Capacitors and Passive Components for Modern Electronics

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Tomáš Zedníček, Ph.D.

EPCI, European Passive Components Institute
T.G.Masaryka 477, 563 01 Lanškroun, Czech Republic
e-mail: tom@passive-components.eu

INTRODUCTION

The passive component technology has been often considered as the "easy and not so important" part of the electronic circuits while the main attention is paid to the development of active components and integrated circuits. The development of passives was mostly left in hands of industrial profit oriented companies with limited chance to heavily invest in an expensive fundamental research. Nevertheless, the complexity of passive component technologies is not trivial as it can be seen on the first moment. Features of capacitors, as the case study example, is often dependent to interfaces between the conductive metal electrodes and insulating dielectric layers. The junction, often consisting of metal sub-oxide layers with semiconducting properties, may however play a key role in the capacitor characteristic behaviour. The paper provides an overview and trends on passive component industry and specifically capacitor technologies.

PASSIVE COMPONENTS INDUSTRY

Passive Components Evolution Background

Passive components are often considered by design engineers as "the simple & easy" parts of the circuits and the main attention has been paid towards the active components. In many ways this view is persistent for a whole passive component industry perception since the discovery of transistor in 50th of last century. The leading R&Ds, academia and laboratories worldwide has been focused on fundamental research projects for strategically important active components under a strong financial support from governments and public sources. In consequence, the "simple & cheap" passive components were "left behind" for a development mostly driven by the passive component manufacturers. It has not been financially viable for passive component manufacturers to continue investing in the fundamental research with deeper exploration of new materials, processes and mechanisms knowledge. Thus the **development and continuous improvement within the passive components industry has been practically performed by the individual private companies based on an applied experimental research with pragmatic goals to "resolve technical issue" or to develop something for a secured market with confidence in investment return.** The increasing cost pressure since 90th of the last century together with the fact that a significant cost portion for many passive components has been the labour cost, caused a move of many passive component manufacturing plants outside of Europe (and USA) to cheaper labour countries. Passive components, based on its nature, have been in many ways the "first pioneers" within the electronic industry for the cost saving driven re-location of high volume manufacturing elsewhere.

The situation with perception of passive component industry, particularly in Europe, has improved in past few years per my subjective view. The active component knowledge "counting single electrons" is on such a high technology and knowledge level, that any further small upgrade is taking a lot of effort and investment. However, looking at the PCBs, passive components still occupy more than 70% of the board space. This makes passive components as the "hot target" for the next generation step up upgrade in miniaturisation of electronics. We have already seen some latest practical results to adopt active components technology to create a new generation of nano-scale passive components such as for example 3D silicon capacitors or CMOS IO technology based nano-supercapacitors achieving very promising capacitance volumetric densities bringing new features to wide range of possible applications.

Space Components Market

One of the example of currently fast changing industry is space component market. According to [1], the space-based passive components represents only a minor subset of the $1.6 billion global specialty passive components market but there is an explosive growth in the space commercial sector and continued rapid growth in the government sector. This is a result of commercialisation of space industry in agency driven programs for private (non-government) subjects, low cost study missions (CubeSat, NanoSat …) as well as by the activities from the new private space companies' focused primarily on the space exploration commercial aspects (SpaceX, Virgin Galactic, Boeing …). The value of worldwide government spending on space-based electronics increased from $27.6 billion U.S. dollars to $79.2 billion by 176% in past ten years, making it one of the fastest growing electronics segments in the World. The value of demand from the commercial sector for space-based electronics between 2005 and 2015 has grown substantially. The commercial market for space-based electronics, which did not exist in 2005, is now at least as large as the government market.

CAPACITOR TECHNOLOGIES

It is hardly to find any other component devices that would be capable to offer such wide parameter range as the capacitance value available by various capacitor technologies. The capacitors available on market are covering 17! Ranges of capacitance value from 0.1 pF to 10^{th} of kF. The forms of practical capacitors vary widely, usually it contains two conductive electrodes (plates) separated by an insulating dielectric layer. The conducting electrodes can be in the form of thin films, foils or sintered beads of metal connected to the dielectric directly or through a conductive electrolyte.

Capacitors can be split into **fixed capacitors** with a stable capacitance and **variable capacitors** with adjustable capacitance value. The fixed capacitors can be then divided into **non-polarized** and **polarized** types – see Figure 2.

The non-polarised capacitors are based on a direct interaction between the conducting electrodes and dielectric without other connection media and thus they are also called as **electrostatic capacitors**. Materials commonly used as dielectrics for electrostatic capacitors include ceramic, plastic film, air, vacuum, paper, glass, mica, or silicon oxide layers.

The two basic types of polarised capacitors are **electrolytic capacitors** and **supercapacitors**. Electrolytic capacitors are using thin metal oxides as the dielectric to obtain maximum capacitance values. The thin oxide is formed with fine, high surface structure on one electrode (anode) and the other electrode (cathode) is connected using a conductive media – electrolyte (in form of a liquid, gel or solid phase). Such structure, on the other hand, can however operate in one direction only and the capacitors are polarised devices with marked plus and minus leads for correct connection to the circuit. The highest capacitance value components currently on the market are supercapacitors. There is no classical solid dielectric layer inside the capacitor and the capacitance value is achieved by a electrochemical charge separation and transfer in thin layers around the electrodes. The behaviour is closer to batteries with basic cell voltage (2.3-2.7V) – it means low rated voltage capacitors that has to be combined in series to achieve higher voltage ratings.

Globally, the market for fixed capacitors was estimated at approximately US$21 billion in 2015. Ceramic capacitors are dominating the market with about 47% market value share followed by electrolytic capacitors – see Figure 1. for estimated sales value share percentage. Ceramic capacitors are also representing lower ASP, small size, high volume capacitor portfolio, just their sales domination by units is even higher and it may be close to 80% of unit market share.

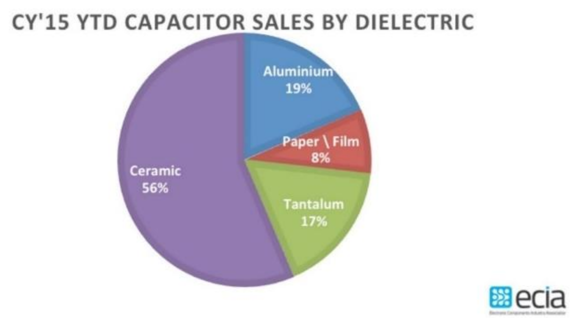

Figure 1. Capacitor sales % by dielectric in 2015, source: ECIA

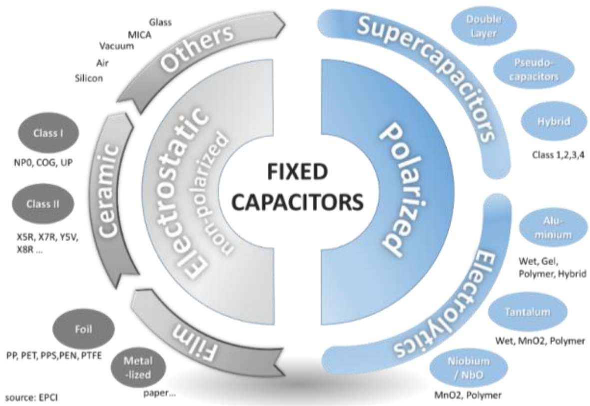

Figure 2. fixed capacitors,% are indicating market share value in 2015. source EPCI, ECI

High CV capacitor strategy

High capacitance in small dimensions and low profiles has been the goal for many applications requiring continuous downsizing for miniaturisation of electronic devices. There are different design strategies among the capacitor technologies in order to obtain the highest capacitance volumetric density. The capacitance value in accordance to equation in Fig. 3. is directly proportional to the material constant ε, surface of electrodes and indirectly proportional to the thickness of dielectric. Thus to achieve maximum capacitance, the capacitor needs to have an insulating material with high dielectric constant on electrodes with very high surface area and a very thin dielectric (high electrical strength of insulating material). See Figure 3.

Electrostatic capacitors are based on thin plane electrodes where high CV is achieved by development of materials with very high permittivity – dielectric constant. This is a typical example of ceramic capacitors where permittivity is in range of thousands and higher. Electrolytic capacitors on the other hand are achieving high capacitance values by creating of fine, high surface area on electrodes, mostly by foil etching (aluminium) or by sintered metal powder technologies (tantalum). Electrochemical capacitors typically store 10 to 100 times more energy per unit volume or mass than electrolytic capacitors. They are achieving such high capacitance due to the electrochemical charge potential that is created in very thin layer (couple of Angstroms, 0.3-0.8 nm).

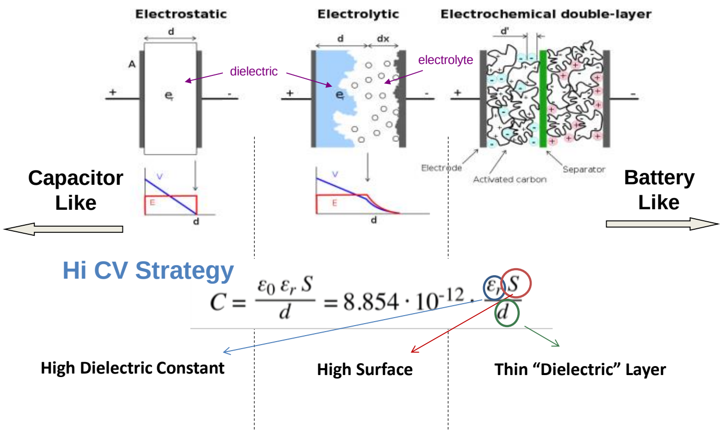

Figure 3. capacitor structures and high CV strategy, source EPCI

Capacitance versus Voltage

It is not only the high capacitance CV value that is of importance, but also what are the operating conditions, especially the working voltage that can be applied to the capacitors. Higher working voltages require thicker dielectric layers that flatten the surface of electrodes and thus limits the use of fine, high surface area of electrolytic capacitors to lower voltages compare to electrostatic capacitors. The electrochemical charge used by supercapacitors has it's defined electrochemical potential – cell voltage - like the batteries and it may lose its efficiency in higher voltage applications as well. High potential variability of dielectric material thickness on electrostatic capacitors is making them the best fit for very high voltage applications, thus film and ceramic capacitors are the most commonly used technologies there. Capacitance versus Voltage charts can be seen in Figure 4. The chart expresses the typical application range of the capacitor technologies, of course, capacitors can be connected in series or parallel to modules in order to increase rated voltage or capacitance. This is especially true in the case of supercapacitors with its" cell voltage" 1.3 to 2.7V and all voltage ratings above are modules made from balanced capacitors connected in series.

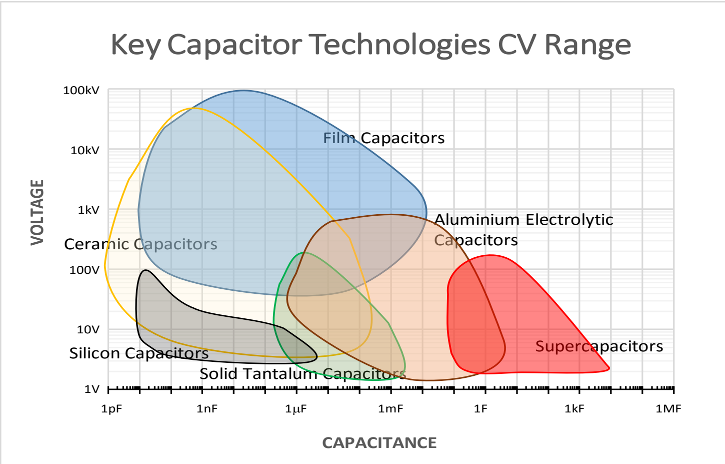

Figure 4. Key capacitor technology Capacitance versus Voltage range, source: EPCI 2016

Supercapacitors store a large amount of charge, nevertheless batteries in general will still have 10 to 30 times the energy storage of supercapacitors of comparable masses. Despite the annual new records of storage energy heights, so far the battle between the supercapacitors and other energy sources have been the" shooting on moving target " as the innovation of other energy sources are also moving well ahead.

The maximum micro-farad per mm^3 value dependency to rated voltage chart is shown at Figure 5. sourced from EPCI search in summer 2016. The chart is illustrating the maximum capacitance volumetric efficiency per rated voltage for the key capacitor technologies.

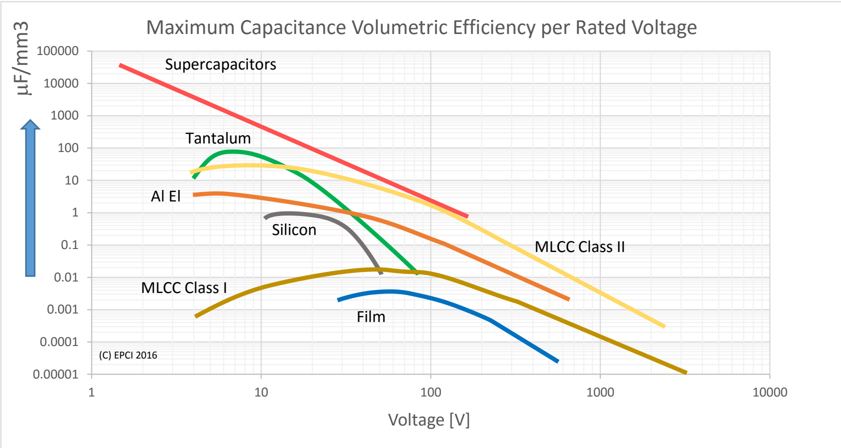

Figure 5. Capacitance volumetric efficiency for key capacitor technologies, source: EPCI 2016

Capacitor Application Trends

<u>DC/DC switching converters</u>

The number one capacitor application usage is smoothing and stabilization of output voltages in wide range of switching power supplies. The selection of a suitable output capacitor plays an important part in the design of switching voltage converters. "Some 99 percent of so-called 'design' problems associated with linear and switching regulators can be traced directly to the improper use of capacitors", states the National Semiconductor IC Power Handbook (Ref.2). The importance of the output capacitor in switching DC/DC converters is related to the fact that it is (together with the main inductor) the reservoir of electric energy flowing to the output and it smooth the output voltage. Today, one can hardly find a consumer, industrial or high reliability electronic device that does not make use of a voltage regulator. Designers basically use two types of regulators, linear LDO (low dropout) and step-down switch-mode DC/DC regulators to convert voltage to lower level. Switching DC/DC regulators are preferred for applications that require a greater difference between input and output voltages because they are more efficient. This switching regulator option has been selected for our experimental measurements as it is the most commonly used approach in today's power supply circuits. See Fig.6 for overview of the various types of switching power supplies.

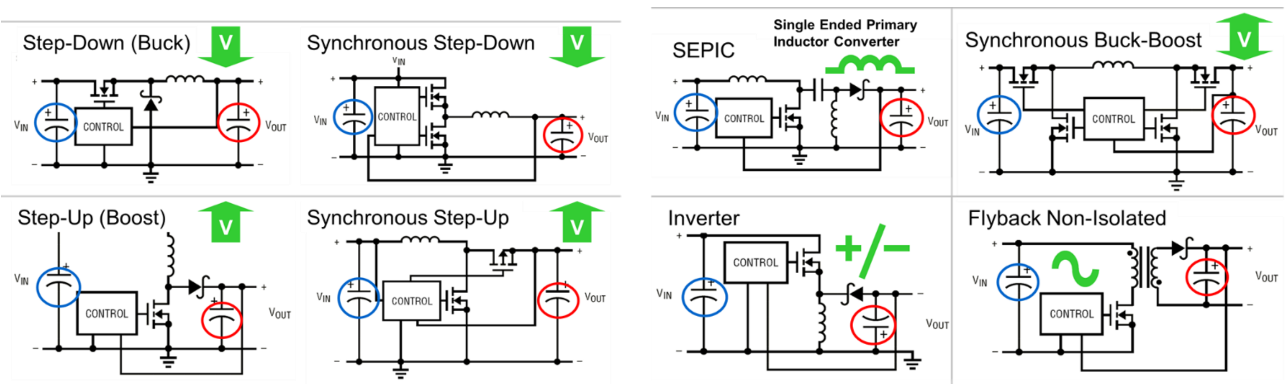

Fig.6. Switching power supply types overview (source: AVX technical paper [3])

The common capacitor selection criteria for the switching power supplies are depending on the following key parameters:

- local character and sink value
- storage inductor value
- converter switching frequency
- ESR and ripple demands (achievable by single or more caps in parallel)

The continuous trend in modern design architecture of DC/DC converter ICs is to provide better stability, resistance against oscillations, higher power output together with smaller & thinner packaging and low cost. Thus the demand for capacitor parameters is including:

- Low ESR, High Ripple Current
- Low ESL, Higher Frequency
- Lower Capacitance Needed
- Small & Low Profile
- Low Cost
- Effective switching fr. 250kHz – 2Mh

The continuous improvement is leading to changes in the prime output capacitor technology selection guide. The original high capacitance tantalum or aluminium capacitors are replaced by lower capacitance, lower ESR polymer aluminium, MLCC ceramics class II and even the latest ICs architectures are using low capacitance values of MLCC class I or 3D silicon capacitors. Completely capacitor-less switching DC/DC converter IC architectures has been recently released to the market.

<u>LDO Low Drop Out Regulators</u>

There are three functions of a capacitor connected to an output of LDO:

- Local electrical energy reserve
- RF noise coupling to ground
- Feedback stability factor for LDO

Simplified structure of LDO with external input/output capacitor and feedback resistors is shown in Figure 7.

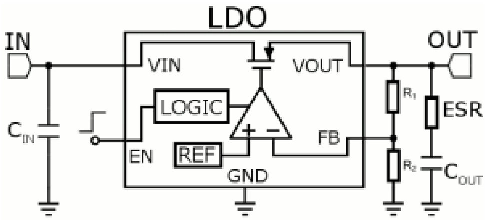

Figure 7. : Simplified LDO and typical external components

It is commonly known that output capacitor influences the gain & phase margin of the LDO loop and thus stability of the LDO. The output capacitance and ESR value with a connected load and its parameters are of the critical importance for the LDO operation.

The capacitor's ESR was the main limitation especially in the case of older LDO circuits where too low ESR of MLCC capacitors could not be used with LDO. The new LDO generation has improved dramatically stability of the loops and it can be said that even MLCC capacitors can be used with LDO now – see Figure 8. Nevertheless, it is of importance to check the LDO datasheet for the defined capacitor's ESR working range. It has to be also noted that the ESR stable operation range has to maintained under all environment conditions – it means to count with its stability with temperature, moisture etc.

The older LDO generation was using tantalum output capacitors that provided ideal ESR window including its stability with temperature. The cost down pressure to replace tantalum capacitors to cheaper MLCCs resulted in development of the newer generation of LDOs capable to operate with significantly lower ESR values.

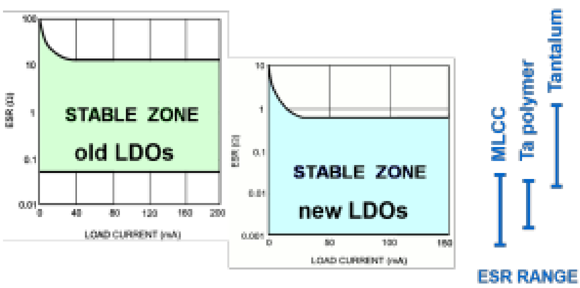

Fig.8. ESR stability window comparison between the older and newer LDO generation.

Nevertheless, the latest generation of LDOs recently introduced to the market in 2016 is bringing a completely new capacitor-less architecture eliminating the needs of output capacitors completely.

GaN transistor revolution

The upcoming revolution in DC/DC converter application may be present by advancement in GaN transistor technology. The GaN technology has presented a niche market until recently when new designs outperforming MOS systems has been introduced to the market.

The GaN transistor design features (latest specification example):

- high efficiency ~ 96%
- higher switching frequency up to 40Mhz
- higher power in smaller / thinner design
- from low to high voltages: 650-1200V (needed by EV)

Example ratings:

- 5mm x 6mm x 0.9mm package that can deliver 70-A load at up to 5.5V output and efficiency better than 95 %
- 60A continuous load capability within just a 0.5mm maximum thickness and efficiency close to 99%

The development and introduction of the GaN technology is further accelerating the capacitor requirement trends seen on the MOS. The efficient switching frequencies up to 40MHz compare to 2MHz in the case of MOS technology may completely eliminate the use of electrolytic capacitors on the output, replacing it with MLCC Class I or silicon capacitors.

SUMMARY

Passive components today are still representing majority of discrete components on the board. Capacitors are many times the critical components connected across the power rail and its reliability has a key influence on the whole system functionality. The wide range of available capacitor technologies covering 17 ranges of capacitance values are bringing unique solutions to various type of diverse applications. The general trends in key applications are lower ESR, lower ESL, higher frequencies but also capacitor-less IO architectures. On the other hand, new capacitor technologies such as 3D silicon or supercapacitors are enabling further passive component growth in electronic devices.

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