VICTOR MEEDIJK

SELECTING THE BEST RESISTOR/CAPACITOR

There are a lot of factors to consider when selecting the proper capacitor for your design or project. In this article we'll look at those factors, and which of the many, many types of capacitors is right for your application.

Part 2 AS WE SAW LAST TIME, there are a lot of factors you should consider in selecting resistors for your projects and designs. As you might expect, the same holds true for capacitors. In capacitor selection, you should consider such things as operating temperature, humidity, AC ripple, and operating frequency. In addition, capacitance, as well as other capacitor specifications such as current rating, leakage current, voltage rating, and life expectancy, should be considered so that the device chosen will be appropriate for the application at hand.

Materials used in manufacturing a capacitor, as well as how those materials have been assembled, will effect capacitor specifications. As an example, capacitance is based upon electrode area and the type and thickness of the dielectric used. Varying any or all of those things will, of course, change the capacitance of the device. But that is not the only parameter that will change.

For instance, if the electrode surface area of an aluminum electrolyic capacitor is increased (to increase the unit's capacitance) through the use of finely etched electrode foils, the device will have a larger ESR (*E*quivalent *S*eries *R*esistance) than similar smooth-metal foil units. That is because the ESR depends upon the volume of the foil used.

You can also increase capacitance by using dielectrics with high dielectric (high-K) constants. But capacitors that use high-K dielectrics are not as stable (they are more sensitive to temperature and voltage variations) and generally have a higher dissipation factor than capacitors that use dielectrics with lower dielectric constants.

Capacitor package styles also should be considered. High lead inductances, common to tubular units, restrict high-frequency performance. Tubular ceramic capacitors however, are the most stable form of capacitor and, since there is no opposing electrode to provide stray capacitance pickup, almost the total capacitance is provided by the ceramic.

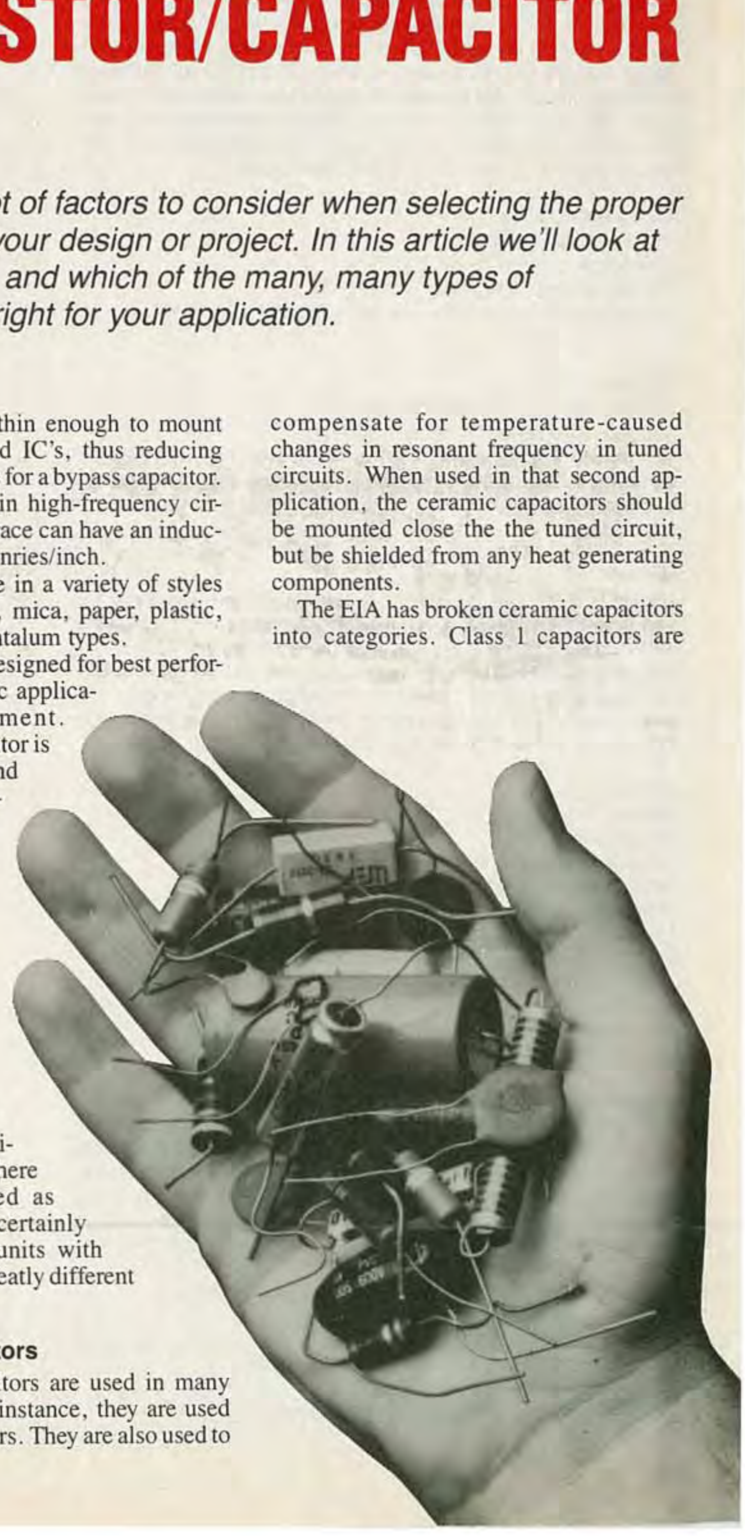
Dipped or molded radial-lead packages reduce interconnection impedances by allowing the capacitor to be mounted close to a PC board surface.

Chip capacitors have contacts, rather than leads, to even further reduce interconnection impedances. In addition, those devices are thin enough to mount beneath unsocketed IC's, thus reducing the length of a trace for a bypass capacitor. That is important in high-frequency circuitry since a PC trace can have an inductance of 10 nanohenries/inch.

Capacitors come in a variety of styles including ceramic, mica, paper, plastic, aluminum, and tantalum types.

Each type was designed for best performance in a specific application or environment. Each type of capacitor is discussed below, and the important specifications and considerations that pertain to the type of capacitor are summarized in Table 2. Table 3 is a glossary of capacitor terms and specifications.

One note about Table 2—the specifications shown there are only provided as guidelines. It is certainly possible to find units with slightly, or even greatly different specifications.



Ceramic capacitors

Ceramic capacitors are used in many applications. For instance, they are used as bypass capacitors. They are also used to compensate for temperature-caused changes in resonant frequency in tuned circuits. When used in that second application, the ceramic capacitors should be mounted close the the tuned circuit, but be shielded from any heat generating components.

The EIA has broken ceramic capacitors into categories. Class 1 capacitors are

TABLE 2—CAPACITOR SELECTION GUIDELINES

CERAMIC
Values: 1 pF to 2.2 μF
Tolerance: 10% or 20%
Voltage rating: 3.3 volts to 6 kilovolts DC
Dissipation factor: to 5%
Temperature coefficient: to 200,000 PPM/°C
For NPO's—
Tolerance: .25% to 10%
Temperature coefficient: 0±30 and 0±60 PPM/°C
Notes: General purpose high insulation-resistance devices used for transient decoupling of IC's and compensation of reactive changes caused by temperature variations. Applications include filtering, bypass, and non-critical coupling in high frequency circuits. Frequency sensitive (capacitance will vary with frequency) so characteristics should be measured at intended operating frequency. Should be mounted next to components being compensated, and shielded from sources of heat. Due to low voltage failure problems, should not be operated significantly under rated voltage under humid conditions. In circuit design, considerations should be given to changes in the dielectric constant caused by temperature, electric field intensity, and shelf aging.

CERAMIC CHIPS
Values: 10 pF to .18 μF
Tolerance: 5 to 20%
Temperature range: −55 to +125°C
Insulation resistance: greater than 100,000 megohms

MICA
Values: 1 pF to .1 μF
Voltage ratings: 100 to 2500 volts DC
Temperature range: −55 to +150°C
Temperature coefficient: −20 to +100 and 0 to +70 PPM/°C
Derating factor: 60% voltage (dipped case) and 40% voltage (molded case)
Mica chips—
Values: 1 to 10,000 pF
Voltage rating: to 500 volts
Notes: Used in timing, oscillator, tuned circuits, and where precise high frequency filtering is required. Capacitance and impedence limits are very stable and capacitors perform very well at frequencies of 10 kHz to 500 MHz. Devices using silver in their construction are very susceptable to silver ion migration resulting in short circuits. Failures can occur in a few hours if capacitors are exposed to DC voltage stresses, humidity, and high temperature.

GLASS
Values: .5 to 10,000 pF
Tolerance: to 5%
Voltage rating: 100 to 500 volts DC
Temperature range: −55°C to +125°C
Temperature coefficient: 0 to 140 PPM/°C
Notes: High insulation resistance, low dielectric absorption and fixed temperature coefficient. Has much higher Q than mica devices. Performs very well at high frequencies up to 500 MHz and can operate in range of 100 kHz to 1 GHz. Capable of withstanding severe environmental conditions but are susceptable to mild mechanical shocks and should be mounted accordingly.

PAPER/PLASTIC DIELECTRICS
Many dielectric and case configurations are available. Each type has its own characteristics. For example, metalized paper units have low insulation resistance and are prone to dielectric breakdown failures. Plastic types have superior moisture characteristics than paper units. Polycarbonate and Mylar types are used in applications that require minimum capacitance change with temperature, such as tuned or timing circuits.
Metalized polycarbonate and polycarbonate film—
Values: up to 50 μF
Voltage rating: to 1000 WVDC
Dissipation factor: .5% (at 25°C and 120 Hz)
Temperature range: −55 to +125°C
Derating factors: 50% voltage; 80% of rated temperature
Notes: DC blocking, filter, bypass, coupling, and transient supression applications. Close tolerance, high frequency capability (40–400 kHz) and high insulation resistance. Not suitable for sample/hold circuits, fast settling amplifiers, or filters due to dielectric absorption characteristics. Small size, medium stability, and long life expectancy under load.

Metalized polyester/polyester foil—
Values: .001 to 100 μF
Voltage rating: up to 1500 WVDC
Dissipation factor: 1% (at 25°C and 120 Hz)
Temperature range: −55 to +125°C (with 50% derating above 85°C)
Notes: See polycarbonate for typical applications. Moisture resistant and high insulation resistance. Small size, medium stability and very good load life. Capacitance will however vary widely with temperature. Foil units are generally lower cost than metalized types. Polyester film is commonly known as Mylar, which is a DuPont trademark.

Polystyrene foil—
Values: to 10 μF
Voltage rating: up to 1000 WVDC
Dissipation factor: .03% (at 25°C and 120 Hz)
Temperature range: −40 to +85°C without derating
Notes: Used in timing, integrating, and tuned circuits. High insulation resistance, and small capacitance change with temperature. Has excellent dielectric absorption characteristics. Large size with excellent stability and very good load life.

Paper/metalized paper/paper foil—
Values: to 100 μF
Voltage rating: to 5000 WVDC
Temperature range: −30°C to +100°C (derated by 30% over 75°C)
Temperature coefficient: greater than 4,500 PPM/°C
Notes: General purpose. Medium stability and very good load life. Large size; low cost. Metalized paper has paper coated with thin layer of zinc or aluminum and are smaller than metal foil units. They are, however, prone to dielectric breakdown of insulation resistance and have poor surge handling capability. Paper foil units used in high voltage/high current applications. Their dissipation factor varies with temperature. Maximum temperature is +125°C.

Polypropylene foil/metalized polypropylene—
Values: to 10 μF
Voltage rating: to 400 volts DC and 270 volts AC (foil units: 200 to 1600 volts DC and 300 to 440 volts AC)
Temperature range: −55°C to +105°C

Notes: Foil units are used in tuned circuits, integrating circuits, timing circuits, and CRT deflection circuits. Metalized units are used in DC blocking circuits. Good high frequency capability, high insulation resistance, close tolerance, high stability, and excellent dielectric absorption characteristics.

Less common types—
Polysulfone: Similar to polycarbonate and polyproplyene capacitors. Small size, high temperature range (to 150°C), suitable for high-frequency applications, and high insulation resistance. Excellent in high current and military applications. Not for sample/hold, fast settling amplifiers, or filters due to dielectric absoption characteristics. Poor history of availability.
Polyvinylidene fluoride: Considered experimental; Has high dielectric constant (about four to twelve times that of polyester devices), which results in a very small sized capacitor. Those units suffer from significant capacitance change with temperature, particulary at low temperatures.
Polyethylene terphthalate: For applications that require high reliability; high insulation resistance at high temperatures.
Metalized paper polyester/paper polyester foil: The foil unit has a slightly better dissipation factor than the metalized type. Operating temperature of −55°C to +125°C with voltage ratings of 240 to 600 (DC) available.
Paper polyproplyene: Available in voltage ratings of 400 to 800

(AC). Operating temperature from −40°C to +80°C.
Teflon/Kapton: Has a temperature range of −55°C to +250°C with a temperature coefficient of .009%/°C. Teflon's extremely low dielectric absorption makes it good for critical sample and hold circuitry. Those capacitors used in specialized applications such as oil well drilling equipment. Those capacitors are large in size since the dielectric is not available in thin gauges.
Parylene: Manufactured by Union Carbide, those capacitors are equivalent to polystyrene types in performance but are rated to +125°C, versus +85°C for polystyrene.

TANTALUM ELECTROLYTIC
Solid type—
Values: .001 to 1000 μF
Temperature range: −55°C TO +85°C (if derated, to +125°C)
Voltage rating: 6 to 120 volts DC
Tolerance: 5% TO 20%
Leakage current: varies with temperature
Derating factor: 50% voltage
Notes: Used in low-voltage DC applications such as bypass, coupling, and blocking. Not for use in RC timing circuits, triggering systems, or phase shift networks due to dielectric absorption characteristics. Also not recommended for applications subject to voltage spikes or surges. High capacitance in a small volume with excellent shelf life. Solid types not temperature sensitive and have lowest capacitance-temperature characteristic of any electrolytic unit. Dielectric absorption and high leakage currents make them unsuitable for timing circuits. Except for non-polarized units, these devices should never be exposed to DC or peak AC voltages in excess of 2% of their rated DC voltage. To prevent failures due to leakage or shorting when series connecting for higher voltages, parallel each unit with a shunt resistor.
Chip types—
Values: .068 to 100 μF
Tolerance: 5% to 20%
Voltage rating: 3 to 50 volts DC
Temperature range: −55°C to +125°C
Leakage current: varies with temperature.
Non-solid types—
Values: .5 to 1200 μF
Tolerance: −15 to +30, and 20%
Voltage rating: to 350 WVDC
Temperature range: −55°C to +85°C (if derated, to +125°C)
Leakage current: varies with temperature
Notes: Polarized foil units are used for bypassing or filtering out low-frequency pulsating DC. Allowance must be made for leakage current. Not suitable for timing or precision circuits due to wide tolerences. Large values available. Etched foil has 10 times the capacitance per unit volume as plain foil types. Peak AC and applied DC voltages should not exceed rated maximums. Usable to 200 kHz. Non-polarized foil are used in tuned low-frequency circuits, phasing low-voltage AC motors, and in servo systems. Sintered slug units are used in low-voltage power supply filtering and in DC applications. Can not withstand any reverse voltage. Leakage current lowest of all tantalum types; no appreciable leakage below 85°C. Usable to frequencies of 1 MHz.

ALUMINUM ELECTROLYTIC
Values: .68 to 220,000 μF
Tolerance: −10 to +75%
Voltage rating: up to 350 volts
Temperature range: −55°C to +85°C (if derated, to +125°C)
Dissipation factor: varies with temperature
Temperature coefficient: varies with temperature
Notes: Used in filter, coupling, and bypass applications where large capacitance values are required and capacitances above nominal can be tolerated. Sum of the applied AC peak and DC voltages should never exceed the the rated DC voltage. Aluminum electrolytics are larger than tantalum electrolytics but less expensive. Loss of capacitance, to as little as 10% of rated value, will occur as the aluminum oxide electrode electrochemically combines with the electrolyte. Oxide film deterioration also requires capacitors to be "re-formed" after storage to prevent dielectric failure. That involves application of rated voltage for a period of 30 minutes, or more, to restore initial leakage current value. Over time, dissipation factor can rise by as much as 50%. Four terminal devices are available (two leads for each connection) that offer low ESR and inductance at high frequencies. Those units were designed for use in switching power supplies.

TRIMMER CAPACITORS
Values: range from .25 to 1 pF and 1 to 120 pF.
Glass/Quartz: Low loss, high Q, and high stability for high tuning sensitivity applications. Frequency range up to 300 MHz.
Sapphire: High level of performance between 1 and 5 GHz.
Plastic: High grade units can be operated up to 2 GHz.
Ceramic: Smallest sized single turn units with maximum capacitance under 100 pF. Capacitance changes with temperature.
Air: High level of performance through UHF Band, from 300 MHz to 1 GHz.
Mica: Has wide capacitance range and relatively high current handling capability.
Vacuum/Gas: Used for high voltage applications. Values from 5 to 3000 pF, with voltage ratings from 2 to 30 kilovolts (DC).

those that have very predictable temperature vs. capacitance characteristics. One type of Class 1 ceramic capacitor is the NPO (*N*egative-*P*ositive-Zero) capacitor. That designation means that the negative and positive temperature coefficients of the device are zero and that they suffer almost (nothing is ever absolute) no change in capacitance vs. temperature. Other Class 1 capacitors have very predictable changes in capacitance with temperature. For instance, a ceramic capacitor that is specified as N750 has a negative temperature coefficient of 750 parts-per-million, per-degree-centigrade. That is, for each degree centigrade the temperature rises, the capacitance of the unit will drop 750 parts-per-million.

Class 2 capacitors are those that are non-linear. Their temperature coefficients are specified by a three letter code that specifies the low and high temperature ranges and the maximum change in capacitance from that at 25°C. Table 4 shows the EIA Class 2 code, and what the various designations mean. As an example, an X7R capacitor will vary in capacitance by no more than a factor of ±15% over the temperature range of −55°C to +125°C.

Mica capacitors

There are two types of mica capacitors. One type is a stacked foil unit consisting of alternate layers of metal foil (or deposited metal film) and sheet mica insulators. The metal foil layers are connected together with tin-lead foil strips with terminals attached by using solder coated pressure clips.

The second type of mica capacitor is the silver-mica capacitor. Those have a silver electrode material screened on the mica stampings, which are then assembled as described above. The silver-mica capacitors are very susceptible to silver-ion migration, which can occur within a few hours, when exposed to high DC-voltage stress, high humidity, and high temperature. The ion migration results in the capacitor short circuiting.

To keep internal inductance small for high-frequency use, button-style silver-mica capacitors have the anode connected through the center of the stack of mica sheets. The other terminal is formed by the case, which is connected to all points around the outer edge of the electrode. That design permits the current to fan out in a 360° pattern from the center terminal thus providing the shortest RF current path from the center terminal to the chassis.

One of the more common micas used for capacitors is Muscovite mica, which comes from India. That substance has a dielectric constant between 6.5 and 8.5, can be split into thin sheets, is non-porous, and does not readily absorb moisture.

Mica capacitors are temperature and frequency stable, have a low dissipation factor, and perform well at frequencies up to 500 MHz. Those high precision units are used in a variety of applications, including tuning circuits, oscillators, filters, and RF power circuits.

Glass capacitors

Glass capacitors are used in applications that require high stability in a hostile environment. Those devices can withstand vibration, acceleration, extreme moisture, vacuum, and high operating temperatures; they are, however, susceptible to damage from mild mechanical shocks. They have a life expectancy of 30,000 hours or greater.

Glass capacitors perform very well at high frequencies up to 500 MHz, and have a frequency range of 100 kHz to 1 GHz. Because of their characteristics, those devices are commonly used in missile and spacecraft electronics.

Paper/plastic capacitors

Paper and plastic capacitors are used in applications that require high and stable insulation resistance at high temperatures, and good capacitance over a wide temperature range. (However, an exception to that are the metalized—we'll talk about metalization in a moment—paper units, which have low insulation resistance and are prone to dielectric breakdown.) Plastic types are less affected by humid conditions than paper units since they are non-absorbent. Plastic capacitors, such as polycarbonate and polyester (Mylar) types, are generally intended for applications where minimum capacitance change with temperature is required. They are especially suited for tuned and precision-timing circuits.

In metalized capacitors, a thin film of metal is deposited directly on the paper or plastic dielectric. Doing that gives the capacitor a "self-healing" characteristic called "clearing." If there is a hole or contaminent in the dielectric of the capacitor, a short may occur, resulting from the heavy current flow in the fault area. In a metalized capacitor, that heavy current flow will melt away a very small part of the thin metal film, thus disconnecting the fault from the capacitor. These capacitors are best for analog circuits because the momentary current flow during the clearing action may result in a spurious signal and cause false triggering in digital logic circuits.

Metalized plastic devices work well in switching power-supply output filters because they have a comparatively low ESR, as well as stable temperature characteristics. When using those capacitors in such an application, however, be sure that the unit selected is rated to handle the voltage surges produced by the circuit.

Tantalum electrolytics

Tantalum capacitors offer high capacitance in a small package size and have an excellent shelf life. Various types of tantalum electrolytic capacitors are available including solid, sintered slug, plain foil, etched foil, wet slug, and chip. Applications include low-frequency filtering, bypassing, coupling, and blocking. The solid types are not temperature sensitive and have a lower capacitance-temperature characteristic than any other electrolytic capacitor.

Applications that tantalums are not suitable for are in RC timing circuits, triggering systems, or phase-shift networks. That's because they have high "dielectric absorption" characteristics. That is, when a capacitor is discharged, the dielectric retains a residual charge. Thus, even if a capacitor that has a high dielectric absorption characteristic has been discharged to "zero," it may still be holding a considerable charge. That, as you might imagine, can cause considerable problems in timing circuits and the like.

Tantalum capacitors also are not recommended for circuits that produce spikes, surges, or pulses. If their voltage rating is exceeded by even a few volts, the device is likely to fail.

Tantalums may be polarized or non-polarized. Polarized capacitors should never be exposed to a reverse DC or peak AC voltage greater than 2% of its rated DC voltage. Non-polarized units, as their name would apply, do not suffer from that limitation. Non-polarized units are made up of two polarized units in series with their cathodes connected together.

Aluminum electrolytics

Aluminum electrolytic capacitors are generally larger than tantalums, and are less expensive. One problem with aluminums is that they will change capacitance (drift) over time. That is caused by the aluminum oxide electrodes chemically combining with the electrolyte. Because of that, capacitance can drop substantially, to 10% of rated values. Those units also have a limited shelf life due to oxide film deterioration and must be "re-formed" after long periods of storage. Re-forming consists of applying the capacitor's rated voltage to the unit for a period of 30 minutes. Re-forming also prevents dielectric breakdown or shorting. In addition, the dissipation factor of these devices can rise as much as 50%.

To prevent electrolyte evaporation and component cleaning problems, aluminum electrolytics sometimes have an epoxy end seal. However, without a vent, such

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TABLE 3—GLOSSARY

DC leakage—Small current that flows through or across the surface of the dielectric or insulation of the capacitor.
Dielectric—Insulating material between the plates of a capacitor.
Dielectric absorption—A property of a capacitor's dielectric such that even when the capacitor is discharged to zero, a residual charge remains stored in the dielectric.
Dissipation Factor—Important in AC applications, it is the ratio of effective series resistance (ESR) to capacitive reactance X_C, and is usually expressed as a percentage. The dissipation factor factor varies with temperature, humidity, and frequency.
Electrolyte—Current conducting solution (liquid or solid) between two electrodes or plates of a capacitor.
Equivalent series resistance (ESR)—Energy losses in the capacitor due to lead resistance, termination losses, and dissipation in the dielectric.
Insulation resistance (IR)—Measure of a capacitor's insulation quality expressed either in megohms or as a time constant, RC, in seconds. That value determines a capacitor's leakage current for a continuously applied DC voltage when a capacitor is fully charged.
Temperature coefficient—A capacitor's change in capacitance per °C. May be positive, negative, or zero and is usually expressed in parts per million per °C (PPM/°C).
Working voltage (WVDC)—The recommended maximum voltage at which a capacitor should be operated
Quality factor (Q)—A figure of merit used mostly in tuned circuit applications. It is defined as a 1/DF or X_C/ESR.

TABLE 4

Letter Symbol	Low Temp.	Number Symbol	High Temp.	Letter Symbol	Maximum Capacitance Change
Z	+10°C	2	+45°C	A	±1.0%
				B	±1.5%
				C	±2.2%
		4	+65°C	D	±3.3%
Y	−30°C			E	±4.7%
		5	+85°C	P	±10.0%
		6	+105°C	R	±15.0%
X	−55°C			S	±22.0%
		7	+125°C	T	±22%–33%
				U	±22%–56%
				V	±22%–82%

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capacitors may explode if exposed to reverse or overvoltage conditions.

Aluminum electrolytics are used in filtering, coupling, and bypass applications were large capacitances, and capacitance that are higher than the nominal value, can be tolerated.

Trimmer capacitors

Trimmer capacitors fall into three categories: multi-turn, single turn, and compression types. Multi-turn capacitors have either glass, quartz, sapphire, plastic, or air dielectrics, while single-turn devices use ceramic, plastic, or air dielectrics. Compression types use a mica dielectric.

Glass, quartz, or air dielectric devices are selected for applications requiring low loss, high Q, stability, and tuning sensitivity. Glass and quartz devices are used at frequencies up to 300 MHz. Air dielectrics are usable to about 1 GHz. For frequencies of 1 GHz, sapphire dielectrics offer the best performance.

Ceramic and plastic styles are less expensive, with high grade plastic dielectric devices being usable at frequencies up to 2 GHz. **R-E**