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Capacitors

A survey of present day capacitor technology and applications

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This is a survey of the properties and parameters involved in the construction and use of capacitors and dielectrics. Simple equivalent circuit analysis is also explained. The second half of the survey deals with different types of capacitors: electrolytics, paper, plastic film, mica and ceramic. The construction of each type is described together with particular properties of each type and their circuit application. Finally an applications chart relates the different properties and parameters.

Progress in semiconductor technology has led to an increasing dependence on the role of commercially available capacitors in a circuit. A glance at any electrical network reveals that about 30% of the components used are capacitors; and that about 40% of all failures encountered are due to misuse in circuit application of these capacitors.

The impedance of a capacitor, Z, largely controls its behaviour in any circuit application. The manner in which this impedance deviates from that of a true capacitor requires the construction of an equivalent circuit for practical capacitors. This can be done quite simply and Fig. 1 shows the familiar parallel plate capacitor together with its equivalent circuit.

We can reduce this circuit to a simple resonant circuit (Fig. 2) whose impedance curve (impedance vs frequency) when plotted on log-log. graph paper is a hyperbola whose shape and orientation depends on the values of L_s, R_s, and C (Fig. 3).

We can make the following observations:

- f small $Z \approx 1/2\pi fC \approx X_c$
- f resonant $Z \approx R_s$ (20kHz→1MHz)
- f large $Z \approx 2\pi fL_s \approx X_{Ls}$

The resonant frequency of capacitors varies considerably from about 20kHz for electrolytic capacitors to around 1MHz for plastic film types and is even higher for ceramics. Fig. 4 shows the impedance curve of a tantalum electrolytic capacitor. The prime cause of the curve deviating from a hyperbola is temperature differences which affect the parameters of a capacitor in a non-linear fashion, so in some applications manufacturer's data must be consulted.

The inductance of the capacitor is largely controlled by the dimensions of the external leads and the method of connection to the capacitor section. In tubular capacitors the ratio of the length of the capacitor section to its diameter is also significant. To minimize the effect of inductance, most electrolytic capacitors have low inductance windings. Fig. 5 shows a reduction in inductance by a factor of 26 by this method.

As a rule of thumb the inductance of a normal capacitor, length 1cm, is of the same order as a piece of 22 swg wire of length 1cm.

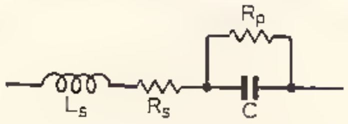

Fig. 1. Equivalent circuit of a typical capacitor: L_s—equivalent series inductance, R_s—equivalent series resistance, R_p—leakage resistance (or parallel loss resistance), C—apparent capacitance.

Fig. 2. Simple series resonant circuit where $Z=\sqrt{R_s^2+(X_{Ls}-X_c)^2}$

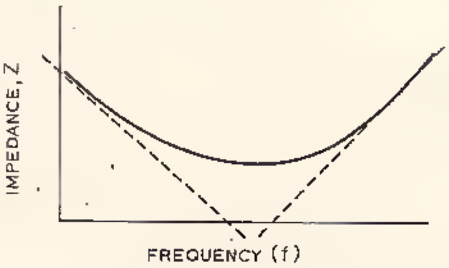

Fig. 3. Impedance versus frequency curve of the simple resonant circuit shown in Fig. 2.

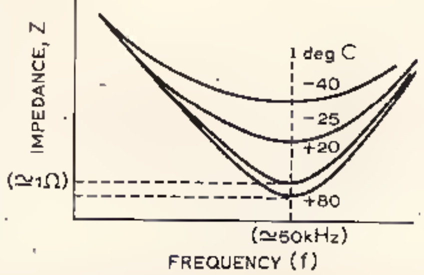

Fig. 4. Impedance curve for a tantalum electrolytic capacitor.

For capacitance value a temperature coefficient (t.c.) is defined by:

$$\text{t.c.} = \frac{\Delta C \times 10^6}{C.\Delta t}$$

$$= \frac{\text{change in capacitance} \times 10^6}{\text{orig. capacitance} \times \text{change in temp.}}$$

$$= \alpha \text{ppm}/^\circ\text{C}$$

where ppm = parts per million.

By defining the temperature coefficient in this manner it is independent of the units of capacitance.

It is usual to operate capacitors well below their resonant frequency, and thus neglect the effects of inductance. Fig. 2 simplifies to an equivalent circuit which is universally used, that of a "lossy" capacitor in Fig. 6.

By considering this circuit one can develop terms which are extensively used throughout the capacitor industry. From

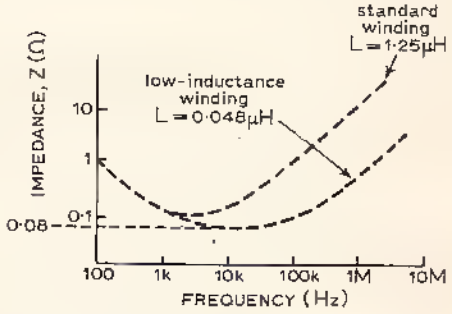

Fig. 5. Impedance reduction obtained by low inductance winding.

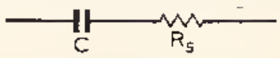

Fig. 6. Equivalent circuit of a "lossy" capacitor operated well below the resonant frequency.

the phasor diagram, Fig. 7, we make the basic definitions:

Loss angle, δ

Phase angle, ϕ

Impedance, $Z=\sqrt{X_c^2+R_s^2}$

$$\text{Power factor (p.f.)}=\frac{\text{true power}}{\text{apparent power}}$$

$$=\frac{P_s}{Z}=\cos\phi=\sin\delta$$

$$\text{Dissipation factor (d.f.)}=\frac{\text{resistance}}{\text{reactance}}$$

$$=\frac{R_s}{X_c}=\tan\delta$$

For small R_s, d.f.$\approx$p.f. (since $\sin\delta\approx\tan\delta$ for $\delta<0{\cdot}15$)

This relation holds for almost all commercially available capacitors.

It is easily seen that for a good capacitor, δ must be small, but exactly what variations occur with frequency and capacitance value will be important in capacitor application and requires some dielectric theory explained in the appendix.

Leakage current

This quantity is dependent on the parallel loss resistivity (R_p) of the capacitor, which has a negligible effect on the equivalent series resistance, R_s, except for low frequencies. It can be shown that

$$R_p=\frac{1}{\omega CR_s}+R_s$$

The relationship can be understood by considering a perfect capacitor discharging through a resistor as shown in Fig. 10. The behaviour of the circuit is described by:

$$\frac{Q}{C}+\frac{dQ}{dt}R_D=0$$

$$\text{i.e., }\frac{dQ}{Q}=\frac{-dt}{RC}$$

$$(\log_e Q)_0^t=(-t/RC)_0^t$$

$$\text{or: } Q=Q_o e^{-t/RC} \quad (1)$$

$$I=\frac{dQ}{dt}=\frac{I_o}{RC}e^{-t/RC} \quad (2)$$

Eqn. (1) shows that the leakage current varies with time, and thus a fixed value of the current, I, is only realized after a fixed time. For electrolytic capacitors this time is usually 15 minutes.

The quantity RC is known as the time constant of the capacitor and is of the order of days for polystyrene capacitors, and several seconds for electrolytics.

Dielectric absorption

The rate at which a capacitor charges is important. A perfect capacitor when connected to a d.c. supply of E volts would charge according to

$$I=(E/R)e^{-t/RC} \quad (3)$$

In practice, deviation from (3) occurs because if a fully charged capacitor is discharged and allowed to remain open circuit for some time a new charge accumulates within the capacitor showing that a fraction of the original charge has been "absorbed" by the dielectric. A time log therefore exists between the rate of charging and of discharging the capacitor.

Dielectric strength

The voltage at which the dielectric breaks down is a measure of the dielectric strength of the medium. This depends on the test conditions and the thickness of the material. It thus imposes a stress on the medium and is usually measured in volts/metre. Of associated importance is the insulation resistance which will follow approximately eqn (4)

$$R_T=\frac{R_t}{eK(T-t)} \quad (4)$$

where R_T=insulation resistance at temperature T and R_t=insulation resistance at temperature t. K is a constant (0·1 for paper capacitors and 0·05 for mica and ceramic capacitors).

Energy losses

For a perfect capacitor, C, operating at V volts, the energy stored is given by eqns (5) and (6).

$$E=\int_0^V v\,dQ \quad (5)$$

$$=\int_0^V v\,d(C.v)=C\int_0^V v\,dv=1/2CV^2 \quad (6)$$

However, the phase difference between the vectors E and D defined in the appendix causes a hysteresis loop (similar to the B, H curves observed for ferromagnetic materials), between the charge Q, and applied voltage V. The energy dissipated per cycle of the loop will be given by eqn (5) and will vary with the frequency of the applied field, so that the total energy stored in the capacitor will be less than the result predicted by eqn (6).

General considerations

For a parallel plate capacitor working in vacuo, the capacitance, C, between the plates, ignoring edge effects, is given by

$$C=\epsilon_o A/d \quad (7)$$

where ϵ_o is the permittivity of free space, A is the area of plates, d is the distance between plates.

When a dielectric is placed between the plates the capacitance of the system changes to C^1 where C^1 is related to C by

$$\epsilon=\frac{C^1}{C}=\text{permittivity of dielectric or dielectric constant.} \quad (8)$$

From these equations we see that to obtain the highest capacitance in the smallest volume, ϵ must be high, and d must be small. Translated into manufacturing techniques this requires a thin foil of high permittivity capable of withstanding the stresses imposed by the working conditions of the capacitor.

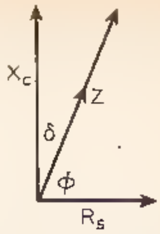

Fig. 7. Phasor diagram related to the equivalent circuit of a "lossy" capacitor.

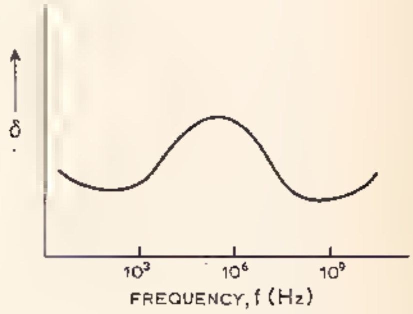

Fig. 8. Loss angle versus frequency for a polar dielectric material.

One has already seen that the cost of obtaining a high permittivity, illustrated by Fig. 8, is its frequency dependence.

The most important considerations in choosing a capacitor for particular applications are: capacity/physical size, and shape; working voltage; frequency characteristics (effect of frequency in impedance and dissipation factor); insulation resistance; environmental conditions (temperature and humidity considerations) and cost.

A brief survey of the types of capacitors available now follows.

Electrolytic capacitors

Capacitors of this type are physically the largest available; their CV product (capacitance value × working voltage) is also large. Typical application of these capacitors is to be seen in power supply circuits and coupling between audio amplifier stages.

The large capacitance evolves from the use of a very thin dielectric film (about 1nm thick). Such a film is realized practically by oxidizing a suitable metal (usually aluminium or tantalum). The method employed is that of anodic oxidation, i.e. by making the metal the anode when immersed in an electrolytic bath.

The resulting dielectric film is extremely strong possessing a dielectric strength of the order of $10^7\,\mathrm{Vm}^{-1}$, although imperfections in this film lead to leakage being a typical characteristic.

For aluminium electrolytic capacitors, the oxide is produced on a 99.99% pure aluminium foil at an oxide thickness proportional to the working voltage of the capacitor. This voltage is often called the polarising voltage and its function is to maintain the oxide film at a specified thickness, thus giving consistent capacitance value.

The foil, now known as the anode foil, is then concentrically wound with another aluminium foil (about 98% pure) which acts as a cathode. The two foils are separated by a layer of highly porous paper and the whole assembly immersed in an electrolyte (usually ethylene glycol) which promotes the forming of oxide film when the capacitor is in operation.

The capacitance section is then placed in an aluminium can which is hermetically sealed. A typical arrangement is shown in Fig. 11.

To give an increased capacitance value in the same physical size the aluminium oxide may be etched. This process effectively increases the area of the dielectric and increases its permittivity from about 7 to about 10. However, electrolytics made in this manner are unable to withstand high currents, compared with the plain foil type.

Tantalum capacitors. These capacitors employ tantalum oxide as a dielectric which has a higher permittivity than aluminium oxide (typically up to 25), and as a result give a high capacitance in a relatively small size.

There are three distinct types of tantalum capacitors available: solid tantalum, wet sintered tantalum and tantalum foil (the construction of this is similar to that of an aluminium foil and will not be discussed).

The electrolyte used is solid manganese dioxide used in solid tantalum types or aqueous phosphoric or sulphuric acid used in the latter two types.

Solid tantalum capacitors. Capacitors of this variety are constructed by sintering tantalum powder particles around a tantalum anode, the resulting assembly is rigid after manufacture and is known as a "slug" (Fig. 12).

By controlling the temperature and time of the sintering process one may control the size of the slug, its density and its oxide content. The purity of the tantalum used is also important since it largely controls parameters such as leakage current and power factor.

The cathode of the solid tantalum capacitor is formed by dipping the slug in a solution of manganese nitrate which when passed through ovens at 300°C decomposes to a semiconductor layer of manganese dioxide, this is then coated with graphite and silver.

A schematic diagram of a complete solid tantalum capacitor is shown in Fig. 13.

The final encapsulation of the solid tantalum capacitor can be in several forms, the most common ones being: polyester sleeve with epoxy end seals, dipped epoxy coated, metal case with resin seal or epoxy resin moulding.

Wet sintered tantalum. The slug used is similar to that employed in the solid tantalum variety; the distinct difference between the two types being in the cathode system. Fig. 14 shows these differences.

Table 1. Comparison of tantalum capacitor types

Parameter	Solid	Wet	Foil
Maximum d.c. voltage rating	100V	125V	450V
CV product	inflexible	inflexible	flexible
Closest capacitor tolerance	±5%	±5%	±10%
Volume efficiency*	2	1	3
D.C. leakage current per *CV* ($AF^{-1}V^{-1}$)	0·02	0·0005	0·01
Temperature stability**	1	2	3
Frequency characteristics**	1	2	2
Reverse voltage	⋗1V	0	⋗3V
Cost*	3	2	1

* ** 1 indicates highest* or best**
2 indicates intermediate stage between 1 & 3
3 indicates lowest* or worst**

Table 1 provides a general comparison for the three types of tantalum capacitors discussed, however for more precise information it is necessary to consult manufacturer's data.

Reliability. (a) solid tantalum: very reliable, working failures generally due to misuse; intrinsic failure due to oxide crystallisation, (b) wet sintered tantalum: failure due to vapour transmission of the electrolyte through the capacitor seal, causing a fall in capacitance and degradation in the dissipation factor; hence hermetic seals are desirable. Aluminium and tantalum foil types also suffer from the same defect.

Paper capacitors

In this type of capacitor a thin sheet of

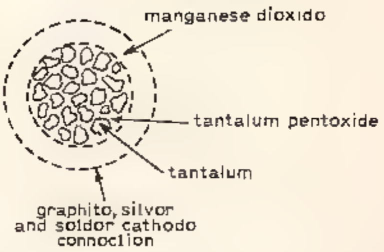

Fig. 12. Solid tantalum capacitor slug formed by sintering tantalum powder particles around a tantalum anode.

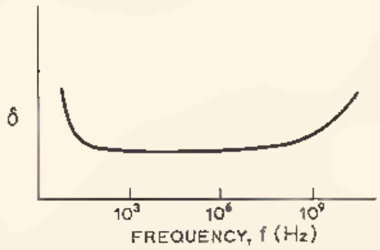

Fig. 9. Loss angle versus frequency for a non-polar dielectric material.

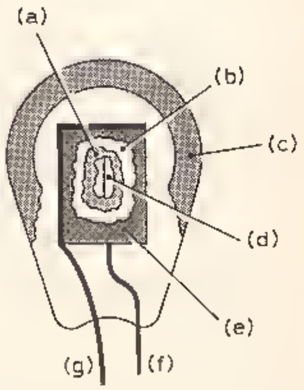

Fig. 13. Schematic of a complete solid tantalum capacitor (a) tantalum impregnated with manganese dioxide (b) graphite layer (c) resin outer coating (d) tantalum shown cut away to indicate anode terminal and tantalum pentoxide layer (e) solder layer completely surrounding cylinder (f) welded anode connection (g) cathode connection.

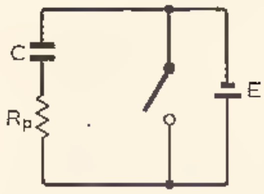

Fig. 10. Perfect capacitor before discharge through a resistor.

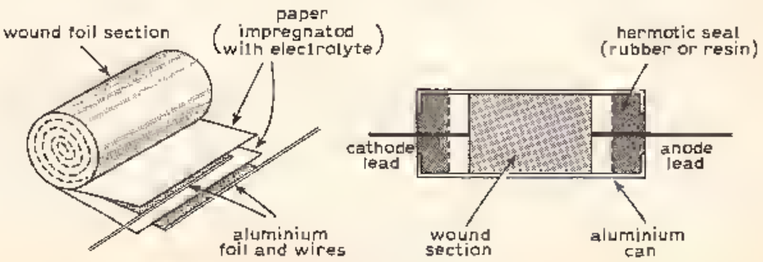

Fig. 11. Construction of an aluminium electrolytic capacitor.

paper is impregnated with another suitable dielectric to prevent moisture absorption (see Table 2 for details of typical dielectrics used). The electrode of the capacitors is usually aluminium and two basic types of capacitor exist, one being the metal foil variety which functions at high voltages and currents, the other being the metallized variety where the dielectric is coated with a thin layer of aluminium or zinc; this method of construction leads to a size reduction due to the thinness of the metallized film but has a disadvantage in that pulse handling is bad.

Encapsulation of paper capacitors is usually by moulding the capacitor element in resin or encasing it in metal cans, the latter being hermetically sealed to prevent evaporation of the dielectric.

Reliability. The power factor of paper capacitors is dependent on the type of impregnant used. In some cases it may be large and will always increase rapidly with frequencies above 10kHz.

A defect in the dielectric of a capacitor will cause an electric arc between the electrodes which will destroy more of the surrounding dielectric and result in catastrophic failure.

The disadvantage is not seen in metallized film types because the heat generated by the arcing process will rapidly vaporize the electrode section, this clearing the short. Metallized film construction is thus not confined to paper capacitors but is used extensively in plastic film types. A schematic diagram of the process is shown in Fig. 15.

Plastic film capacitor

Plastic films are used extensively in capacitor manufacture due to their high reliability and low cost. A number of leaves of plastic film are interleaved with aluminium electrodes rolled into a coil and encapsulated by a metal case or plastic encapsulation. A typical plastic film capacitor is shown in Fig. 16.

Historically, the first plastic film capacitor consisted of polystyrene film, which produced a realiable capacitor, although expensive. Nowadays, numerous plastic films are used and Table 3 gives a synopsis of the relative advantage of the four most common types.

It should be noted that it is not possible to vacuum deposit a metallized film on polystyrene film due to its low melting point.

Mica capacitors

Mica is a naturally occurring silicate which due to its platelike crystal structure, can be laminated into thin sheets suitable for capacitor construction. Being chemically inert and possessing a high permittivity (6·5 to 8·7) mica is capable of a precise electrical performance.

The construction of a mica capacitor is shown in Fig. 17, and consists of a number of small parallel capacitors to form the main capacitor.

Metallized film techniques in mica capacitors have led to the silver mica capacitor becoming extensively available in the capacitor market. In this capacitor, silver electrodes are fired directly onto the sheets of mica giving better stability due to the defined distance of the electrodes and the lack of air pockets in the capacitor (and hence their associated instability).

Encapsulation of the capacitor is commonly by means of a moulded epoxy resin although this does produce a fatigue condition on the capacitor due to the heat of the moulding which affects the reliability of the capacitor. In contrast the dipped mica capacitor, being encapsulated by dipping in resinous material below atmospheric pressures gives better electrical characteristics than the moulded types and high reliability.

Ceramic capacitors

Ceramic capacitors may be divided into two classes; the high permittivity type (high K, $\epsilon \approx 1000$) and low permittivity type (low K, $\epsilon \approx 10$).

Characteristics of the two types are widely different. The low K types possess low power factor, small linear temperature coefficients, and operating frequency capabilities of up to 1000MHz. The high K types have high power factors (dependent on the applied a.c. and d.c. fields due to electrical hysteresis) and non-linear temperature coefficients. By a suitable choice of materials a dielectric can be useful in circuit applications where an otherwise detrimental temperature drift would occur, e.g. tuned circuits and

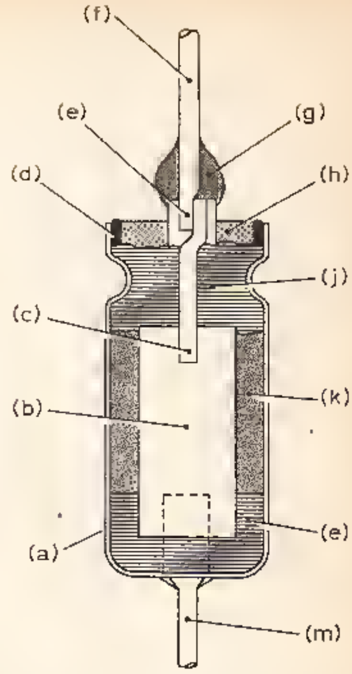

Fig. 14. Schematic of a wet-sintered tantalum capacitor (a) fine silver (b) anodized sintered tantalum anode (c) tantalum wire (d) solder seal (e) tantalum to nickel weld within header (f) nickel wire (g) solder seal between header and external anode lead (h) glass-to-metal seal (j) internal seal (k) electrolyte (l) anode boot (m) cathode.

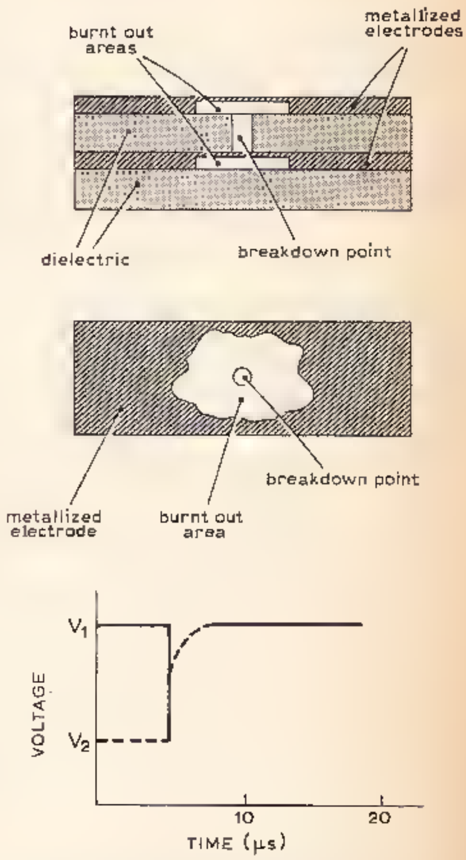

Fig. 15. Process of self healing of a metallized dielectric capacitor. The voltage trace is typical during the process.

Table 2. Dielectrics for paper capacitors

Dielectric	Permittivity (P1)	Permittivity with paper (P2)	Comment
Natural products (oils, waxes, etc)	2·2 to 6·0	≈4	Low dielectric stress due to difference of $P1$ and $P2$
Synthetic halogenated products	5·0	≈5	More evan dielectric stress due to equality of $P1$ and $P2$
Plastic polymers	2·5	≈3·5	Possible voids form in polymerisation; low cost

Table 3. Plastic film dielectrics

Characteristic	Polystyrene	Polyethylene terephlalate	Polycarbonate	Polypropylene
Structure	non polar	polar	polar	non polar
*Permittivity	2·4	3·3	2·8	2·25
Production of film	extrusion	melt casting	extrusion or solvent casting	extrusion
Film thickness (μm)	8	3·5	1·5	8

*decreases with frequency for polar material

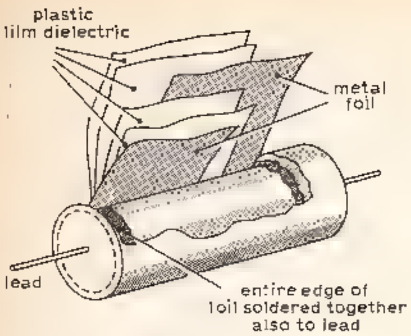

Fig. 16. Constructional features of a plastic film capacitor.

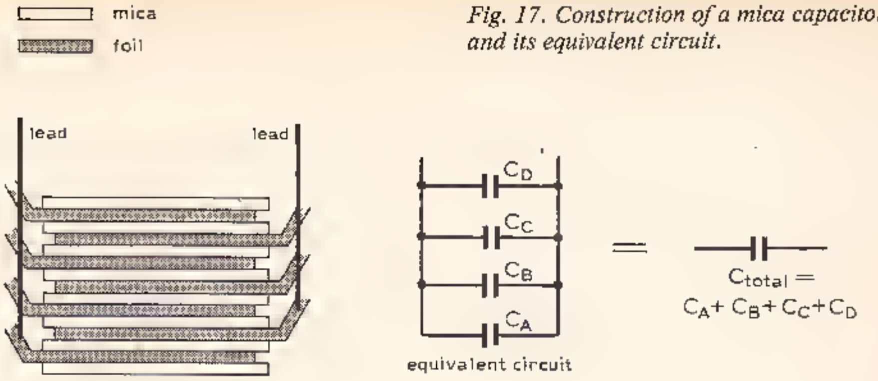

Fig. 17. Construction of a mica capacitor and its equivalent circuit.

filters.

The high K ceramic capacitors are able to give a large capacitance in a small space and find application in decoupling and by-pass capacitors.

Manufacture

The ceramic materials used in capacitor manufacture are made from natural minerals such as steatite, titanium dioxide, and alkaline earths. The ingredients, after being finely ground are compressed, heated to 900° C to remove any impurities; then reground and finally recast in a carefully controlled atmosphere of about 1300° C.

Ceramic capacitors are found in either disc or tubular form. The electrodes are a film of silver fired on to both surfaces of the ceramic. Encapsulation is usually by means of a wax impregnated phenolic dip.

Of particular interest is the barrier layer ceramic capacitor. In this type the high K thin film ceramic plates are fired in a de-oxidising oven so as to convert the plates into a conducting metal. The capacitor assembly is then fired in a reoxidizing oven so as to restore the external surfaces in the assembly to a dielectric. Normal silvering is now applied resulting in two high capacity capacitors connected in parallel.

This technique enables high capacitance to be obtained in a relatively small space.

Further reading and acknowledgement

Most manufacturers provide excellent information on capacitors, among those of particular interest are technical literature by: Waycom, Philips, Plessey, Lemco and Erie.

Of deeper and of a more theoretical nature are "Fixed Capacitors" by Dummer (Pitman) and "Dielectrics" by P. J. Harrop (Butterworths).

The author wishes to thank the staff of the Components Laboratory, Rank Radio International for their consistent help and enthusiasm.

Appendix

It is known that when a dielectric is polarized the electric field (E) within the dielectric is vectorially displaced according to eqn.1.

$$\epsilon_o E = D - P \qquad \text{(A1)}$$

where: ϵ_o = permittivity of free space
D = dielectric displacement of the medium
P = polarization of the medium

This equation can be physically interpreted by considering a dielectric as a collection of atoms, positively or negatively charged, each separated by a small distance, and arranged in some regular pattern to form what is known as a lattice. The dielectric may be fundamentally classified as polar or non-polar according to whether or not it possesses a permanent dipole moment (a dipole consists of two charges equal in magnitude, q, but of opposite sign, separated by a small distance, a. The dipole moment is the quantity qa). Under the action of an electric field, E, the lattice of the dielectric is distorted (or displaced) and its dipole moment is altered in magnitude and direction. The dielectric is said to be polarised.

It is also useful to define the "polarizability" of the medium, X, from

$$P = X\epsilon_o E \qquad \text{(A2)}$$

hence from (A1) and (A2), $D = (1 + X)E$.

This defines the permittivity of the dielectric, ϵ (see general considerations for the physical importance of this parameter) by $\epsilon = (1 + X)$.

The loss angle, δ, is defined as the phase angle between E and D, but is complicated by the fact that X is not dependent on a single variable but on four physically distinct mechanisms viz: electronic polarizability (e), atomic polarizability (a), dipole polarizability (d), space charge (s)

$$X = \alpha e + \beta a + \gamma d + \delta s$$

where ($\alpha, \beta, \gamma, \delta$ are constants dependent on the dielectric).

Capacitor comparison chart

	Polypropylene		Polyester		Polycarbonate		Mica	Paper		Polystyrene	Ceramic		Electrolytic		
	metallized	film/foil	metallized	film/foil	metallized	film/foil		metallized	film/foil		disc/tube	monolithic	aluminium foil	foil	tantalum solid & wet
Insulation resistance Ω	10^5M	5.10^4M	5.10^4M	10^5M	5.10^4M	10^5M	10^5M	3.10^3M	2.10^4M	10^6M	10^2M	10^4M	practical measurement by leakage current		
Dissipation factor	0.0003	0.0003	0.01	0.005	0.005	0.001	0.02 to 0.0005	0.01	0.005	0.0003	0.002 to	0.02	very poor 0.08	poor 0.01	poor 0.0005 to 0.02
Tolerance (%)	5	2	5	5	5	2	0.5	10	5	0.625	10	20	10	10	5
Temperature range (°C)	−40 to 85	−40 to 100	−55 to 125	−55 to 125	−55 to 125	−55 to 125	−55 to 125	−30 to 100	−30 to 100	−40 to 70	−55 to 125	−55 to 125	−20 to 80	−40 to 125	−40 to 150
Size per CV	small	small	small	small	small	small	small	small	large	large	small	small	very small	small	
Stability	fair	excellent	fair	fair	fair	fair	excellent	fair	fair	excellent	fair	fair	fair	very good	excellent
Cost per CV	low	low	low	fair	fair	fair	fair	fair	fair	high	low	low	fair	high	high
Capacitance range (μF unless indicated)	0.001 to 100	100pF to 0.47μF	0.001 to 10	100pF to 0.01μF	0.001 to 100	5pF to 0.01μF	5pF to 0.01μF	0.01 to 100	0.001 to 100	100pF to 0.6μF	5pF to 1μF	0.001 to 10	typically 1 to 22,000	1 to 1000	*CV* product inflexible (3500 max normally)
Voltage (a.c.) (V)	250 to 440	63 to 500	63 to 400	90 to 160	40 to 250	63 to 160		250 to 630	250 to 630	—	63 to 250	—	—	—	—
Voltage (d.c.) (V)	750 to 1000	100 to 1500	100 to 1500	160 to 400	63 to 1000	100 to 400	63 to 630	500 to 5000	—	63 to 1000	63 to 10000	63 to 450	6.3 to 500	6.3 to 300	1 to 50
Temperature coefficient PPM/°C	−170	−120	400	400 (non linear)	150	−50 to −100	100	300	300	−150	non linear positive to 1000 neg		1500	1000 (non linear)	200 to 1000
Appx resonance MHz	0.1	1	0.1	1	0.1	1	1.0	0.1	0.1	1	10	100	0.05	0.1	0.1