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Capacitors: operating principles, current market and technical trends

Atsushi Nishino

Home Appliance Technology Research Laboratory, Corporate Research Division, Matsushita Electric Industrial Co., Ltd., Osaka, 570 Japan

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Abstract

The worldwide market for capacitors was approximately US$ 12.3 billion in 1993, of which production within Japan accounted for approximately 50% and the combined domestic and overseas production of Japanese manufacturers accounted for approximately 70%. The worldwide capacitor market continues to grow by approximately 20% per year as the demand for ICs and LSIs is growing. In conjunction with this special issue on capacitors, this paper presents a corporate perspective on current trends in the capacitor market: capacitor principles; capacitor materials; capacitor types and major characteristics; recent technical trends in capacitors and the future market outlook, and technical problems in the hope of facilitating the understanding of ideas and concepts presented in other papers in this issue.

Keywords: Capacitors; Dielectric constant; Dielectric loss; Electrolytic capacitors; Solid electrolytic capacitors; Electric double layer capacitors; Market survey

1. Introduction

This paper offers a corporate perspective on the capacitor market and recent technical trends in the development of capacitors as part of the special edition on the capacitor market in Japan.

2. Market survey and future prospects

There was some doubt about the continued market viability of capacitors due to the development of IC and LSI devices. These doubts have proven to be unfounded, and capacitor production has risen steadily from 1987 through 1993 as shown in Figs. 1–4 [1]. Even during the global economic downturn of 1992 to 1993, production in Japan rose approximately 10% on a year-to-year basis, and the global production rose approximately 23%. The global market for capacitors is approximately US$ 12.4 billion (in 1993). Capacitor production in Japan is approximately ¥ 580 billion, and Japanese manufacturers produce an additional ¥ 900 billion in the rest of the world, which means that Japanese firms

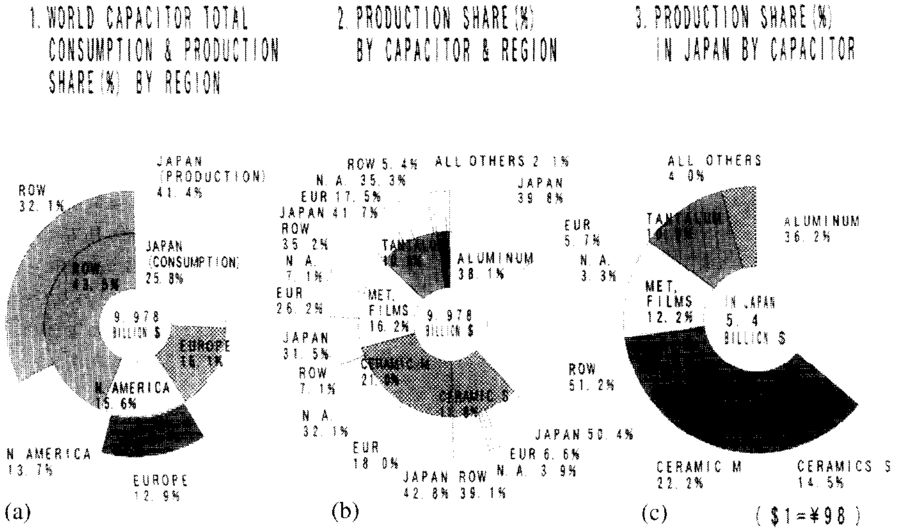

Fig. 1. Graphs, Jan.–Dec. 1992: (a) world capacitor and production share by region (%); (b) production share by capacitor and region (%), and (c) production share by capacitor in Japan (%).

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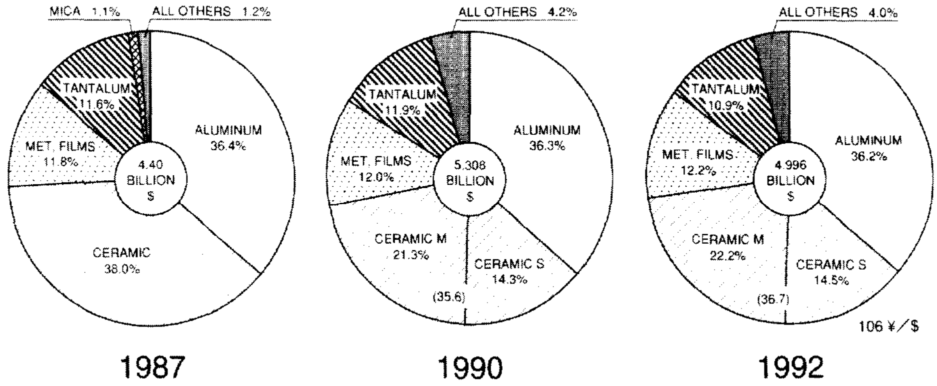

Fig. 2. Production share by various kinds of capacitor in Japan 1987–1992 (%).

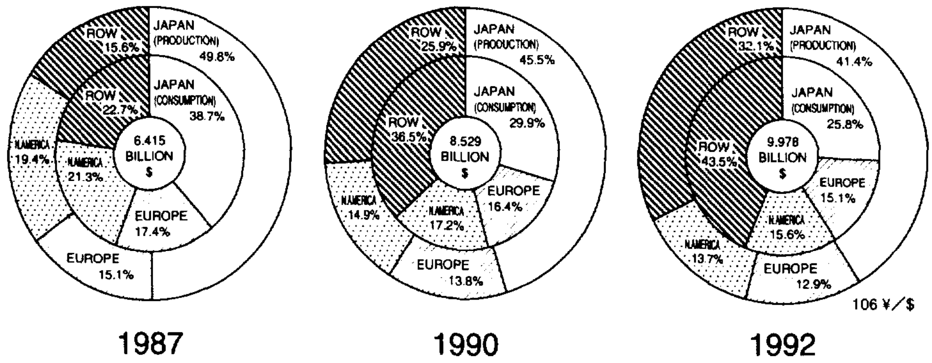

Fig. 3. World capacitor consumption and production share (%) by region, 1987–1992.

account for roughly 70% of total worldwide capacitor production.

In the beginning, capacitors were used primarily in electrical and electronic products, but today they are used in fields ranging from industrial application to automobile, aircraft and space, medicine, computers, games, power supply circuits and other power electronics.

A new trend in capacitors is the electric double-layer capacitor (EDLC) [2,3] having characteristics between those of a battery and an simple capacitor. With the implementation of a Product Liability Law from 1 July 1995, there is a worldwide effort underway to develop solid capacitors and improve capacitor safety.

These efforts have steadily improved the safety and reliability of capacitors, and thereby enhanced their ability for yet a broader application in industry and society.

3. Operating principle and basic characteristics

The operating principle and basic characteristics of capacitors are first described to make this special issue on capacitors more accessible to a wider audience.

3.1. Operating principle

Fig. 5(a) shows the basic structure and Fig. 5(b) the charge accumulating principle of a basic capacitor. Capacitors are made from two metallic electrodes placed in mutual opposition with an insulating material (dielectric) between the electrodes for accumulating an electrical charge. The basic equations relating to capacitors are:

$$Q = C \times E(c) \quad (1)$$

$$C = Q/E(F) \quad (2)$$

$$C = \epsilon S/d \quad (3)$$

where C (μF) is the electrostatic capacity, ϵ the dielectric constant of the dielectric, S (cm^2) the surface area of the dielectric (electrode), and d (cm) the thickness of the dielectric (see Fig. 5). The charge accumulating principle is described below. As shown in Fig. 5(b), when a battery is connected to the capacitor, electric force lines will be developed between the two electrodes, and electrons (free electrons) start moving. Because the electrons carry a negative charge, the electrons are attracted towards the positive terminal of the battery, and thus flow towards the power source.

As a result, an electron deficiency develops at the positive side, which becomes positively charged, and an electron surplus develops at the negative side, which becomes negatively charged. This electron flow continues until the potential difference between the two electrodes becomes equal to the battery voltage. This operation is known as capacitor charging. Because the opposite of an electron flow is current, there is a momentary current flow when the battery is connected to the capacitor.

If the battery is then removed and A and B are directly connected, the electrons flow immediately from the side with

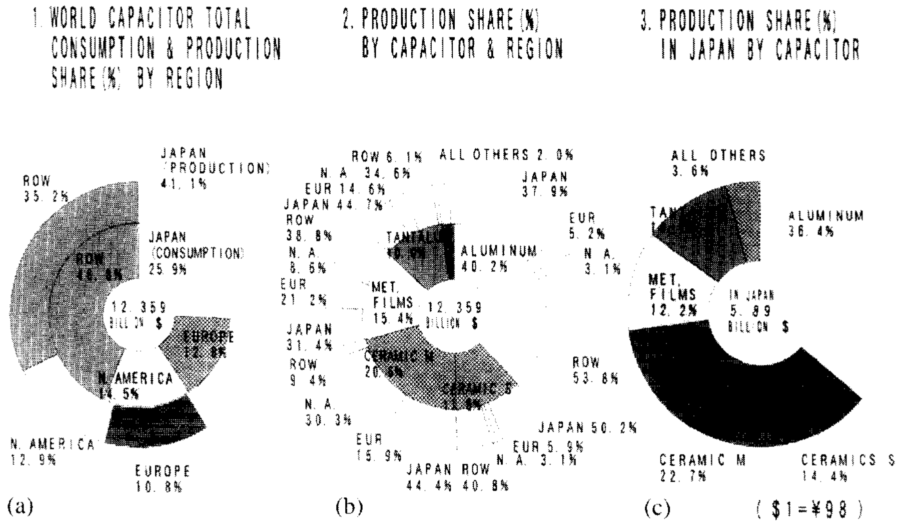

Fig. 4. Graphs Jan.–Dec. 1993: (a) world capacitor consumption and production share by region (%); (b) production share by capacitor and region (%), and (c) production share by capacitor in Japan (%).

an electron surplus to the side with an electron deficiency. This phenomenon is discharging.

3.2. Dielectric constants of various materials

To increase the electrostatic capacity of the capacitor, it is necessary to increase the surface area, S, of the counter-electrodes, decrease the gap, d, between the electrodes, or provide an insulator (dielectric) with a high dielectric constant, ϵ, between the electrodes.

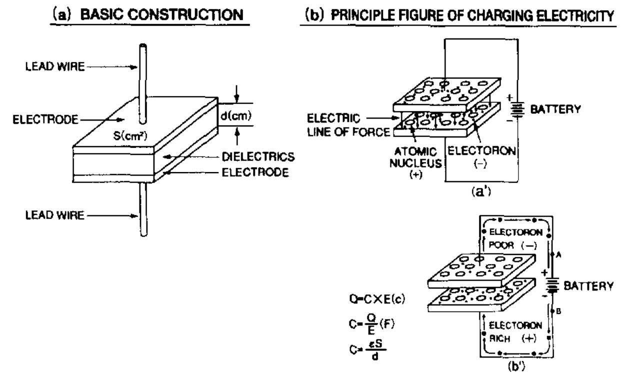

Fig. 5. Basic construction of the capacitor and its principal figure of charging electricity.

Various materials can be used as the dielectric in a capacitor, including air, mica, ceramic, plastic film, and various organic electrolytes. These non-air dielectrics offer a greater insulation than air, and provide greater electrostatic capacity. The dielectric constants of some typical dielectric materials are shown in Table 1.

3.3. Basic characteristics

Because of differences in the charge/discharge characteristics of various capacitors, different types of capacitors can be used to perform different functions in electrical circuits such as oscillation circuits, amplifier circuits, and smoothing circuits as shown in Fig. 6. These are described briefly below.

(i) *Oscillation circuits.* Fig. 6(a) shows an oscillation circuit. The capacitor, C, is charged through resistor, R, or discharged from C through R; the charge/discharge time determines the oscillation frequency.

(ii) *Amplifier circuits.* A coupling capacitor in an amplifier circuit is shown in Fig. 6(b). This capacitor does not pass direct current, and thus prevents mixing the d.c. bias currents on opposite sides of the capacitor. The charge/discharge operation of the capacitor passes only the required a.c. signal through to the downstream circuit.

Table 1
Specific dielectric constant of typical materials

Materials	Specific dielectric constant	Materials	Specific dielectric constant
Vacuum	1	Sulfur	2–4.2
Paper	1.2–2.6	Steatite porcelain	6–7
Paraffin	1.9–2.4	Aluminum porcelain	8–10
Polyethylene	2.2–2.4	Mica	5–7
Polystyrene	2.5–2.7	Insulated mineral oil	2.2–2.4
Ebonite	2–3.5	Aluminum oxide	9.3–11.5
Polyethylene tetraphtharate	3.1–3.2	Tantalum oxide	27.6
		Titanium oxide	16–100
Water	80	Barium titanate	> 10000

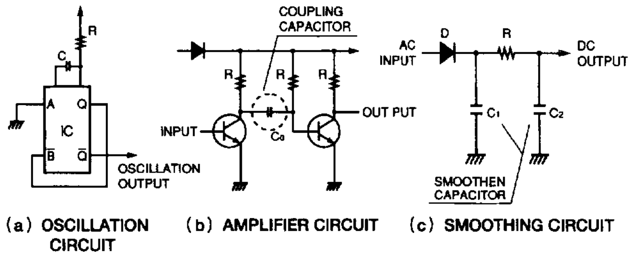

Fig. 6. Characteristic of capacitor on electric circuit.

(iii) *Smoothing circuits*: Fig. 6(c) shows a rectification circuit for extracting a d.c. flow from an a.c. supply. This circuit uses two capacitors C_1 and C_2 and a resistor R to extract a pure d.c. flow with minimal ripple; this operation is called smoothing. This operation produces a nearly flat d.c.output. It should be noted that the time constant, t, of the capacitor is another basic capacitor characteristic, but the discussion of this time constant t is technically more complex and beyond the scope of this article.

3.4. Dielectric loss of the capacitor (tan δ)

Dielectric loss of the capacitor tan δ includes both losses from leakage current and dielectric loss. Dielectric loss refers to the power loss resulting from the phase difference between the applied a.c. voltage and current. This is expressed as tan δ in capacitor catalogs and the literature. Table 2 shows the dielectric loss of some typical capacitor types. (Note that the smaller the tan δ rating, the higher is the usable frequency of the capacitor.) From Table 2 one may observe that styrene, mica, and ceramic capacitors can be used in high frequency applications, and aluminum electrolyte capacitors can only be used for low frequency applications.

4. Capacitor types and their major characteristics

Capacitors are available in a wide range of types, materials, structures, sizes, rated characteristics, loss (tan δ) ratings, and applications. Various capacitor types are shown and summarized in this section; a more detailed discussion can be found in the literature. Table 3 shows the type, specification, size, and loss (tan δ) of some typical capacitors. Table 4 shows selected capacitor types, structures (solid/liquid), and major applications. It is obvious from these Tables that no single capacitor can be used for all applications because of practical limits of the characteristics that can be obtained by different structures and materials.

Table 2
Dielectric loss of the capacitor [a]

Capacitor types	Dielectric loss (tan δ (%))
Paper	<1
Mica	<0.1
Milla	<1
Ceramic	Large at high frequency Small at low frequency
Al electrolytic	Use for only low frequency
Polystyrene	<0.05

[a] Dielectric loss of the capacitor: leak current, and dielectric loss.

For example, it is difficult to build small, precision capacitors with high capacitance, and it is also difficult to make high capacitance capacitors in a compact body with excellent frequency characteristics.

5. Recent technical trends in capacitor development

The most notable recent technical trend in new capacitors is the rapid growth in EDLC demand. For existing capacitors, the problems are: (i) increased demand for solid capacitors, and (ii) greater safety assurance. With respect to (i), there is strong demand for size reduction, higher reliability, and surface-mounting designs for even relatively high capacity electrolyte capacitors, and the trend is towards using solid electrolyte materials.

There is also a growing demand for enhanced safety of capacitor due to the pending implementation of the new Product Liability Law, July 1995. These technical trends are discussed separately: the trend towards solid electrolyte capacitors in Sections 6 and 7, EDLC in Section 8, and safety-related trends in Section 9.

Table 3
Typical kinds of the capacitor (capacitance = 0.1–1 μF, rated voltage, structure)

Capacitor types	Speculation	Dimension (mm)	tan δ
Paper	400 V, 0.1 μF	φ13.0×26.0	<1%
M.P.	250 V, 0.1 μF	φ8.0×25.0	<1%
Mica	100 V, 1 μF	12.0×10×6.0	<0.1%
Ceramic	50 V, 0.1 μF	5.0×4.5×3.5	<2.5%
Thin film	50 V, 0.01 μF	7.0×7.5×3.0	<1%
Al wet electrolyte	50 V, 1 μF	φ10.0×15	<2%
Ta wet electrolyte	50 V, 1 μF	φ9.5×27.0	<8%
Al solid electrolyte	25 V, 0.1 μF	φ4.0×6.8	<6%
Ta solid electrolyte	35 V, 10 μF	8.0×4.6×5.0	<6%
EDLC with organic electrolyte	5.5 V, 0.1 F	φ10.5×5.0	
EDLC with inorganic electrolyte	5.5 V, 0.1 F	φ16.5×14.0	

Table 4
Construction and application of capacitors

Capacitor type	Construction	Main application
Al electrolyte	Liquid	Electronics use
	Solid	High frequency circuit use
Ta electrolyte	Solid	Electronics use
	Liquid	Communication, telephone exchanger
Ceramic	Chip type	Electronics circuits use
	Surp. mout.	Electronics circuits use
Film	Low voltage use	Electronics use
		Noise limiter
		Electric power source
	High voltage use	Phase advancer (high and low voltage use)
EDLC	Small (coin)	Small back-up
	Middle (tube)	Back-up, actuater
Variable	Small type	Ceramic, film, air,
	Variable	Tuner, transmitter

In addition to the above characteristics, endurance characteristics at high temperature (capacitance and leakage current), and noise absorption characteristics are improved with solid capacitors, but a more detailed discussion of these characteristics is beyond the scope of this article.

6. Capacitors using a solid electrolyte

6.1. Outline of solid electrolytes

Of the various types of electrolytic capacitors, there are three types which use an electrolyte: aluminum electrolytic capacitors, tantalum electrolytic capacitors, and electric double-layer capacitors (hereafter abbreviated EDLC) [2,3]. Of these, there are two types of capacitor on the market which use a solid electrolyte: tantalum solid electrolytic capacitors which use manganese dioxide as the solid electrolyte naterial, and aluminum solid electrolytic capacitors which use 7,7,8,8-tetracyano-1,4-quinodimethane (TCNQ) or polypyrrole. The EDLCs on the market use mainly an organic or inorganic material for the electrolyte, and although solid electrolyte EDLCs have been reported [3] on the research level, none have as yet been practically applied.

6.1.1. Advantages of using a solid electrolyte

The advantages of using a solid electrolyte in an electrolyte capacitor are as follows:

(i) Because the electrolyte is solid, there is no chance of electrolyte leakage from the capacitor.

(ii) By using a solid electrolyte, improvements in the various characteristics of the capacitor can be expected, such as the temperature characteristics, frequency characteristics, electron spin resonance, tan δ, endurance characteristics, etc.

(iii) The heat resistance with respect to solder reflow (temperature such as 220–250 °C) during high-density mounting can be improved.

6.1.2. Disadvantages of using a solid electrolyte

It is extremely difficult to fill uniformly the interior of the tantalum or aluminum porous anode with the solid electrolyte material, or, when diffusing, to fill the solid electrolyte material so that there is no change in the properties of the solid electrolyte; therefore, when using a solid electrolyte, the capacity achievement rate is generally poor.

In general, solid electrolytes have ion conductivity and electron conductivity. Therefore, when using a solid electrolytic capacitor as an electronic component, it is necessary to select a solid electrolyte material having a high electronic conductivity with a high oxygen donor property to obtain low values of leak current and tan δ.

Solid electrolytes have poor productivity and high costs.

6.2. Tantalum solid electrolytic capacitors

6.2.1. Outline of tantalum solid capacitors

There are two types of tantalum electrolytic capacitors on the market: wet electrolytic capacitors which use sulfuric acid as the electrolyte and solid electrolytic capacitors which use MnO_2 as the solid electrolyte.

Up until 1970, the wet type was primarily used in circuits requiring a relatively high level of reliability, such as communication equipment and telephone switch boards. However, in recent years, with communication equipment consuming less power and being smaller in size as a result of the development of ICs, LSI chips and VSLI chips, it has become possible to ensure sufficient reliability and long life for solid electrolytic capacitors. Thus, most of today's tantalum electrolytic capacitors use a solid electrolyte. In addition, although sufficient research and development being done on solid electrolytic capacitors based on organic materials [4], because of the insufficient capacity achievement rate, this type of capacitor has yet to reach practical application.

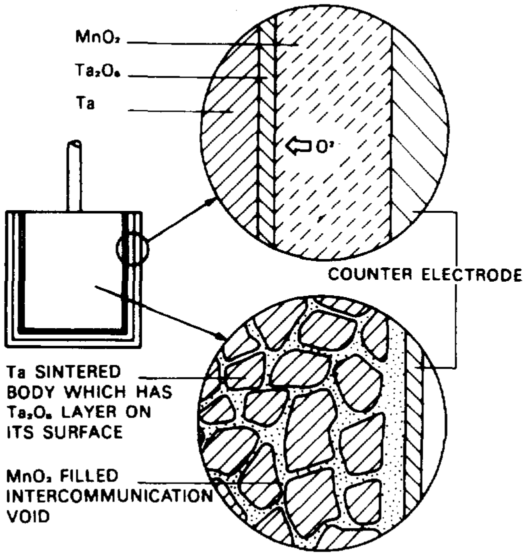

Fig. 7. Cross-sectional view of a tantalum solid electrolyte capacitor.

6.2.2. Construction of a tantalum solid electrolytic capacitor

Fig. 7 shows a cross-sectional view of the construction of a tantalum solid electrolytic capacitor [7–10]. Pure tantalum powder (size: 0.5 to 4 μm) with a capacity value of approximately 30 000 to 50 000 is primary-sintered into aggregate particles of 20 to 30 μm, and then secondary sintering is carried out using that powder after the desired shape is obtained. An anodic oxidation film of Ta_2O_5 is then uniformly formed on the surface of this sintered body. Next, as shown in Fig. 8, a solid electrolyte of MnO_2 is formed on this Ta_2O_5 dielectric film by pyrolysis. The condition of this pyrolysis-formed MnO_2 greatly affects the characteristics of the tantalum solid electrolytic capacitor [5–7].

6.2.3. Self-healing mechanism of tantalum solid electrolytic capacitors

Fig. 9 illustrates the self-heating mechanism of tantalum solid electrolytic capacitors [5,6]. If breakage of the Ta_2O_5 dielectric film of the tantalum capacitor occurs, the oxygen of the MnO_2 is utilized to repair the break in the film and the MnO_2 is reduced to Mn_2O_3, thus increasing the resistance.

6.2.4. Characteristics of tantalum solid electrolytic capacitors

The characteristics of typical tatalum solid electrolytic capacitors will be given in figures in Section 7.

6.3. Aluminum solid electrolytic capacitors

6.3.1. Outline of aluminum solid electrolytic capacitors

As shown in Fig. 1, the total worldwide production of aluminum electrolytic capacitors amounted to US$ 3.8 billion, 99% of which were of the wet type. Aluminum solid electrolytic capacitors still account for a share of less than 1%. Unlike tantalum solid electrolytic capacitors, organic solid electrolyte materials are used in aluminum solid electrolytic capacitors. Mainly, there are two types: (i) a functional polymer (polypyrrole, hereafter abbreviated as PPY) and (ii) an organic semiconductor (TCNQ salt).

The discussion will be focused primarily on PPY.

6.3.2. Construction of an aluminum solid electrolytic capacitor

Fig. 10 shows a diagram of the construction and an equivalent circuit of a typical aluminum solid electrolytic capacitor. The surface of the aluminum foil is etched and then oxidized in order to form a dielectric layer of Al_2O_3. Next, MnO_2 solid electrolyte material is formed on the surface of that dielectric layer, and on top of that a layer of PPY organic solid electrolyte material is formed by electrolytic synthesis. Following this, the positive and negative electrodes are mounted to complete the electronic component.

Fig. 11 shows the electrical conductivities of various types of electrolyte materials. From Fig. 11, it can be seen that the electrical conductivities on PPY, MnO_2, and the electrolytic solution commonly used for aluminum electrolytic capacitors are 100, 0.1, and 0.01 S/cm, respectively. This means that the electrical resistance of PPY is approximately 10 000 times lower than that of the electrolytic solution used for conventional aluminum electrolytic capacitors.

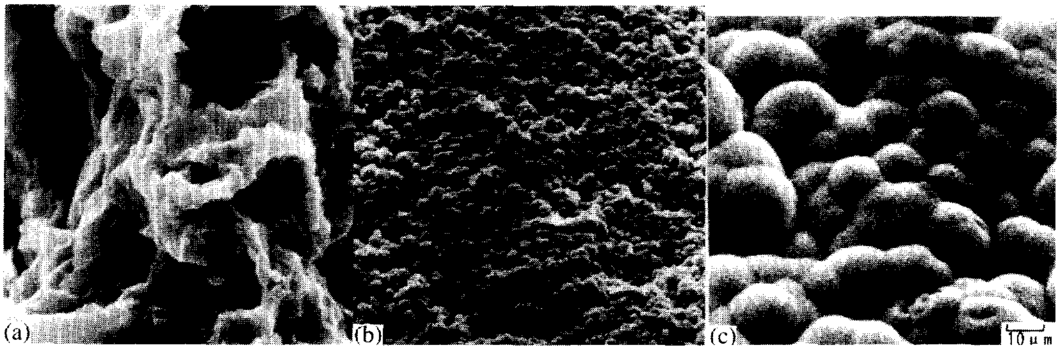

Fig. 8. MnO_2 solid electrolytes for tantalum capacitors: (a) MnO_2 made by conventional furnace pyrolysis, temperature: 320 °C; (b) MnO_2 made with a new radiational furnace, pyrolysis temperature: 220 °C, and (c) MnO_2 made by electrolysis with an $Mn(CH_3COO)_2$ solution, electrolysis temperature: 40 °C.

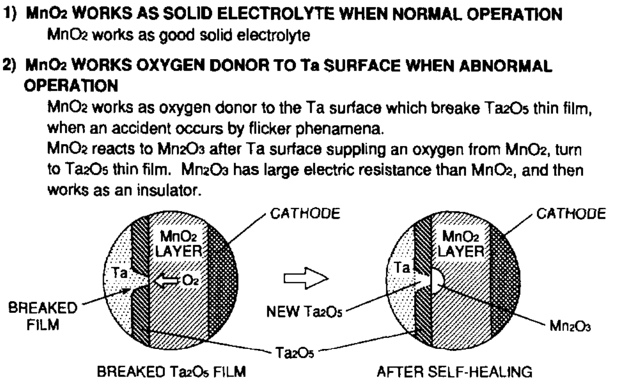

Fig. 9. Self-healing function of the tantalum solid capacitor.

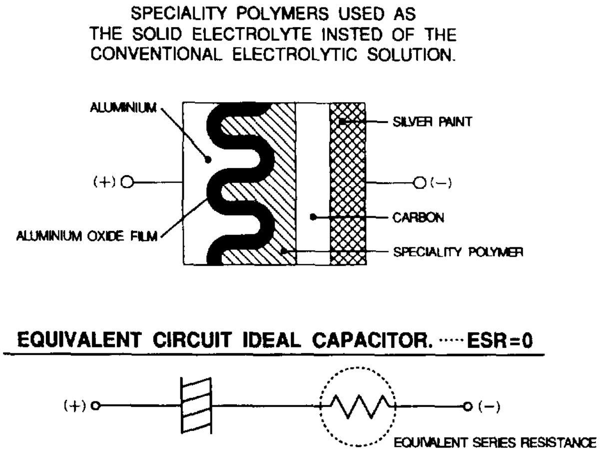

Fig. 10. Contraction of speciality polymer and capacitor.

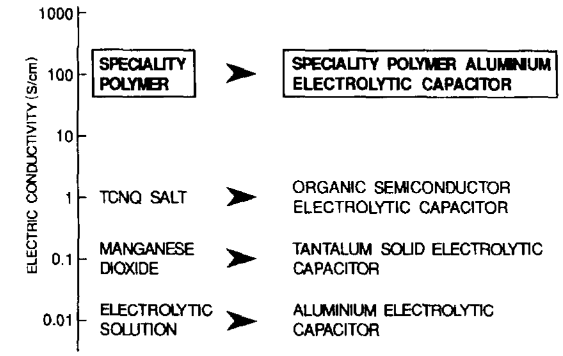

Fig. 11. Electric conductivities of various electrolyties.

7. Characteristics of aluminum solid electrolytic capacitors

In comparing them with other types of capacitors, for convenience, we will refer to aluminum solid electrolytic capacitors for which PPY is used as the solid electrolyte material as 'specialty polymer capacitors' (SP CAPs). Fig. 12 shows a photograph of the external appearance of an SP CAP. In order to improve the high-frequency characteristics, the SP CAP has four terminals. In addition to the compact size and large capacity which are characteristic features of electrolytic capacitors, SP CAPs have many other excellent features as well. These superior features are believed to be the result of the fact that the PPY thin film has an excellent electrical conductivity of 100 S/cm, and also of the fact that the PPY electrolyte layer is very thin, 40 μm. An explanation of the detailed characteristics of SP CAPs is given below.

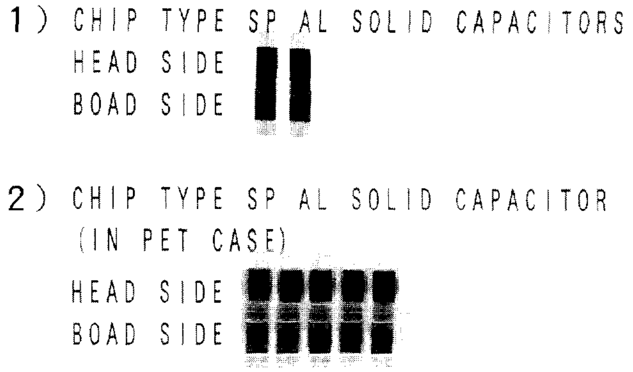

Fig. 12. Outlook of the speciality polymer solid capacitor (speciality polymer aluminum electrolytic capacitors).

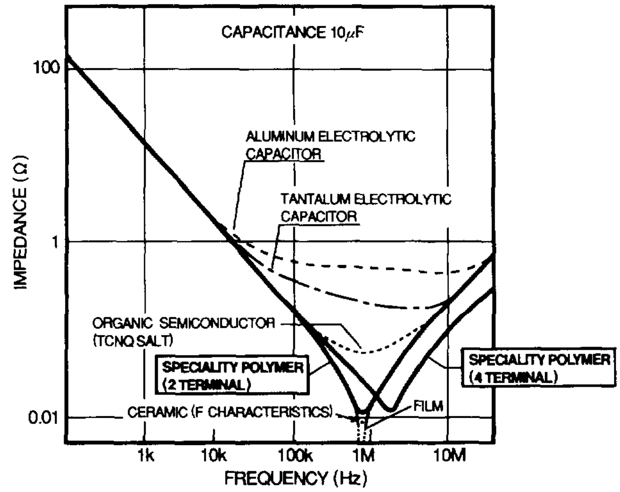

Fig. 13. Impedance–frequency characteristics.

Fig. 13 shows a comparison of the frequency characteristics of an SP CAP wiht those of other types of capacitors. Up until now, among large-capacity capacitors, ceramic capacitors were generally considered to exhibit the most ideal frequency characteristics. However, the frequency characteristics of a four-terminal type SP CAP exceed those of a ceramic capacitor. In particular, the impedance of an SP CAP in the high-frequency band range (at around 1 MHz) is less than 1/20 that of a conventional aluminum electrolytic capacitor. This means that it is possible to replace a conventional aluminum electrolytic capacitor with an SP CAP having less than 1/20 the capacity of the aluminum electrolytic capacitor.

Fig. 14 shows the temperature characteristics of the capacitance of various types of capacitors. The SP CAP exhibits stable capacitance–temperature characteristics. For comparison, the characteristics of a tantalum capacitor and an aluminum electrolytic capacitor using TCNQ salt have also been plotted. From this figure, it can be seen that both the tantalum and aluminum solid electrolytic capacitors exhibit a low temperature dependency and flat characteristics across a wide temeprature range of −50 to 150 °C. This is one of the most important features of solid electrolytic capacitors.

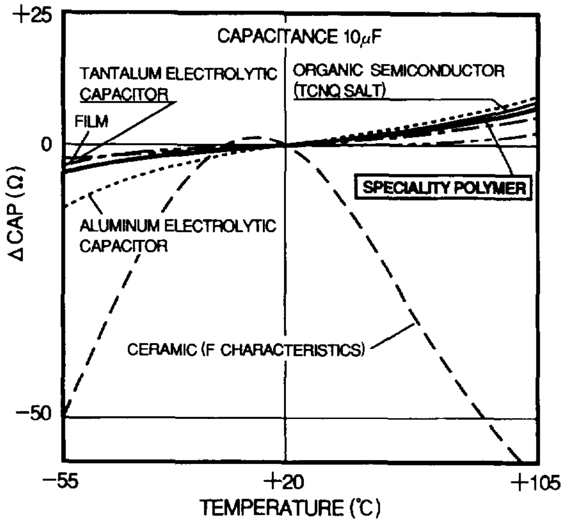

Fig. 14. Capacitance–temperature characteristics.

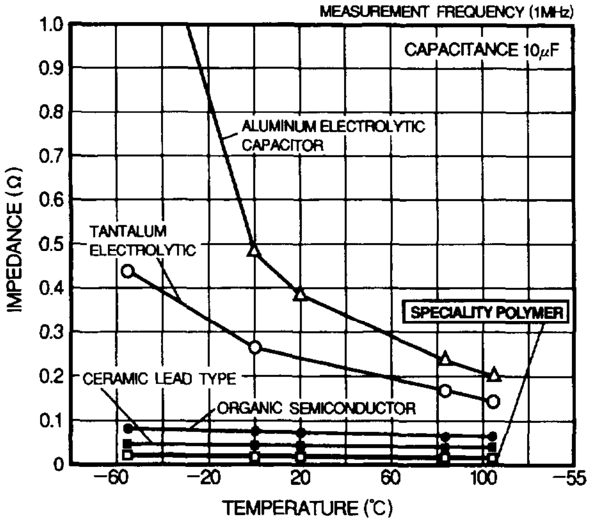

Fig. 15. Impedance–temperature characteristics.

Fig. 15 shows the temperature characteristics of the impedance of various types of capacitor. The SP CAP and the electrolytic capacitor using TCNQ organic semi-conductor both exhibit excellent characteristics similar to those of a ceramic capacitor.

8. Electric double-layer capacitors (EDLC)

EDLC is a new type of capacitor offering new features by means of characteristics between those of a battery and a simple capacitor [2,3]. After a ten-year-long 'infancy period' following the initial EDLC development, these capacitors have enjoyed more recently a greater market acceptance with sales reaching between ¥ 9–10 billion (data from 1994). We believe that EDLCs represent the next generation in capacitor design with the EDLC market expected to grow to ¥ 100 billion by the year 2000. The basic operating principle, structure, and applications for EDLCs are summarized in this article. For more information, please refer to related articles by Yoshida et al.

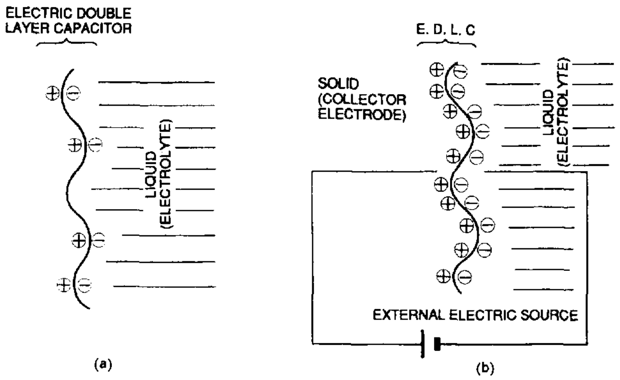

Fig. 16. Model of electric double-layer capacitor.

8.1. EDLC principle and structure

In general, positive and negative electrical charges are arrayed in counter position with an extremely short distance between both at the contact interface between two difference phases (e.g., solid electrode and liquid) (see Fig. 16(a)). This charge distribution layer is called the electric double layer. There are various explanations for this interfacial charge distribution. In the EDLC shown in Fig. 16, activated carbon powder and activated carbon fiber are used for the solid, and an organic electrolyte such as propylene carbonate or tetraethylammonium perchlorate is used as the liquid electrolyte.

Fig. 16(a) shows the electric double layer when there is contact between the activated carbon and the organic electrolyte, and Fig. 15(b) shows the state when an electric field is applied from an external source to this double layer. EDLCs are essentially non-polar, but the polarities are indicated for convenience. Fig. 17 illustrates the basic concept of EDLC operation. This capacitor is made from a pair of polarizable electrodes (activated carbon fiber cloth) and electrolyte solution. The capacitance, C, accumulated in the electric double layer formed at the interface between the polarizable electrodes and electrolyte solution is defined by Eq. (4):

$$C=[\int \varepsilon/(4\pi\sigma)]\mathrm{d}S \quad (4)$$

and the accumulated charge, Q, when an external field $\sigma=1$ is applied, is defined by Eq. (5):

$$Q=[\int \varepsilon/(4\pi\sigma)\mathrm{d}S](2\phi 1-\phi 0) \quad (5)$$

where ϵ is the dielectric constant of the electrolyte, σ the distance from the electrode interface to the center of the ion, S the surface area of the electrode interface, and $\phi=0$ is a normal number in mV.

A cross section of a coin-shaped EDLC is shown in Fig. 18(a), and a layer-built EDLC in Fig. 18(b). As described above, EDLCs are basically non-polar, and are formed by forming a plasma spray layer of aluminum as a collector layer on one side of the activated carbon fiber cloth, which is then impregnated with an electrolyte through a separator. The assembly is then sealed.

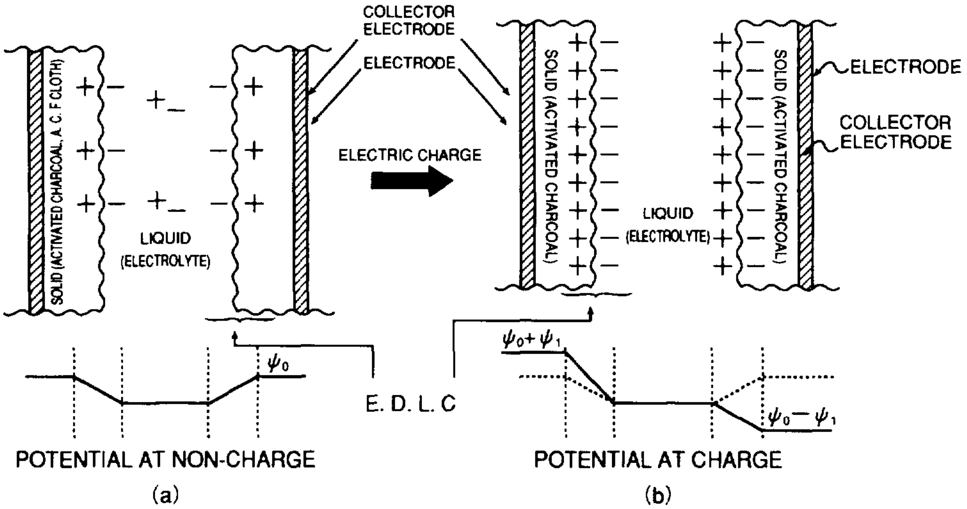

Fig. 17. Structure of electric double-layer capacitor.

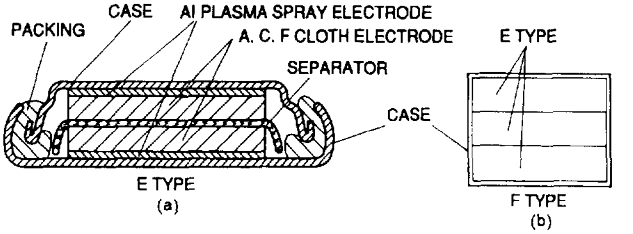

Fig. 18. Structure of E-type and F-type EDLC capacitors (polarizable electrode; phenolic ACF cloth + Al plasma spray).

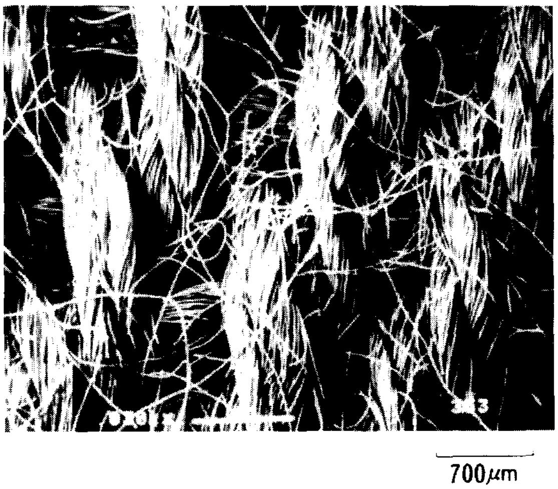

Fig. 19. SEM of the carbon fiber cloth made from phenol resin.

Fig. 19 is a scanning electron microscopy (SEM) image of the surface of the activate carbon cloth. Phenol fibers, each approximately 15 to 18 μm in diameter, are bundled in groups of 200 to 300, and then woven into a cloth. Various weaves, including plain weave, twilled weave, basket weave, and satin weave, and weights can be selected according to the application.

8.2. EDLC applications and future prospects

EDLCs are available in various electrical capacities and shapes for selection according to the intended application.

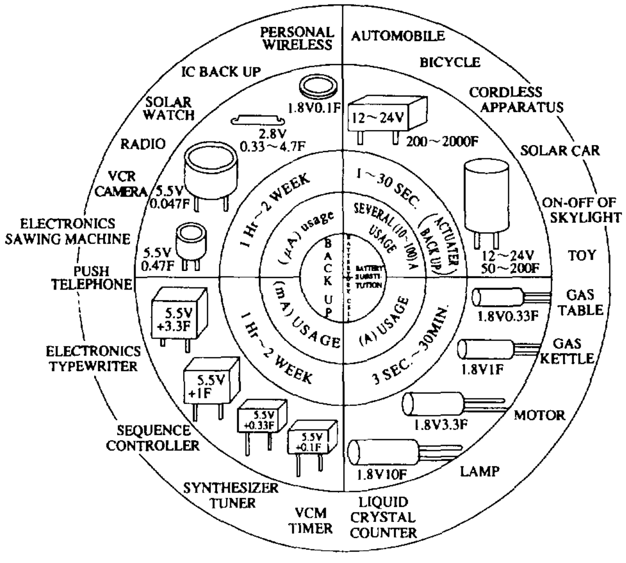

Fig. 20. Classification of EDLC usages.

Specific applications are described in some of the other articles in this issue. Some general applications and the future of EDLC are briefly described here.

Fig. 20 summarizes the types, capacities, and major applications for EDLCs. EDLCs with a capacitance of 300 F or less are already mass produced, but the mass production of 300–1500 F EDLCs is still in a pilot stage. Future demands for EDLCs is expected to be high, and research is now focused on proving their reliability, safety, durability, and service life characteristics.

Fig. 21 compares the discharge capacity of various EDLCs used with different types of battery. High capacity EDLCs will be the major focus of futur research.

EDLCs have superior instantaneous charge/discharge characteristics, a wider endurance temperature range than batteries, and a semi-permanent charge/discharge cycle life.

Disadvantages relative to batteries include a discharge capacity per unit volume that is 1/20 to 1/50 that of batteries. This gap is, however, closing rapidly. Research on improving

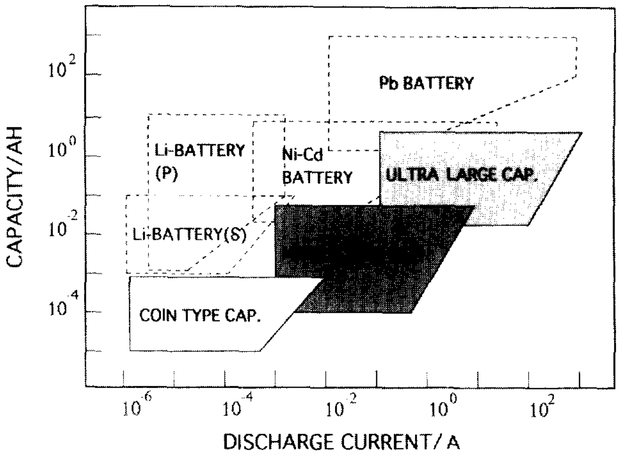

Fig. 21. Comparison of batteries with EDLCs.

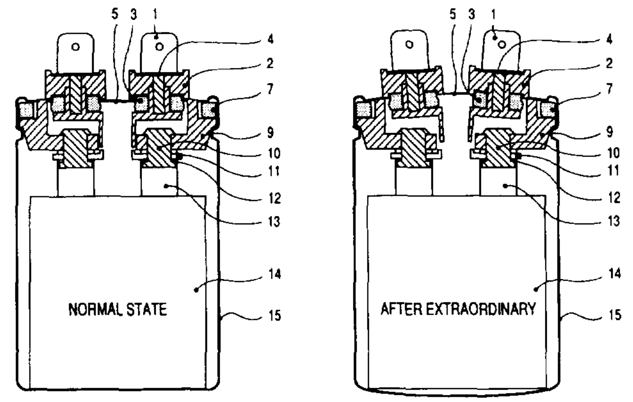

Fig. 22. Construction of aluminum liquid electrolytic capacitor with safety mechanisms.

the service life and reliability of batteries by using batteries and EDLC together is being pursued primarily in the USA and Japan.

9. Capacitor safety

As discussed in Section 2 above, capacitors are used in virtually all fields of industry, including consumer products, business machines, industrial inverters and other power electronic applications. Rapid progress in reducing capacitor size, weight, and impedance, improving high ripple current resistance, increasing service life, and improving other reliability and performance characteristics is also being made in each of these fields. Existing safety standards for capacitors include both JIS and IEC standards [11–13].

Growing social concern about the safety of electronic devices and manufacturer concerns about product liability have combined to improve capacitor safety. Some specific methods as applied to aluminum electrolyte capacitors, for which market the demand is greatest, are summarized below.

9.1. Capacitor breakdown mechanisms

Capacitor-related accidents can be traced to various factors, including abrasion from extended use, manufacturing defects, and abnormal operating conditions (excessive temperatures, excessive ripple currents, over-voltage, etc.).

When a ripple current (a.c. current) is applied to a capacitor, capacitor temperature rises according to the equation heat generated Q (W) $= IE \tan\delta$ where I is the current, E the voltage, and $\tan\delta$ is the tangent of loss angle. Towards the end of the normal service life, $\tan\delta$ increases, and the balance between the heat generated and the heat emitted is disrupted. This leads to an abnormal temperature rise, which induces a further increase in $\tan\delta$ and a chain reaction ensues.

As a result of this phenomenon, the vapor pressure of the electrolyte solution rises, decomposition gases are emitted, the pressure of the decomposition gas inside the case increases, the pressure relief valve operates, and the electrolyte converted to high temperature vapor is rapidly released. If other adverse conditions happen to occur at the same time, further secondary damage can occur. This can be prevented by various means, two of which are described below.

9.2. Structure of a safety mechanism

Fig. 22 shows a cross section of an aluminum electrolyte capacitor with a safety mechanism. When the internal pressure of the capacitor rises, the aluminum cover [5] deforms, and tensile stress works on the aluminum tab [11] comprising a weak member provided between the top cover [4] and fixed plate [9]. This aluminum tab ruptures when the internal pressure exceeds a predetermined threshold, and the capacitor becomes electrically open.

9.3. Characteristics in forced operation tests

Fig. 23 shows the forced breakdown test method, and the difference in product characteristics resulting from the presence or absence of a capacitor safety mechanism.

Capacitors provided with this safety mechanism do not emit smoke or do not burn even under abnormal conditions, thus preventing secondary damage to peripheral equipment, and thereby assuring the safety of the capacitor.

In tantalum solid electrolyte capacitors with safety mechanism, a fuse is built in the capacitor as a safety device, and when abnormal conditions develop, the fuse will blow.

10. Future outlook for capacitors

10.1. Tantalum soild electrolytic capacitors

Improvement of material characteristics means:

(i) higher levels of performance achieved through lighter weights and smaller sizes to accommodate high-density mounting;

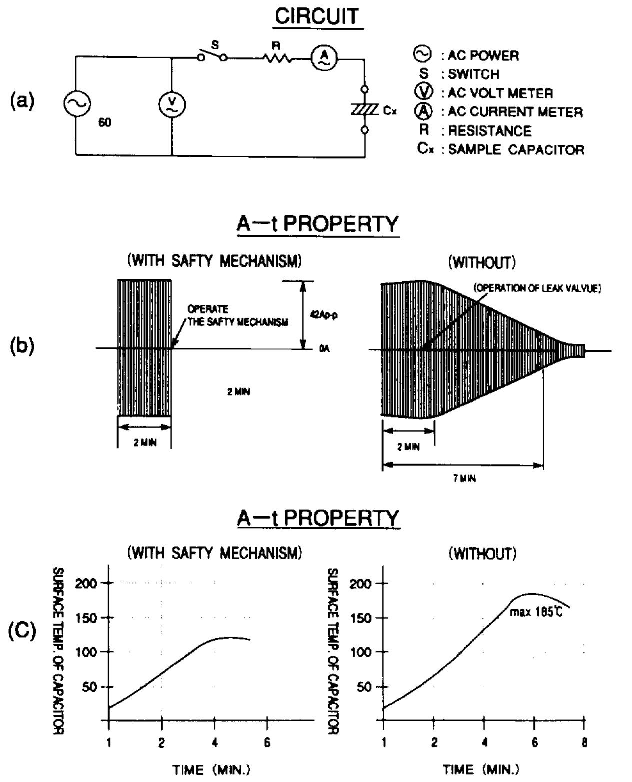

Fig. 23. Test method for compulsory destruction of an aluminum electrolytic capacitor: (a) circuit of test method: (b) effect of the safety mechanism (with/without, current–time), and (c) surface temperature of capacitor (with/without).

(ii) improvement of the capacity value of tantalum powder (current value: 30 000 to 50 000; future values: 50 000 to 90 000), and

(iii) higher purity of the tantalum powder (improvement of the leakage current characteristics, and of the characteristics to withstand high temperatures and high humidity).

Improvement of various other characteristics leads to:

(i) safety and prevention of obstacles (open mechanism for the insertion of fuses, etc.);

(ii) lower ESR (lower ESR achieved through the development of new electrolyte materials, etc., and the improvement of materials engineering technology), and

(iii) improvement of the percentage of chip-type capacitors (current: 68%; future (by the year 2000): 85 to 90%).

10.2. Aluminum solid electrolytic capacitors

Improvement of material characteristics involves:

(i) development of new materials superior to TCNQ and PPY;

(ii) improvement of the characteristics of organic solid electrolyte materials (improvement of the stability, fluidity, viscosity, etc., at the processing temperatures), and

(iii) lower costs.

Improvement of various other characteristics leads to:

(i) development of an aluminum foil suitable for organic solid capacitors;

(ii) improvement of the capacity achievement rate when using an organic solid electrolyte material, and

(iii) thermostability during mounting in order to accumulate smaller sizes and lighter weights.

11. Conclusions

Recent capacitor market trends, capacitor principles, and major capacitor functions have been discussed. The primary technical trend in the development of capacitors is towards solid electrolyte capacitors, the major characteristics of which were discussed. The basic structure, characteristics of, and application in new EDLCs (electric double-layer capacitors) were given. Selected technical problems and future prospects for major capacitor grades are summarized.

As mentioned in this paper many technology analysts once questioned the future of the capacitor market with the development of IC and LSI devices, but the latter development actually leads to a rapid improvement in reducing capacitor size and weight while improving the capacitor performance, characteristics, and functionality. The result has been a solid growth in the capacitor market as evidenced even by the most recent market statistics.

Improvement in the capacitor characteristics have also greatly expanded the range of potential capacitor applications to include home appliances and consumer electronics (A/V), as well as the automotive industry, space industry, and industrial machinery and equipment.

The development of new functional materials and processing methods is expected to continue meeting these changing demands. By balancing supply and demand, we believe the capacitor market will continue to expand in the years to come.

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