be connected using surface mounting techniques or soldered, or they are epoxide and connected with gold wires or ribbons. The dielectric in a capacitor can be of single-layer type or of multilayer dielectric type. So, this shows the appearance of a commercial chip capacitor.

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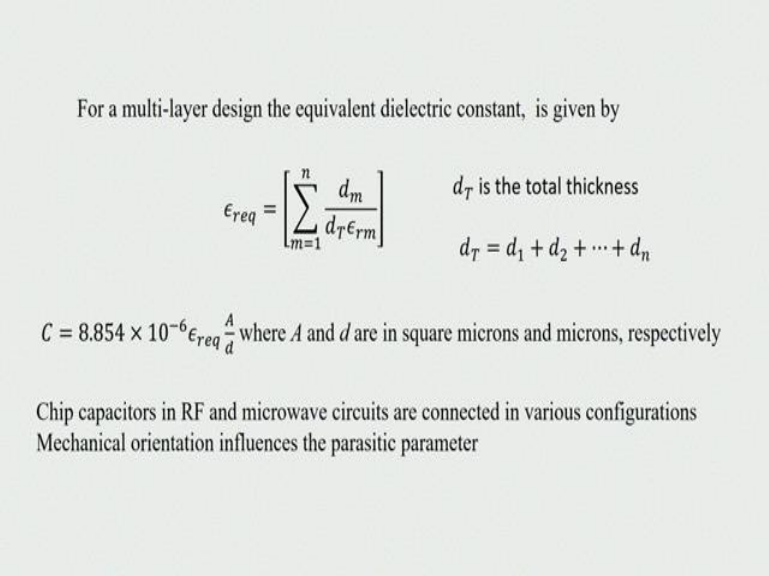
$$\epsilon_{req} = \left[\sum_{m=1}^{n} \frac{d_m}{d_T \epsilon_{rm}}\right]$$

d_T is the total thickness

$$d_T = d_1 + d_2 + \cdots + d_n$$

$C = 8.854 \times 10^{-6} \epsilon_{req} \frac{A}{d}$ where A and d are in square microns and microns, respectively



For a multi-layer design the equivalent dielectric constant, is given by

$$\epsilon_{req} = \left[\sum_{m=1}^{n} \frac{d_m}{d_T \epsilon_{rm}}\right]$$

d_T is the total thickness

$$d_T = d_1 + d_2 + \cdots + d_n$$

$C = 8.854 \times 10^{-6} \epsilon_{req} \frac{A}{d}$ where A and d are in square microns and microns, respectively

Chip capacitors in RF and microwave circuits are connected in various configurations
Mechanical orientation influences the parasitic parameter

For a multilayer design, the equivalent dielectric constant is given by ER equivalent is equal to, if we have N number of dielectric layers, each having epsilon R M or dielectric constants, epsilon R M and DM is the thickness of individual layers, and DT is the total thickness. Then we can write DT is equal to D1 plus D2 plus DN.

And C can be finally calculated in terms of 8.854 10 to the power minus 6. This factor comes because of epsilon naught. And epsilon R equivalent A by D, when this A and D are in square microns and microns. Chip capacitors in RF and microwave circuits are connected in various configurations, and because chip capacitors in RF and microwave circuits are connected in various configurations, mechanical orientation, the manner in which they are connected, it influences the parasitic parameter for such capacitors.

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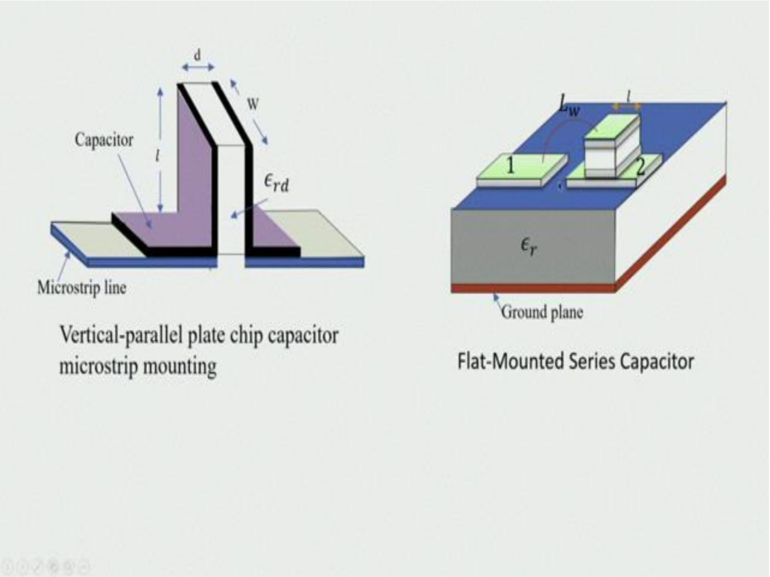

Vertical-parallel plate chip capacitor microstrip mounting

Flat-Mounted Series Capacitor

So, this is the connection of a vertical-parallel plate chip capacitor with a microstrip mounting. So, here is the microstrip line and this forms the capacitor, and the capacitor is placed vertically. Then we can have flat-mounted series capacitor, where we have a wire connecting one of the plates of the capacitor to the line, and there is a gap.

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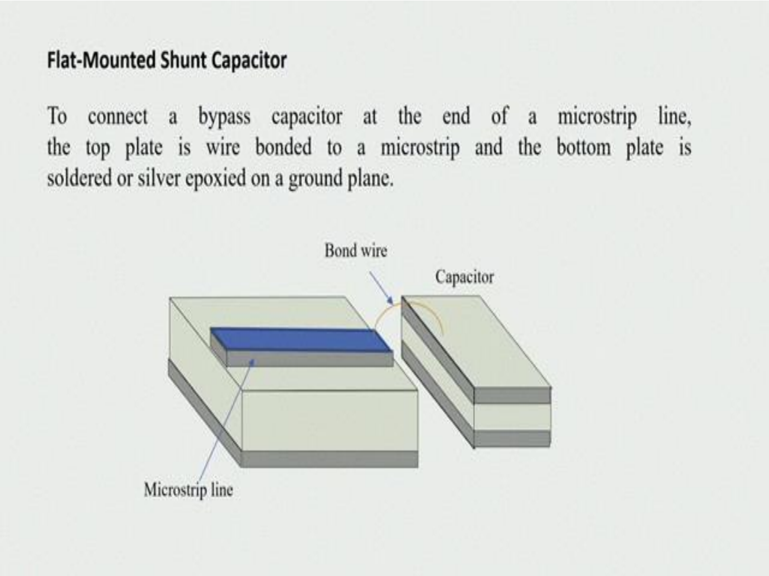

Flat-Mounted Shunt Capacitor

To connect a bypass capacitor at the end of a microstrip line, the top plate is wire bonded to a microstrip and the bottom plate is soldered or silver epoxied on a ground plane.

To connect a bypass capacitor at the end of a microstrip line, the top plate is wire bonded to microstrip, and the bottom plate is soldered or silver epoxide on the ground plane. So, here we can see that this bottom surface will be either soldered or silver epoxide, and the top plate of the capacitor will be connected to the end of the microstrip line.

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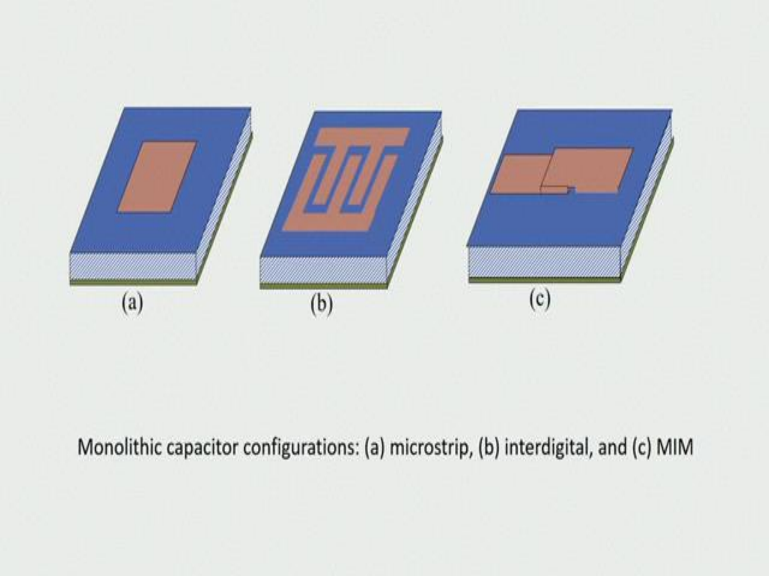


Monolithic capacitor configurations: (a) microstrip, (b) interdigital, and (c) MIM

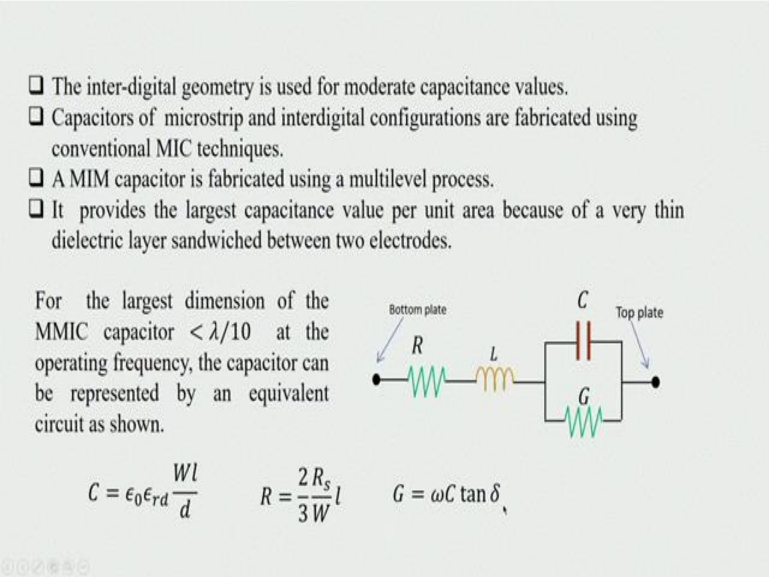
Monolithic capacitors can be realized in various configurations. We have microstrip configuration, interdigital structure, and MIM or metal-insulator metal configuration.

(Refer Slide Time: 32:33)

$$C = \epsilon_0 \epsilon_{rd} \frac{Wl}{d}$$

$$R = \frac{2}{3} \frac{R_s}{W} l$$

$$G = \omega C \tan \delta$$



- ❑ The inter-digital geometry is used for moderate capacitance values.
- ❑ Capacitors of microstrip and interdigital configurations are fabricated using conventional MIC techniques.
- ❑ A MIM capacitor is fabricated using a multilevel process.
- ❑ It provides the largest capacitance value per unit area because of a very thin dielectric layer sandwiched between two electrodes.

For the largest dimension of the MMIC capacitor $< \lambda/10$ at the operating frequency, the capacitor can be represented by an equivalent circuit as shown.

$$C = \epsilon_0 \epsilon_{rd} \frac{Wl}{d} \qquad R = \frac{2}{3} \frac{R_s}{W} l \qquad G = \omega C \tan \delta$$

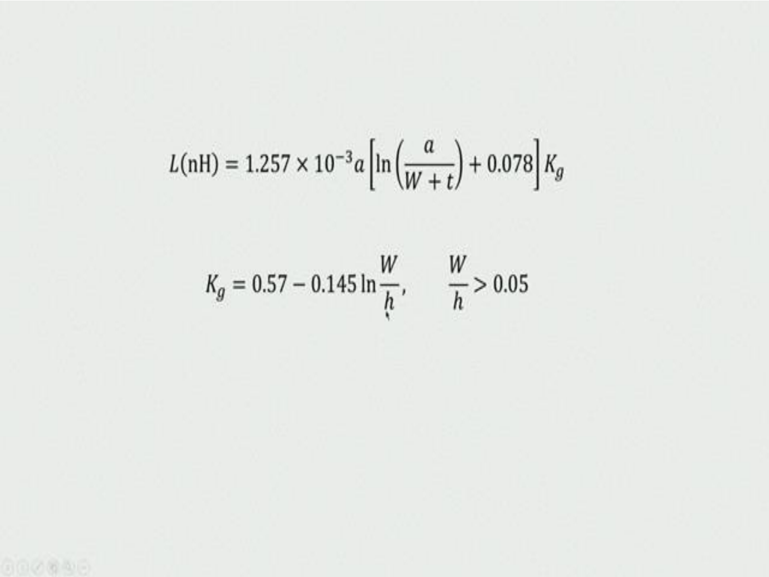
Interdigital geometry is used for moderate capacitance values. Capacitors of microstrip and interdigital configurations are fabricated using conventional MIC techniques. A MIM capacitor is fabricated using a multilevel process. It provides the largest capacitance per unit area because of a very thin dielectric layer sandwiched between two electrodes.

For the largest dimension of the MMIC capacitor being less than lambda by 10 at the operating frequency, the capacitor can be represented by an equivalent circuit, which is shown. Now, this is the capacitor with its parasitic elements between the top and bottom plates, and these values can be calculated. C, it is WL by D epsilon RD. R 2 by 3 RS W L by W. G, the conductance is omega C tan delta.

(Refer Slide Time: 34:08)

$$L(\mathrm{nH}) = 1.257 \times 10^{-3} a \left[\ln\left(\frac{a}{W+t}\right) + 0.078\right] K_g$$

$$K_g = 0.57 - 0.145 \ln\frac{W}{h}, \quad \frac{W}{h} > 0.05$$



$$L(\mathrm{nH}) = 1.257 \times 10^{-3} a \left[\ln\left(\frac{a}{W+t}\right) + 0.078\right] K_g$$

$$K_g = 0.57 - 0.145 \ln\frac{W}{h}, \quad \frac{W}{h} > 0.05$$

And L in nano henry can be calculated using this formula, where this K_g depends on W by H.