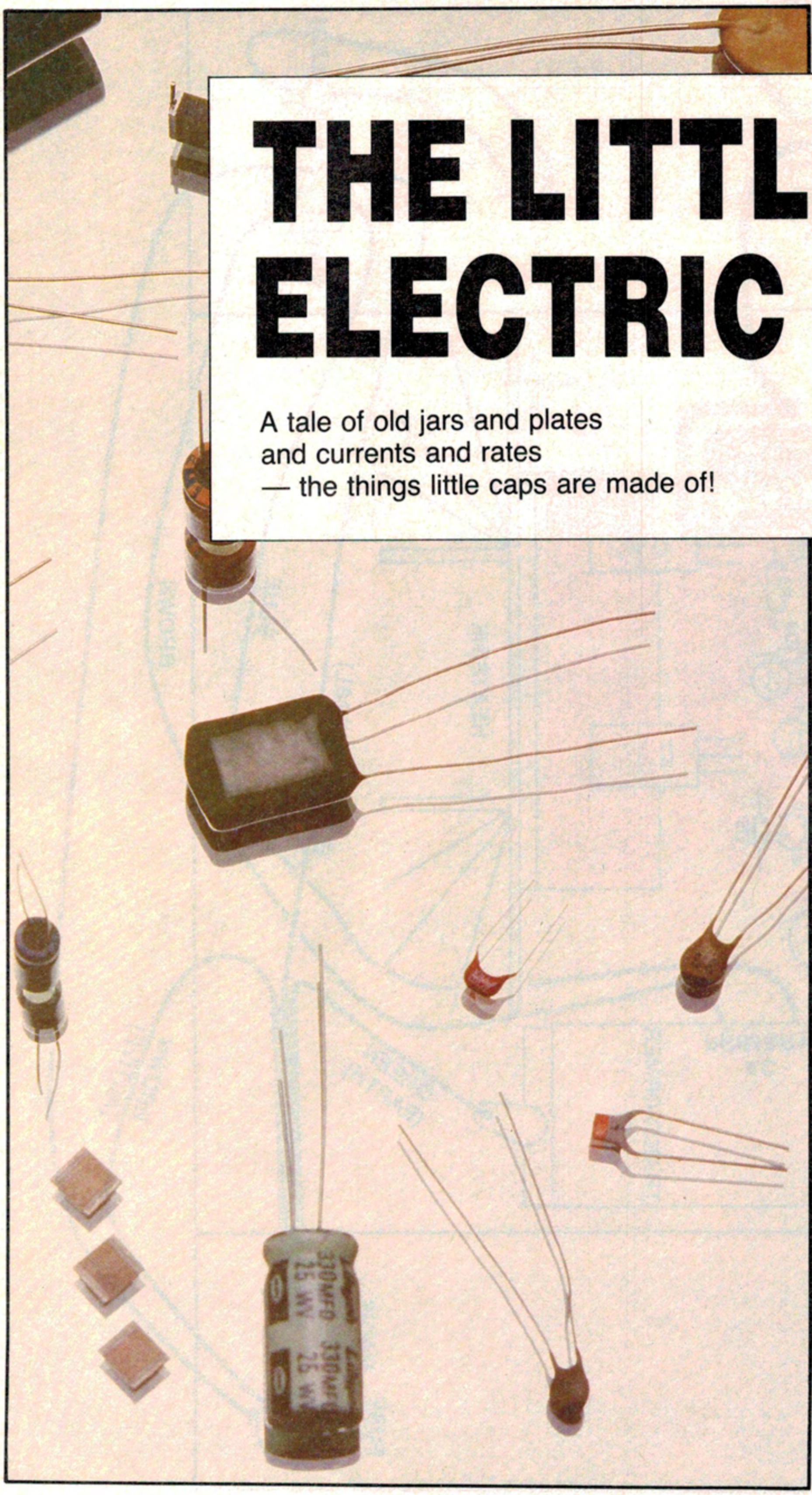
THE LITTLE ELECTRIC STORE

A tale of old jars and plates
and currents and rates
— the things little caps are made of!



Capacitors

IT WAS FASHIONABLE during the years of the renaissance to dabble in 'natural philosophy' via practical experiments. In 1745 a German cleric with intellectual pretensions did just that. He set up a glass jar and filled it with water, then sealed the top of the jar with a cork, through which had been driven a copper stake. To the copper stake he connected an electric machine, a device in which a spinning glass globe was rubbed to create an electrical charge. Nothing seemed to happen, so he stopped the machine, and grabbed hold of the glass jar. Instantly, his muscles contracted and the glass went flying. E.G. von Kleist had discovered capacitance.

To put the scene into context: electricity was still a mysterious force, but enough work had been done for people to believe that it was manageable, subject to laws that could be uncovered by reason and experiment. One of the questions that plagued experimenters was whether electricity was the kind of thing that could be stored.

The Reverend von Kleist proceeded with the thoroughly reasonable proposition that the way to store electricity was probably the same way you store most small things: in a bottle. The bottle was glass, a known insulator, and inside was water, a conductor. Of course, when he disconnected the wire he gave himself a bad shock, probably the worst ever experienced up to that time. It "stunned his arms and shoulders", he later wrote.

It so happened that one of the finest minds in Europe, belonging to Professor van Musschenbroek, was also working on the problem. He duplicated von Kleist's work, also getting a shock for his pains. Van Musschenbroek was first to publicize it, and

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so the device was named after the town where he did his experiment. The electric bottle is known to us today as the Leyden jar.

An explanation of the strange effects of the Leyden jar was not long in coming. The glass was an insulator, the water a conductor, the hand of the experimenter also a conductor, especially when wet from pouring water into the jar. Van Musschenbroek realized that in such a device the effects of electricity were condensed. It was, he said, a "condenser" for electricity. Today we call such a device a capacitor.

Practical capacitors were developed almost as soon as an explanation of the Leyden jar effect. These simply substituted metal foils for the water and the experimenter's hand. Connection to the inner conductor was via a chain threaded through a rubber stopper.

So, what was this wonderful new effect that had been discovered?

Fields

Capacitance is a measure of the ability to store electric charge. To understand how this works it's necessary to go back and think about some fundamentals of physics and electricity. Matter is composed of atoms, and all atoms are electrically neutral. However the constituents of the atom are not. The nucleus has a positive charge and the electron a negative charge.

One of the fundamentals of electronics is that unlike charges attract and like ones repel. So, if we have a point with a surfeit of electrons, and another point with a lack of them, then all the electrons will flee the negative point and congregate at the postive point. However, this is not the whole story, because how many electrons flow depends on the type of material they are imbedded in. Some materials, such as copper and aluminium, encourage electron flow. We call them conductors. Other don't, and we call them insulators or dielectrics.

What's happening? Electron orbits, normally circular, are distorted by the presence of a charge. There is a gradient of force across the electron orbit, so that on the side closest to the origin of the force, the disrupting force is stronger than on the side furthest away. This turns the orbit into an ellipse. The stronger the force, the steeper the gradient, the more elliptical the orbit. When this distorting force gets too great, the electrons sheer off and become negative ions. The amount of force necessary to achieve this depends on the quality of the material. The atoms in conductors are vulnerable, those in dielectrics resistant.

The problem with this account is that it involves what is known as "action at a distance". The electrons are depleted *here* and the atom reacts *there*. Exactly the same problem worried Newton when he was working on the theory of gravitation. We can explain things with an abstract mathematical idea called a field. Fields have been involved in gravitation and magnetic theory as well as in electrical theory.

You can give a field some kind of physical reality and delineate it with equi-potential lines. That is to say, lines along which the strength of the field is the same. At right angles to this run field lines, which indicate the direction of movement of a free charged particle in the field. As you can see from Figure 2 the rules are that field lines leave and enter their source at right angles; they never cross, and they flow from a positive point to a negative one.

Another way to think about the field: consider what the presence of the field means to the atom across which it is impressed. Each of these has electrons in an orbit of greater or less eccentricity. This is a higher energy state that normal, and thus represents a source of energy. It is potential energy, however, since one can't get at it until a conducting path is provided. Then it becomes real energy, showing itself in the deflection of an ammeter. In effect, the electric field is an energy store.

TABLE 1: COMPARISON OF DIELECTRICS (courtesy Rifa)

Type	Poly-propylene	Poly-styrene	Poly-ester	Ceramic NPO	Ceramic Hi-K	Mica	Aluminium oxide	Tantalum oxide
e	2.2	2.4	3.3	450	12000	7	10	28
typical capacitance	10n-100µ	47p-50n	1n-10µ	1p-10n	1n-10µ	1p-100n	100n-1F	10n-1000µ
max V dc	2000	500	600	200	100	500	450	125
dissip-ation factor	0.05	0.02	0.8	0.1	3	0.2	10	10
typical tolerance	5%	1%	10%	10%	80%	1%	30%	5%

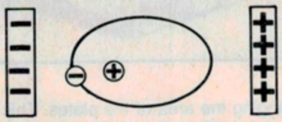


Figure 1. The elliptical path of an electron around the nucleus of an electric field.

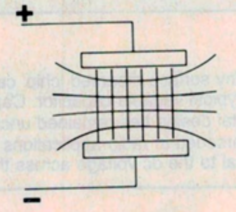


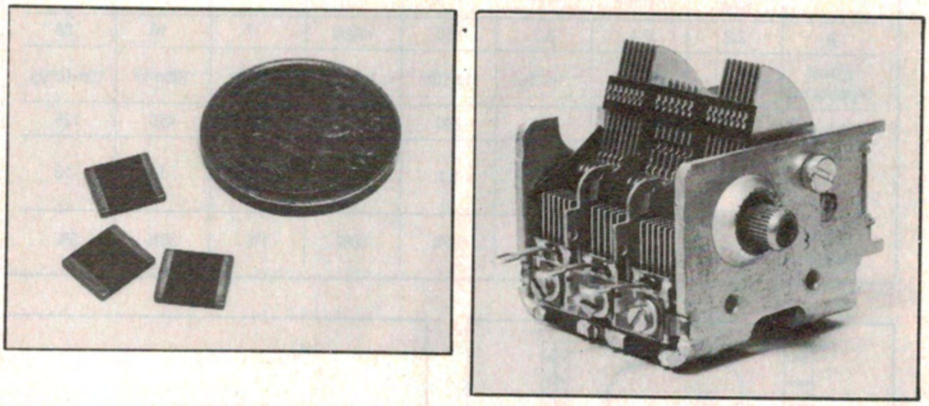
Figure 2. The field between two conductors. The vertical lines are the equi-potential lines which connect points of equal potential. The horizontal lines are the field lines and represent direction of movement of a free charged particle.

Practical capacitors

So how do we turn this theory into a practical capacitor? The earliest capacitors consisted of two sheets of parallel metal with an air gap. This is still a preferred method of doing things for variable caps. Early in the game however, it was discovered that other materials make better dielectrics, and for most applications solid materials are used.

There are two main types of capacitors, both conforming to the general pattern of conductor-dielectric-conductor. One is the foil type, in which a strip of dielectric, like mica or ceramic is sandwiched between two strips of conducting foil. Leads are soldered to the foil and the whole assembly heated to seal it against moisture.

A variation on this theme is called "metallization", particularly favoured with the plastic dielectrics like polyester and polystyrene. Here the conductor material is vapourized in a vacuum container and deposited onto the dielectric, which is then wound up to form the capacitor. This method has the advantage that it is possible ▶



Above. Tiny surface mounted 'chip' capacitors.
Right. A typical variable capacitor. Capacitance is varied by changing the area of the plates. This fundamental design has remained unchanged since the birth of radio, although variable capacitors are now often superseded in radio applications by varactor diodes which have a capacitance level directionally proportional to the dc voltage across them.

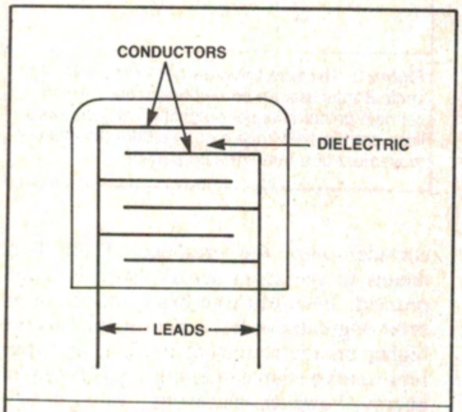


Figure 3. A typical capacitor.

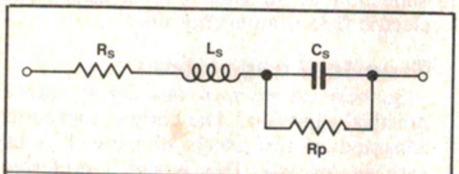


Figure 4. The equivalent circuit of a capacitor showing inductance and resistance in series with the capacitance. The capacitor is also shunted by resistance.

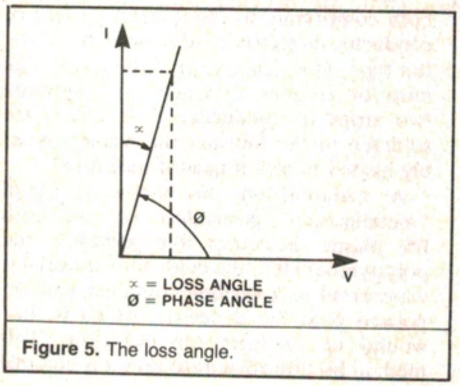


Figure 5. The loss angle.

to make the metal layer extremely thin, in the order of microns. Modern techniques allow the dielectric to be of this order of thickness as well, so an extremely compact capacitor results.

Even more compact are the new monolithic capacitors, especially intended for surface mounting. These SMDs (surface mount devices) are made from microslices of ceramic and silver packaged in a cube a few millimetres on a side. It's possible to obtain up to 0.1 μF by this method, sufficient to bypass TTL in typical applications.

The other major type of capacitor is the polarized electrolytic. A metal post composed of aluminium or titanium serves as the anode. An extremely thin oxide layer is grown on the outside of the post to serve as the dielectric. The cathode is an electrolyte. Normally an electrolyte is a liquid, but in this case the electrolyte is impregnated in paper or some other porous substance. With this structure it clearly makes a difference which way the current flows through it, and in fact this type of capacitor can only be used when the current flows in a single direction.

Equivalent circuits

In theory a capacitor is simply a capacitor. In practice, a capacitor, like every other device on a circuit board, has capacitance, inductance and resistance. The only difference is that the capacitance is controlled, and hopefully, the inductance and resistance minimized.

The equivalent circuit of a real capacitor is shown in Figure 4. It shows series inductance, and both series and parallel resistance. The series inductance is present in the device leads and indeed, in the body of the component itself. As one would expect, the inductive effects increase with frequency, and so the practical effect on the capacitor as a whole is a decrease in the impedance up to a certain frequency, called the resonant frequency, followed by an increase. This effect is present in all capacitors, but it can be minimized by careful design, and also by careful mounting on a pc board. The rule is: keep the leads short.

Series resistance is a measure of loss in the capacitor. It is measured as the loss angle or dissipation factor. These are different ways of approaching essentially the same thing, and they are often used interchangeably, especially in ac theory. Theoretically, in a pure, ie, lossless capacitor, there is a phase difference between current and voltage of 90 degrees. Current leads voltage. In a resistor there is no difference. In a practical component the resultant phase angle is a result of the vector sums of resistance and capacitance (see Figure 5). As a result, the loss angle is a good measure of the extent to which power is absorbed in the capacitor, and thus a measure of the extent of series resistance.

Parallel resistance is more commonly known as insulation resistance, and in fact is a measure of the ability of the dielectric to carry a direct current. As the area of the dielectric and thus the capacitance goes up the insulation resistance comes down.

Compromise

Given all this, what are the limits that constrain capacitor design? As always when dealing with nature, there are compromises to be made.

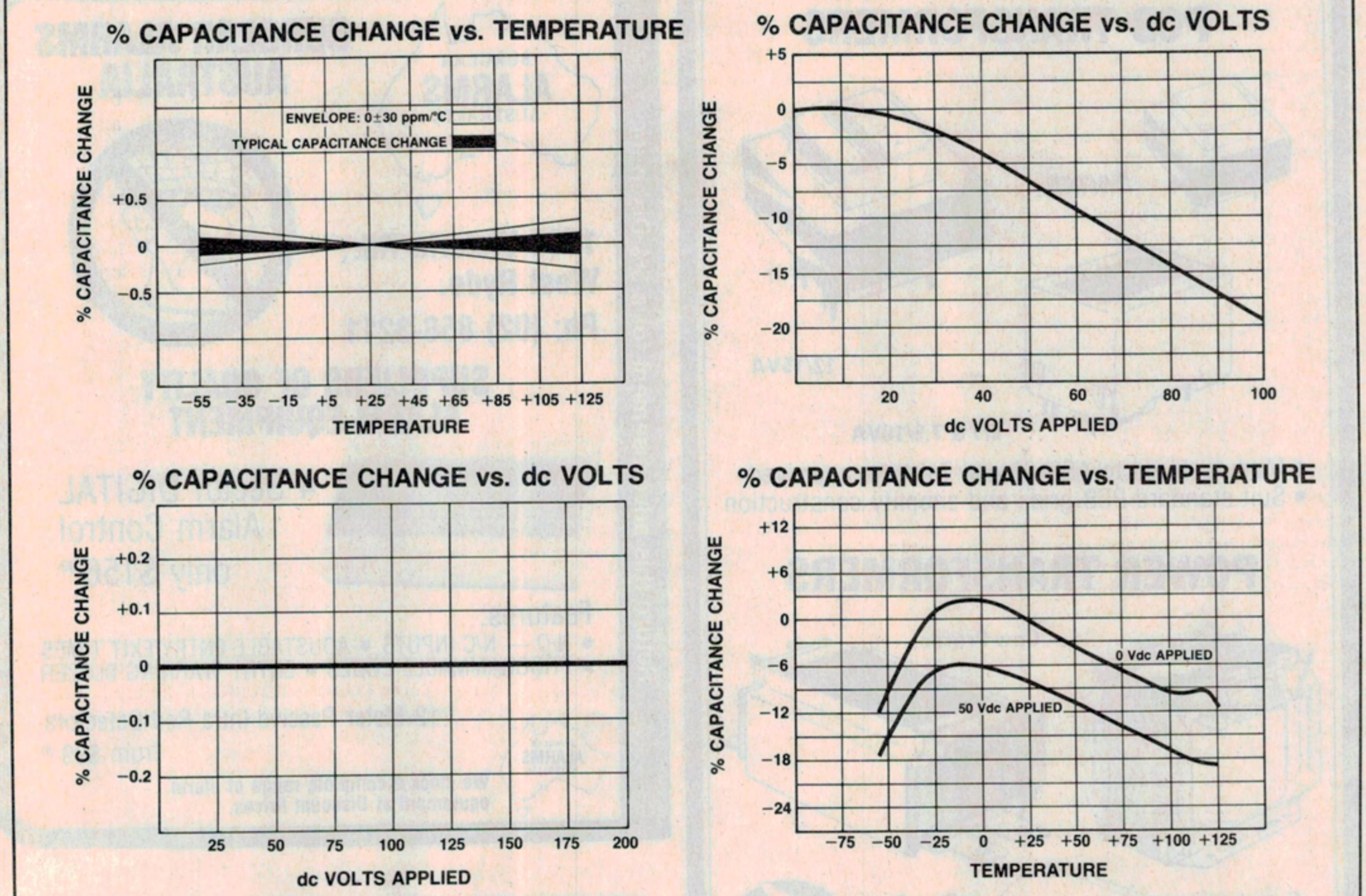
Capacitance in any capacitor is proportional to $e \times \frac{A}{d}$

where e = the dielectric constant, A is the conductor area and d the distance between the conductors. Since the maker usually wants to get as much capacitance into as small an area as possible, he can do any of three things: increase A or e; or decrease d.

Increasing e has been a preoccupation of scientists since 1745. However, as we will see, high values of e often have nasty side effects. Modern trends have included research into plastics that has seen products like polystyrene and polypropylene join standards like polyester. Research is also going on into the creation of new types of ceramics.

The problem is that large dielectric constants are associated with some undesirable electrical properties. Perhaps the most notable in a practical sense is that such dielectrics are unstable. They tend to be sensitive to temperature, frequency and voltage, and any or all of them can cause the capacitance value to change quite dramatically.

The most dramatic example of this can be seen in ceramic capacitors. Ceramic is not, as often imagined, a single type of dielectric. In fact ceramic capacitors are made by mixing up a brew of 'powders'; a little of this, a little of that. Graphs of capacitance against temperature and dc volts are shown in Figure 6 for two types of dielectric, NPO and BX. With an NPO dielectric, a capaci-



% CAPACITANCE CHANGE vs. TEMPERATURE

% CAPACITANCE CHANGE vs. dc VOLTS

% CAPACITANCE CHANGE vs. dc VOLTS

% CAPACITANCE CHANGE vs. TEMPERATURE

Figure 6. Comparison of two ceramic dielectrics.

tor about a millimetre cubed can have between 1 and 150 pF of capacitance. An equivalent sized BX ceramic capacitor will range between 100 pF and 5.6 nF.

The state of the dielectric also changes with frequency. Most significantly, the dissipation factor increases dramatically with frequency in any given dielectric, and as usual, it's the ones with the higher dielectric constant that are hardest hit. Tantalum for instance, has much worse high frequency response than either ceramic or plastic film capacitors. Ceramic or plastic can be used to decouple high frequency transients from integrated circuits; tantalum is essentially useless in this application.

Another factor is the question of ageing. There are many applications where there is a requirement for capacitors to last 30, 40 or even 50 years without significant changes in capacitance. Expensive equipment in telephone exchanges would be a prime example. Front runners for this application are polystyrene and polypropylene, with dielectric constants around three.

Designers have a number of tricks up their sleeves to increase the value of A. Perhaps the earliest, and still the commonest technique is to roll the dielectric up like a Swiss cheese (see Figure 7). A rather more subtle measure is to increase the microscopic corrugations in the surface of the conductor, thus effectively increasing A without increasing the bulk of the whole assembly. Etched aluminium surfaces do just this, resulting in substantial increases of A. Perhaps the most spectacular example is NEC's Supercap which uses a layer of activated carbon that is so rough it has a surface area of 10,000,000 cm^2 for every gram of carbon. Going down this route has resulted in a farad of capacitance in a 20-cent sized package. (See ETI March 1985 for a description of Supercaps.)

Manufacturers have made some remarkable achievements in pursuit of super thin film dielectrics. In 1951 Du Pont in the USA announced Mylar, the first of the plastic films suitable for miniature capacitors. It is still in use today as "Mylar C" and available down to 1.5 µm. Films of these dimensions are used by Wima in Germany to produce ultra miniature capacitors with lead spacings only 2.5 mm apart. Paper layers in metallized capacitors have been produced that are only 10 µm thick. Rifa is now manufacturing polypropylene dielectrics as thin as 4 µm. Research is currently underway that will allow large scale manufacturing of 1 µm sheets.

There are many problems with relying on super thin dielectrics. Some idea of scale: 20 layers of Mylar film one on top of the other would be thinner than a human hair. For a start there are mechanical problems that come from handling materials that thin. It tears easily and is very susceptible to heat. However these problems can be overcome (at a price). What cannot be overcome is the voltage sensitivity of such capacitors. All things being equal, the thinner the dielectric the less voltage you can put across it. ●

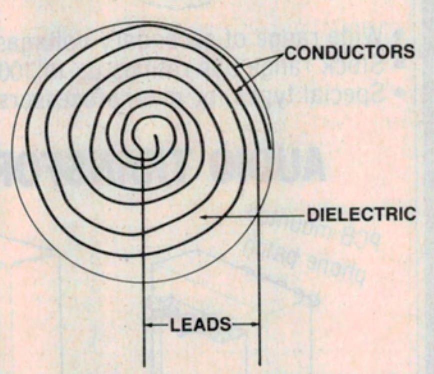


Figure 7. Structure of a typical thin dielectric metallized capacitor.