SMD FILM CAPACITORS FOR INTEGRATING A/D CONVERTERS

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Key words: integrating A/D converter, SMD film capacitor, dielectric absorption, humidity, surface resistance, polymer dielectric

Abstract: Lead free technology has significantly influenced the choice of commercially available capacitors, especially those intended for surface mount. A case study of the appropriate SMD capacitor selection for a high accuracy integrating A/D converter is presented. The converter is part of a smart sensor that encompasses a simple microcontroller and an analog transducer, which is in this case a platinum resistor. An overview of traditional and new polymer dielectric materials is given with the emphasis on the commercial selection of SMD capacitors. Trends of the film capacitor industry in the recent years are explained through the physical properties of the materials used and the imposed legislative restrictions. The often overlooked pitfalls of capacitor selection are sequentially described. The effect of the dielectric absorption of the charge on the conversion error is theoretically analyzed for the intermittent mode of operation. Inaccuracy due to the recovery of the absorbed charge is eliminated by the use of a polyphenylene sulfide (PPS) film capacitor; however, at high humidity some capacitive sensors exhibit abnormal deviations.

Based on some additional experiments, we determine the influence of the capacitor's parallel resistance on the conversion result. The synergic impact of high humidity and temperatures, and flux residues on the surface resistance of stacked capacitors is proven by experimental measurements carried out in a climatic chamber. The experimental measurements of SMD capacitor insulation resistance show that naked stacked capacitor construction is not suitable for a relative humidity above 80%. In such cases, slightly larger encapsulated SMD capacitors must be used to maintain the desired high accuracy.

SMD filmski kondenzatorji za integracijske A/D pretvornike

Kjučne besede: integracijski A/D pretvornik, folijski SMD kondenzator, dielektrična absorpcija, površinska upornost, polimerni dielektrik

Izvleček: Prepoved uporabe svinca v tehnologiji izdelave tiskanih vezij je pomembno vplivala na tržno ponudbo kondenzatorjev, namenjenih za površinsko montažo. V prispevku je podan potek izbire ustreznega kondenzatorja za integracijski A/D pretvornik z visoko ločljivostjo. Sam D/A pretvornik je del inteligentnega senzorja, ki ga sestavlja mikrokrmilnik in ustrezen analogni merilni pretvornik, v opisanem primeru je to platinski upor. V delu je najprej podan pregled polimernih dielektrikov s poudarkom na njihovi rabi za SMD komponente. Trendi zadnjih let v industriji kondenzatorjev za elektroniko, so opisani s stališča fizikalnih lastnosti dielektričnih filmov in prepovedi rabe svinca v elektronskih napravah. Spregledane pomanjkljivosti izbranega tipa, so podane zaporedno, kot so se pojavljale pri razvoju. Izpeljali smo analitično zvezo med dielektrično absorpcijo kondenzatorja in pogreškom posamične pretvorbe. Merilno napako zaradi sproščanja absorbiranega naboja v času pretvorbe, smo odpravili z uporabo polifenil sulfidnega (PPS) kondenzatorja.

Z eksperimenti v klimatski komori smo ugotovili, da imajo nekatera vezja nenormalno velika odstopanja, ki nastanejo zaradi vpliva vlage na gole PPS kondenzatorje. Izpeljali smo analitično zvezo med velikostjo skupne upornosti med sponkama kondenzatorja in merilno napako. Ugotovili smo sinergični vpliv vlage, temperature in ostankov fluksa na površinsko upornost nezaščitenih kondenzatorjev, ki so izdelani z zlaganjem metaliziranega filma. Meritve izolacijske upornosti so pokazale, da takšni kondenzatorji niso primerni za vlažnosti zraka nad 80 %. Za precizni integrator so primernejši dimenzijsko nekoliko večji SMD kondenzatorji v plastičnem ohišju.

1. Introduction

Electronic integrators offer a simple solution for achieving an accurate A/D conversion of low voltage levels whenever the speed of conversion doesn't play a significant role. Dual slope integrating A/D converters can be implemented by low cost digital microcontroller and a simple additional analog circuit. Such A/D converters can be used for accurate conversion voltages that are proportional to slowly varying physical quantities like temperature or atmospheric humidity.

Conversion errors due to the non-idealities of the analog components, i.e., the input offset voltage of the operational amplifier (opamp), are minimized by a simple solution, so that low-cost analog components can be used. The choice of utilized capacitor seems unimportant since the value of capacitance does not appear in the conversion equations at all /1/. Such an approach is over-simplified but this fact does not become obvious until experimental measurements of prototypes under various climatic conditions are performed. The physical dimensions of electronic circuits are steadily decreasing, which is a consequence of the growing demand for hand-held devices. The introduction of surface-mount technology (SMT), which became widely used around the year 1990, engendered important changes in the field of high performance metallized film capacitors. The small size of SMD capacitors has raised many problems in their construction, because of the intense heat transfer from the metallized soldering pads to the plastic dielectric film during the reflow soldering process.

The first widely used SMD capacitors were multilayer ceramic chips (MLCC). This construction and the high relative dielectric constant of the ceramics result in such capacitors having a high capacitance packing density and relatively low equivalent serial resistance (ESR). The inorganic nature of the dielectric used in MLCCs minimizes the impact of the thermal stress during soldering. Polymer film capacitors are much more affected by the raised temperature levels because of the thermoplastic nature of the dielectric film. The choice of SMD polymer film capacitors on the electronic components market is predominated by trough-hole film types and by ceramic SMD chips. As a consequence, film capacitors are rather expensive, therefore cheaper alternatives are used wherever it is possible.

In the next chapter an overview of the important polymer dielectric materials is given, followed by a case study of the capacitor selection for an integrating A/D converter. Finally, the results of practical experiments are presented. The comments on the outcomes and some practical hints for the selection of appropriate SMD polymer film capacitors conclude the paper.

2. Materials for film capacitors

The traditionally used plastic materials for dielectric films in capacitors are polystyrene (PS), polyester (PE), polycarbonate (PC) and polypropylene (PP). These materials are used for film capacitors with low loss and stable capacitance in the range from 1 nF up to 10 µF. Film capacitors below 1 nF are offered only by a small number of producers; and especially SMD types are very rare. The range of capacitances below 100 pF is almost exclusively covered by C0G ceramic capacitors (Table 2), which are featured with a low capacitance temperature coefficient α_C and the dissipation factor $\tan\delta$.

2.1 Polystyrene capacitors

For years, polystyrene (PS) capacitors were the best choice for critical analog applications. In the middle of the 1990s the production of PS capacitors slowly ceased. There were several reasons that caused polystyrene capacitors to disappear from production. The maximal operating temperature of PS film and capacitors is very low, only 85°C (see Table 1). Additionally, the low heat resistance of PS film allows neither the construction of SMD components nor the vacuum-deposition of aluminum, hence only film/foil capacitors were (are) produced. This construction lacks the self-healing capability, i.e., the ability to clear faults (such as pores or impurities in the film) under the influence of voltage. Although PS capacitors have low absorption of moisture, they can be easily damaged by printed board cleaning solvents. PS capacitors that are still available from old stocks are not intended for new designs. New materials like polyphenylene sulfide (PPS) should be used instead of PS.

2.2 Polycarbonate capacitors

Polycarbonate (PC) metallized film and film/foil capacitors were traditionally the logical choice for high performance applications for operation at elevated temperatures. This material is featured with a negligible temperature coefficient α_C for temperatures in the range of 20°C ÷ 40°C, which is the common operating temperature range of precision electronic equipment. In spite of the higher operating temperatures of this film, commercially available PC capacitors for surface mount were never produced. In the year 2000, the major producer of PC capacitors WIMA from Germany /2/, ceased their production after finding it unprofitable. This decision caused the major producer of capacitor grade PC film, Bayer AG, to stop its production upon completion of the final order. Nevertheless, PC film capacitors are still available and produced at least by Electronic Concepts Inc. form USA with its own in-house produced dielectric film /3/. Polycarbonate film is almost the perfect material for high performance capacitors but is very sensitive to moisture absorption, thus good encapsulation is required to protect the dielectric film against humidity. Hermetically sealed PC capacitors are available only with wired trough-hole terminals and are primarily intended for military applications.

2.3 Polyester capacitors

Polyester films have become the standard dielectric for capacitors in electronic applications. Polyester film for capacitors is biaxially oriented polyethylene terephthalate (PET) developed by DuPont in the mid-1950s and is well-known under the trade name Mylar. This material has good mechanical and electrical properties for temperatures in the range from -55°C to +125°C. Their high dielectric strength, and the highest dielectric constant among commercially used dielectric films, make PET capacitors cheap and volume-effective. Metallized PET film capacitors are produced in any combination of the construction alternatives given in Table 1.

Table 1: Manufacturing and construction alternatives of PET capacitors

Parameter	Alternative	
Environmental protection	Naked	Protected
Mounting terminals	SMD	Trough hole
Construction	Stacked	Wound
RoHS compliance	Yes	No

These capacitors are the most frequently used type of plastic film capacitors in electronic circuits - primarily for DC or low frequency purposes - because the dissipation factor $\tan\delta$ of polyester is the highest among contemporary film materials. Even though it is not a high quality material, in many respects, PET films perform much better than multilayer ceramic capacitors (MLCC) using X7R or Z5U dielectric ceramics. Some producers, e.g., AVX /4/, offer PET-HT capacitors with an improved temperature range of up to +125°C with a nominal voltage derating factor of 1.25 %/°C above T_R = 105°C, which represents an increase of 20°C with respect to the standard types.

2.4 Polypropylene capacitors

Polypropylene (PP) film has, for many years, been used for high performance applications, especially for medium and high power electronic circuits where high impulse current capability is required. This material has very low dielectric absorption *DA* making a PP capacitor the best choice for the charge-storing device in precision integrators, sample and hold amplifiers and other electronic circuits that retain analog signals in the form of electric charge. Additionally, PP capacitors are characterized by a constant temperature coefficient α_C = -200 ppm/°C and the second highest volume resistivity among dielectric film materials (Table 2). The main deficiency of PP is its somewhat limited temperature range, which prevents the construction of PP as an SMD component. Standard PP capacitors use metallized film and film/metal foil construction for self-healing and high impulse current capability, respectively.

2.5 Polyphenylene sulfide capacitors

Polyphenylene sulfide (PPS), a dielectric material with excellent electrical and thermal properties, was invented by Toray/Japan. This chemical company started the production of capacitor grade PPS film in 1988 under the trade name of Torelina®, and is still the only producer. In the same year PPS capacitors were made commercially available by WIMA/Germany, but their production was plagued with many difficulties. In 2001 WIMA /2/ temporarily ceased their production due to problems connected with inconsistent film quality and availability. A detailed examination of self-healing of different metallized polymer films by Walgenwitz et. al. /5/ has shown only insignificant distinctions among PET, PEN and PPS. In any case, achieving self-healing in PPS film is not a particular problem. The problematic availability of PC capacitors, the European Council Directive on the Restriction of Hazardous Substances (RoHS Directive, 2002/95/EC) /6/, and good the mechanical properties of biaxially oriented PPS film at higher temperatures have prompted numerous activities for the reliable production of PPS capacitors. The construction of SMD film capacitors has become very demanding due to the elevated melting point of leadless soldering compounds. After the break in 2000 WIMA restored the production of PPS capacitors, encouraged by a mixture of technological and commercial factors. After 2001 both trough hole and SMD types of PPS metallized capacitors were made generally available by several manufacturers.

PPS has excellent electrical properties that exceed PC in many aspects. Almost no sensitivity to humidity and a far higher operating temperature range are the most important attributes of PPS when compared to PC. Despite the advantages of PPS film (expressed by the figures in Table 2), this material has two shortcomings. Firstly, it is expensive and secondly, it is produced only by Toray/Japan, which may cause hitches in its supply.

2.6 Polyethylene naphtalate capacitors

Polyethylene naphtalate (PEN) was not used for film capacitors until 2000. The RoHS directive adopted by the EC in 2003 caused producers of electronic components to utilize substitutes for the existing materials as these could not stand the thermal stress generated by elevated soldering temperatures without significant degradation. The electrical properties of PEN film are very similar to those of PET, but the overall performance of PEN is inferior - provided that the maximum operating temperature is not taken into account /7/. PEN capacitors are larger than the corresponding PET types because the dielectric constant ε_r and the dielectric strength E_B of PEN are lower. The ratio of PEN capacitor size to the corresponding PET capacitor is between 1.5 and 2. PEN film SMD capacitors are in compliance with the RoHS directive, and are suitable for IR or vapor phase reflow processes. PEN capacitors are

Table 2: Properties of capacitor dielectric materials

Parameter	Unit	Dielectric								
		PS	PC	PET	PEN	PP	PPS	PTFE	C0G	X7R
Dielectric constant ε_r		2.2	2.9	3.3	3.0	2.2	3.0	2.0	12...40	700...2000
Dielectric strength	V/μm	100	200	400	300	600	250	150	200	
C temperature coefficient α_C	Ppm/°C	-120	±80	+600	+200	-300	-150	-80	±30	±1000
Dissipation factor tanδ (1 kHz)	10^{-4}	5	15	80	80	5	20	1	15	350
Volume resistivity ρ	Ωcm	10^{18}	10^{16}	10^{17}	10^{17}	10^{18}	10^{17}	10^{19}	10^{17}	10^{16}
Dielectric absorption *DA*	%	0.01	0.1	0.5	1.2	0.02	0.05	0.01	0.6	2.5
Operating temperature T_{min}/T_{max}	°C	-55 125	-55 100	-55 105	-55 125	-55 100	-55 140	-55 200	-55 125	-55 125
Self-healing		no	yes	yes	yes	yes	yes	no	no	no
SMD configuration		no	no	yes	yes	no	yes	no	yes	yes

also featured with improved temperature stability with respect to PET. The capacitance temperature coefficient α_C of PEN is approximately only one third of the α_C of PET. The dielectric absorption *DA* of PEN is the biggest among the polymer film dielectrics. Its value of approximately 1 % is the order of magnitude of *DA* specified for MLCCs using X7R ceramics.

2.7 Other dielectric materials

Three types of dielectric materials, that have not been mentioned previously, are also listed in Table 2. Polytetrafluoroethylene (PTFE) better known under DuPont Company's trade name Teflon®, is an excellent insulating material, but PTFE film capacitors are very rare. Proper metallization of PTFE film is very difficult, this material is very expensive and films of a thickness < 6 μm are not commercially available /7/. PTFE capacitors are used in high power applications where their high operating temperature range and low dissipation factor justify their high price.

The data on ceramic dielectric materials in Table 2 are given for comparison, since MLCC chips are very popular and cheap. In fact only COG ceramics, also known as NPO, are a real match for polymer films as far as stable high performance capacitors go. In addition to the materials discussed, X7R ceramics offer a cost and room efficient solution when large capacitances in small packages with low equivalent serial resistance (ESR) are required.

3. Capacitor for integrating A/D converter

3.1 Four slope integration

Dual slope integration is a well-known method for accurate A/D conversion /1/. Accuracy and resolution are two distinctive features of such A/D converters. The resolution of integrating converters is determined by the ratio between the period of the clock that is used for counting and the time of integration, which is measured in clock periods. Arbitrary resolution can be achieved by appropriate selection of these two parameters, but at high resolutions conversion times can become unacceptably long, since maximal counter frequencies are limited. On the other hand, the accuracy of the result is determined by the used reference, if everything else is done ideally.

Integrating A/D conversion is very useful for measuring slowly varying quantities, e.g., strain, temperature, humidity, illumination etc. Furthermore, smart sensors with digital output can be designed as a combination of a standard microcontroller, an integrating A/D converter, and an analog sensor of a physical quantity. Low cost uncalibrated sensor devices may be used, without compromising the accuracy of the final result because the deficiencies of the analog sensing device are compensated numerically. The required signal conditioning data are obtained by calibration in the final stage of production and consequently stored in the nonvolatile portion of memory.

The pitfalls of capacitor selection are illustrated by the case of the small resistive temperature sensor. The important, i.e., the analog part of the smart sensor is shown by the simplified schematic diagram in Figure 1.

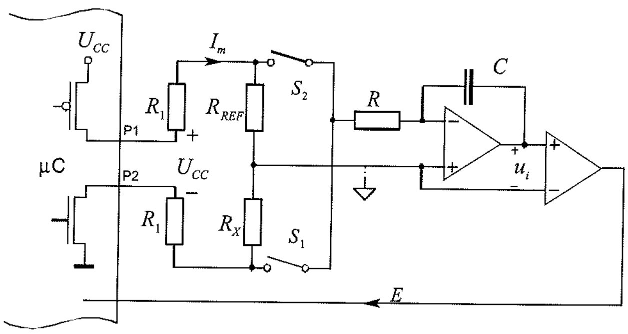

Fig. 1: Integrating A/D converter

The conversion is initiated by closing switch S_1 for fixed time t_0 determined by a certain number of clock periods. The integrator output voltage u_i ramps up, reaching a maximum value that is proportional to the voltage across the sensor resistance R_X. At the end S_1 is opened and S_2 is closed. The output ramps down with a slope that is proportional to the voltage of a very stable resistor R_{REF}. When the integrator voltage becomes negative with respect to analog ground, the timer inside the microcontroller is stopped by the negative edge of the comparator output *E*. The plots of main converter signals are shown in Figure 2.

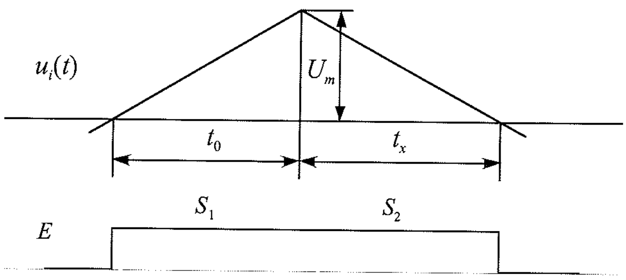

Fig. 2: Time diagram: u_i integrator output, E comparator output

The peak integrator voltage can be expressed by

$$U_m = I_m R_x \cdot \frac{t_0}{RC} = I_m R_{REF} \cdot \frac{t_x}{RC} \qquad (1)$$

where I_m represents the measuring current through the sensor R_X and reference resistor R_{REF}, respectively. From the unknown resistance of the sensor is given by

$$R_x = R_{REF} \frac{t_x}{t_0} \qquad (2)$$

meaning that only the stability of R_{REF} has influence on the result accuracy. This would be true if the opamp and comparator were ideal. The dual slope principle is not sensitive to the instability of the integrator time constant RC as long as the constant remains unaltered during conversion time $t_0 + t_x$. The integrator peak voltage U_m given by remains unaffected by the comparator input offset voltage, since the counting of both times, charging t_0 and discharging t_x, are started and stopped at the same integrator voltage, respectively. The actual conversion is started by closing S_2 until the integrator output u_i becomes negative then both switches (S_1 and S_2) are toggled. The charging time t_0 counter is not triggered until the rising edge of the comparator output E.

The input offset voltage U_0 of the opamp in the integrator induces an error that can be expressed as

$$\Delta R_X = \frac{2U_0}{I_m} \qquad (3)$$

with I_m denoting the measuring current (Figure 1). As it is shown in /8/ this error is compensated by reversing the polarity of the measuring current I_m, which is done by negation of the logic outputs P1 an P2 (Figure 1). The accurate result is the mean of the results obtained with both polarities of the current I_m

$$R_x = R_{REF} \frac{t_{x1} + t_{x2}}{2t_0} \qquad (4)$$

The procedure with four slopes of integration, shown in Figure 3, doubles the required conversion time, but low cost opamps with offset voltages $|U_0| \leq 1$ mV may be used.

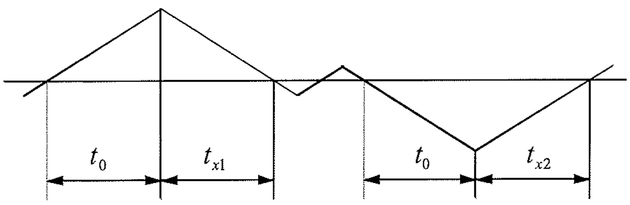

Fig. 3: Plot of the integrator output $u_i(t)$ in the four slope A/D converter

3.2 Dielectric absorption

The analyzed integrator is part of an intelligent resistive sensor of small physical dimensions (25 × 9 mm), therefore small passive components are used. The long integration time, which is necessary to achieve the prescribed resolution, and the low supply voltage require relatively large capacitance C = 100 nF that prevents the integrator output from reaching saturation. The first logical choice was an X7R ceramic chip capacitor, characterized by its small dimensions and SMD package. The value of capacitance appears neither in eqn. nor in , therefore the temperature coefficient and tolerance are not important for this purpose.

Experimental tests have shown poor accuracy in the intermittent mode of operation. The sensor was designed for battery powered systems, so the analog part of the circuit is powered only when the conversion takes place. Dielectric absorption of the capacitor has been overlooked, and the effect of the absorbed charge has not been noticed in continuous mode since the capacitor mean voltage is zero.

For the great majority of capacitor applications the dielectric absorption coefficient DA is not an important parameter. It matters only in some sample and hold circuits, and as is obvious, in integrators that operate once in a while and have long integrating times. This phenomenon can be measured as a small voltage that reappears across the open capacitor terminals after a charged capacitor has been thoroughly discharged. When voltage is applied to the capacitor plates a certain small part of the stored charge becomes bound on the surface of the dielectric. The process of charge recovery is governed by pretty long time constants that depend merely on the used dielectric material. Measurement of the absorption coefficient DA according to the standard MIL-C-19978 D /9/ is depicted in Figure 4.

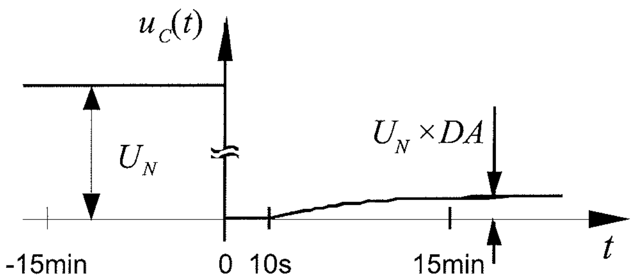

Fig. 4: Timing and definition of voltages associated with the measuring of the dielectric absorption (U_N denotes nominal voltage).

The effects of dielectric absorption in electric circuits are studied by suitable models that replace the capacitor in question. These models /10/, /11/ can be quite complex but in most cases a simple model shown in Figure 5 is sufficient for basic understanding. For commonly used dielectrics, 50% of the final voltage is recovered in 1 to 10 seconds, whereas it can take as much as 15 minutes to reach within 5% of the final value.

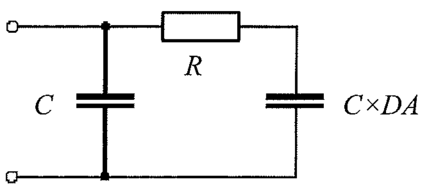

Fig. 5: The basic model of the dielectric absorption in capacitors

The resistance in the model of Figure 6 is given by

$$R = \frac{\tau}{DAC} \qquad (5)$$

where t denotes the dominant recovery time constant and DA is the absorption coefficient (Table 2). The values of τ for particular materials are usually not specified and have to be determined by experimental measurements if a greater accuracy than the generally presumed range from 1 to 10 s is desired.

Detailed analysis has shown that the integrating capacitor was charged almost to supply voltage (U_{cc} = 3.3 V) when the negative supply pin of the amplifier chip was not tied to ground to reduce supply current. The error caused by recovered charge is drastically reduced by the four slope integration method. The error of n-th successive measurement after the amplifier is turned on is given by

$$\frac{\Delta R_X}{R_X} = \frac{U_{C0}\,DA}{2U_m}\left(1 - e^{-\frac{T}{\tau}}\right)^2 e^{-\frac{2T}{\tau}(n-1)} \tag{6}$$

where U_{C0} is the integrating capacitor initial voltage, $T = t_0 + t_X$ is the conversion time of one polarity, τ is the dominant time constant of the absorbed charge recovery, and U_m is the peak voltage of the integrator (Figure 2). The used ceramic chip capacitor has turned out to be completely inadequate for accurate temperature measurements on the basis of platinum resistors. Errors due to the dielectric absorption of the consecutive resistance measurements of the platinum resistor R_x (Pt 1000) are shown in Table 3. The results are expressed as temperature errors in °C using the temperature coefficient of platinum 3850 ppm/°C. The values in Table 3 are calculated using for two different absorption coefficients, whereas the other parameters are the same: U_{C0} = 3.3 V, U_m = 1V, τ = 3s, T = 1s. The errors calculated for X7R ceramics are in good agreement with the measurements, which have initiated more detailed analyses.

Table 3: Error of consecutive A/D conversions expressed in temperature

Consecutive measurement no.	ΔT [°C]	
	DA = 2.5% (X7R)	DA = 0.05% (PPS)
1	0.860	17×10^{-3}
2	0.442	8.84×10^{-3}
3	0.227	4.54×10^{-3}
4	0.116	2.33×10^{-3}
5	0.059	1.19×10^{-3}

The theoretical error caused by the absorption of PPS film SMD capacitor is smaller than the desired resolution of the design, therefore raw conversion data, i.e., timer counts that measure time t_x, have been observed. The raw results of consecutive conversions (after power up) are within plus minus one count, provided that the temperature is constant.

4. Tests in climatic chamber

4.1 Naked PPS SMD capacitor

Encouraged by the theoretical results (Table 3) an adequate substitution for the X7R MLCC has been found in the form of the stacked PPS film capacitor. These capacitors are almost a perfect choice and feature a very low absorption coefficient DA and very low dissipation $\tan\delta < 5\cdot10^{-4}$ in the temperature range from -25°C to 80°C. The data for PPS shown in Table 2 are rather misleading because the worst values over the whole temperature range are given. In addition, PPS capacitors are available as small SMD components that save space on the PCB and fit on solder pads provided for the former ceramic capacitor. The construction of naked stacked film capacitors is shown in Figure 7. The lateral side is usually left without any coating /4/.

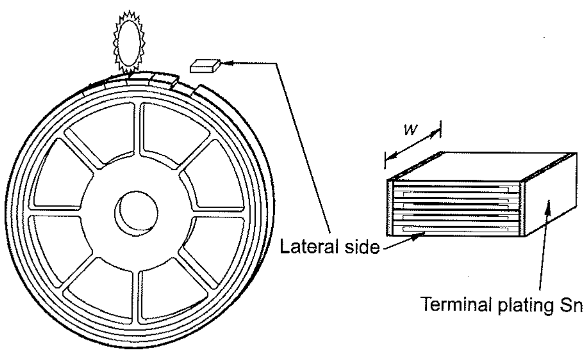

Fig. 6: Production and construction of stacked naked PPS film chip capacitors

In stacked-film production technology, large rings of metallized film are wound onto core wheels with diameters up to 60 cm. Then the rings are sawed apart obtaining well defined width (dimension W in Figure 6). In this way, capacitances with very low tolerances are obtained, since the active body is very homogenous, without the air pockets which are typical of flattened wound bodies. Actual measurements have proved that PPS capacitors have negligible dielectric absorption; hence no differences have been detected between the results of the first and immediately repeated measurements.

Upon the verification of the calibrated sensors, some of them returned values that were up to 2°C lower than the actual temperature in the chamber, which was 12°C. Among the 120 devices under test, about 10% were bad, i.e., $|\Delta T| > 0.1$°C. It turned out that humidity inside the chamber had run out of control. At temperatures around 12°C the humidity had exceeded 90%. The deviation of certain circuits was obviously influenced by humidity, so protection against moisture should improve the performance of the PCB in humid environments. Polyurethane coating applied to the assembled PCBs did not help. The deviations of the bad circuits remained unacceptable.

Since it was not clear which part of the circuit was affected by humidity, several experiments were carried out. The results in Figure 8 show that high humidity and temperature affect the four slope A/D converter. In this experiment the temperature dependent resistors (Pt1000) of three sensors were kept outside the climatic chamber at a constant temperature, while the PCBs were exposed to temperatures increasing in increments at high humidity and decreasing at low humidity, respectively. As one can note from the plots in Figure 7, the impact of the temperature increments in the presence of high humidity is not the same for all circuits, but when humidity is low the circuits are left virtually unaffected.

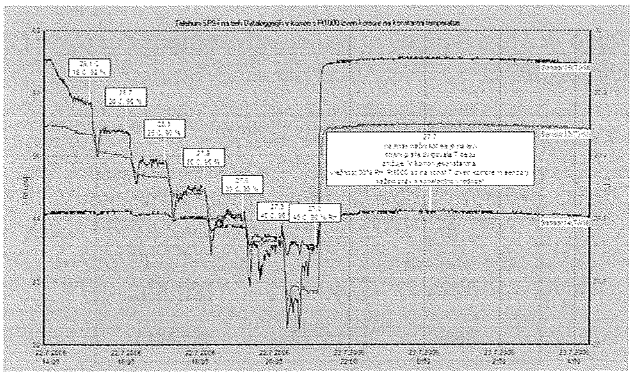

Fig. 7: Measurement results of three sensors with naked PPS capacitors: at high humidity RH = 90% the chamber temperature was increased in 5°C increments from 15°C to 45°C, then the air was dried to RH = 30% and the temperature was decreased to 15°C, again in decrements of 5°C. Each step of this temperature reduction lasted 1hour.

Next, the integrating PPS chip capacitors of the three tested samples were replaced by encapsulated PET capacitors with wire terminals and then the same experiment was repeated. The plots that are shown in Figure 8 reliably indicate that certain PPS chip capacitors were affected by high humidity and not the PCB itself. The results registered by the third sensor are meaningless since a fault occurred during the replacement of the capacitor. The steps in the upper and middle plot are a consequence of the temperature coefficients of each reference resistor R_{REF}, because the sensors were kept at different, i.e., constant temperatures during the test.

4.2 The influence of humidity on insulation resistance

Obviously, some of the used PPS capacitors were influenced by moisture. The influence of absorbed moisture on capacitance was excluded by empirical immersion tests, so only the surface resistance between capacitor terminals R_P remains as the possible cause of inaccurate conversion, if this resistance is decreased due to air humidity.

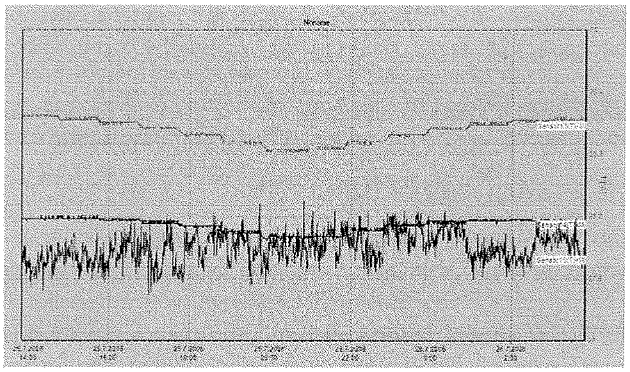

Fig. 8: Measurement results of three sensors with encapsulated PET capacitors: at RH=90% the chamber temperature was increased in increments of 5°C from 15°C to 45°C (the left half of the diagram), then the air was dried to RH=30% and the temperature was decrementally reduced down to 15°C.

Firstly, we have to estimate the order of magnitude of such a decrease of resistance that could cause the observed inaccuracies. As is shown in Figure 9, the parallel resistance represents a leak for the charge stored in the integrating capacitor. The sensitivity can either be derived from the exact analytic solution, or a few simple approximations can be used. The latter alternative is presented as follows.

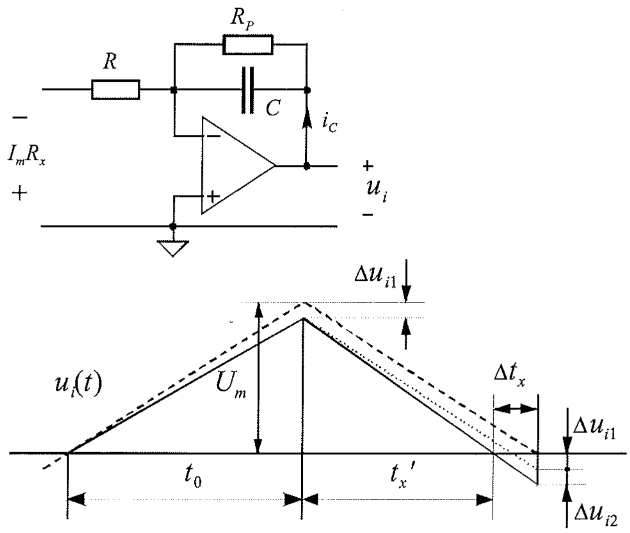

Fig. 9: Integrator with insulation resistance R_P (above), plot of integrator output voltage u_i with (——) and without R_P (- - -) (bellow)

At the end of the first step of conversion the peak integrator output is reduced by

$$\Delta u_{i1} = \frac{\Delta q}{C} = -\frac{1}{C}\int_{t}^{t+t_0} \frac{u_i(t)}{R_P}\,dt = -\frac{1}{2}\cdot\frac{U_m t_0}{R_P C} \qquad (7)$$

with Δq denoting the charge that leaks through R_P and U_m is the voltage that would be reached if there were no leakage, i.e., $R_P \to \infty$. The shape of $u_i(t)$ in is considered straight and $\Delta u_{i1} = U_m$ is neglected in the integral. During the second step of conversion, $u_i(t)$ decreases faster than in the ideal case (Figure 9) and after discharging for t_0 it would become negative. The relative error of the conversion

$$\frac{\Delta t_x}{t_x} = \frac{\Delta u_{i1} + \Delta u_{i2}}{U_m} = \frac{2\Delta u_{i1}}{U_m} = -\frac{t_0}{R_P C} \quad (8)$$

where t_x is approximated by t_0, hence $\Delta u_{i2} = \Delta u_{i1}$. In our special case where the actual input voltage is proportional to the resistance of the platinum temperature sensor it is convenient to express the difference between the measured and the actual temperature

$$\Delta T = \frac{\Delta R_x}{R_x} \cdot \frac{1}{\alpha_R} = -\frac{t_0}{R_P C \cdot \alpha_R} \quad (9)$$

where α_R denotes temperature coefficient of platinum. The plot of this temperature deviation for C = 100 nF, t_0 = 0.5 s and α_R = 3850 ppm/°C is shown in Figure 10.

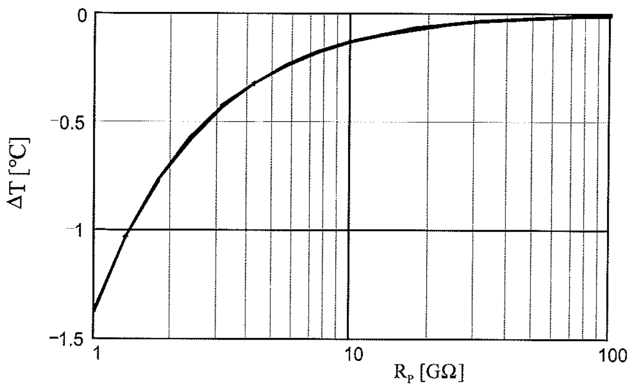

Fig. 10: Deviation of measured temperature vs. insulation resistance R_P

The derivation of eqn. is carried out only for the first phase of A/D conversion because both phases of the actually implemented four slope conversion are equally influenced by the charge leak. According to capacitor producer AVX /4/ the insulation resistance of a 100 nF capacitor is >60 GΩ for T < 75°C. Under normal conditions such values of R_P cannot engender noticeable deviations. Moreover, the constant resistance that appears between the capacitor terminals is taken into account during calibration, so that the conversion results in operation are influenced only if this resistance is decreased owing to environmental influences.

The theoretical plot in Figure 10 shows that the parallel resistance has to decrease to about 1 GΩ when the result fails for approximately -1.5 °C. Such errors can be noted in the experimental results shown in Figure 7, where it is obvious that in the presence of damp air the parallel resistance of some capacitors is reduced to 50% or less by rising the temperature for 5°C.

4.3 Insulation resistance measurements

Both our theoretical and experimental findings have been verified by measurements of two sets of PPS film capacitors (100 nF/16 V), i.e., brand new capacitors and the desoldered ones from the circuits that turned out as bad. The new capacitors were immersed for 24h in a 20% isopropyl alcohol (IPA) water solution. The immersion caused no measurable differences in the capacitance and dissipation factors. The measured capacitance tolerance of all samples was les than 1%. Furthermore, the insulation resistance of the devices was measured at different air humidities. The leakage current at the applied voltage 1 V was measured by a precise picoampermeter. The results are summarized by mean values in Table 4.

Table 4: Mean values of insulation resistance at U_{DC}=1 V and T= 25°C,

Relative Humidity [%]	R_i	
	new	*desoldered*
35%	100 GΩ	100 GΩ
60%	40 GΩ	100 MΩ
90%	10 GΩ	30 MΩ

The results in Table 4 clearly indicate that the origin of the noticed inaccuracies lies in the resistance between the capacitor terminals. PPS capacitors have very low moisture absorption, but the naked types are affected by the side effects of PCB assembly, because the new devices perform much better when leakage is involved. The work of Hunt and Zou /12/ has shown the importance of appropriate selection of the flux in the soldering paste. The residues of soldering fluxes contribute to the surface conductivity as the humidity is increased. This effect is especially pronounced for weak organic acid (WOA) based fluxes at high humidity (> 85%). It has been already mentioned that the PCB's were protected against moisture but that these efforts turned out to be unsuccessful. The tested sensors were washed in deionized water, dried and protected with a thin polyurethane coating (Urethane 71) but the surface of some PPS chip capacitors remained contaminated by flux residues. The applied coating should be substantially thicker, which is a rather unpractical solution.

The weak point of the naked chips is the exposed lateral sides (Figure 7) on which the metal atoms that form the capacitor plates can be found. These lateral sides are additionally vulnerable due to the small gaps between the clusters of stacked dielectric film. It is almost impossible to clean these gaps once they get contaminated. The first prototypes were soldered by hand using ordinary soldering wire filled with resin. In this case, increasing the humidity does not reduce the surface resistivity /12/, therefore the high humidity effects were not noticed until a different technology of PCB assembly was used. It is important to note the fast response of the observed leakage current to the changes in humidity, which obviously points to the fact that only the surface of the capacitor is involved in this process.

5. Conclusion

The choice of SMD film capacitors on the market has gone through significant changes that were initiated by the EC RoHS directive. New high temperature dielectric materials have been introduced in production. PET, PEN and PPS films are used for plastic film SMD capacitors. Special attention must be paid during the assembly of PET capacitors with regard to the reflow soldering process. PEN and PPS capacitors tolerate slightly higher temperatures in the reflow soldering process which in turn is beneficial for the reliability and quality of the leadless solder contacts. PEN capacitors should be avoided if dielectric absorption is important. PPS capacitors are now commonly available from various producers, but are the most expensive.

The construction of the capacitor should be carefully selected for each particular application. Stacked film capacitors have tight tolerances and require the least space on the PCB. As described in this paper, their naked construction is vulnerable to humidity, which reduces the parallel resistance due to surface conductivity. Wound capacitors are made by individually rolling the metallized film ribbons into cylindrical rolls which are then flattened to a prismatic shape. Wound capacitors are less sensitive to humidity, since the outer layers of the roll protect the capacitor core inside. Wound types are available naked or encapsulated in plastic boxes that provide additional protection against the environmental influences. Both variants of wound capacitors require more space on the PCB than the stacked one.

The described case study shows the importance of careful component selection from amongst the variety that is offered on the market. Besides choosing the right dielectric material, it is equally important to consider the construction of the capacitor. Of course, it is almost impossible to anticipate the behavior and interactions of real components that are exposed to harsh climatic conditions. Intensive computer-controlled testing of prototypes in a climatic chamber is an important step in the good design of demanding electronic products.

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