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Commercially Available Capacitors at Cryogenic Temperatures

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1. Abstract

Electronics operated at cryogenic temperature are often developed for the biasing, the front-end readout and the multiplexing of cryogenic sensors. For these cryogenic circuits, capacitors are needed for AC biasing, filtering and AC coupling. Commercially available capacitors are not specified for operation at 77 K or 4 K, and some devices showed a dramatic decrease of capacitance at cryogenic temperature. Furthermore, for voltage biasing of low impedance superconducting sensors (like Transition Edge Sensors – TES), it is very important to know the parasitic resistance of an AC-biasing circuit. In this case, the parasitic Equivalent Series Resistance (ESR) of the capacitor used for the AC-biasing is a bottleneck of the voltage biasing. Involved in TES development and SQUID multiplexing [1], we have characterized the capacitance and the ESR values of some commercially available capacitors at 77 K and 4 K.

2. Introduction

The current development of large array of superconducting bolometers (Transition Edge Sensors – TES) needs also a development of a dedicated cryogenic multiplexer to reduce the wiring between cryogenic to room temperature. Several multiplexing solutions like time domain, frequency domain and coded domain multiplexing are using SQUID (Superconducting QUantum Interference Devices). Whether AC-biasing (for frequency multiplexing), integration (for the SQUID biasing or for the stabilization of SQUID feedback) or more simply DC bias filtering, capacitors are commonly used at cryogenic temperatures.

In this paper, we propose to extend (in term of temperature range) the first part of the work published by Ming-Jen Pan in [2]. This paper shows some measurements of capacitance and dielectric dissipation factor tanδ (1) on several commercially available capacitors cooled down to 77 K. We have used some multilayer SMD (Surface Mount Device) capacitors, similar to those employed in [2], and measured down to 4 K capacitance C and ESR (Fig. 1).

$$\tan\delta = \frac{ESR}{X_C} \quad \textit{where the capacitive reactance} \quad X_C = \frac{1}{\omega C} \quad (1)$$

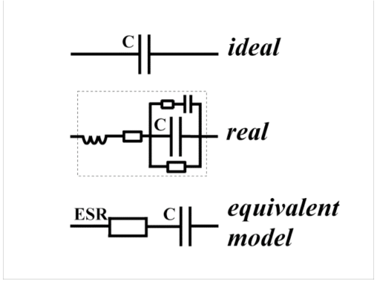

Fig. 1. Ideal capacitor. Real capacitor [3] with additional parasitic components (inductive element is not significant on SMD capacitor technology for our frequency range). Equivalent model with Equivalent Series Resistance (ESR).

3. Devices and Process

Ceramic (X7R, Y5V and NPO) and polymer (Polyester and PolyPhenylene Sulfide - PPS) SMD capacitors have been tested. We use, as the capacitance value of a given capacitor, the average capacitance over a few (3 to 14) samples of the same capacitor technology. Different capacitance values (10 nF, 100 nF and 220 nF) have been also used to confirm that ESR is, in first approximation, inversely proportional to the capacitance specified value. Finally, all measurements have been normalised to a 100 nF capacitance at 300 K. This value is close to those used for TES AC-biasing and allows comparing C and ESR relative evolution values of different technologies without problem of precision on the absolute value. For ESR normalization, we have assumed a direct reciprocal proportion with C.

Capacitances and ESR values at 1 kHz, 10 kHz and 100 kHz have been performed by using a *HIOKI 3532-50* LCR meter. Capacitors were immerged into liquid nitrogen (77 K) and liquid helium (4 K) by using a deep probe. For several capacitors (NPO and Y5V), we have also made measurement at intermediate temperatures (in the cold helium gas) to have a better idea of values evolution. For all measurements a preliminary de-embedding of parasitic elements (long cables used to performed cryogenic measurements) was done.

After cryogenic measurements, capacitance and ESR was re-checked at 300 K to eventually detect some damage due to thermal cycling.

Table I. *Synthesis of Capacitance and ESR measurements at 300 K, 77 K and 4 K normalized to 100 nF at 300 K.*

Capacitor type	Measured capacitance (100 nF at 300 K)		f \ T	Measured ESR		
	77 K	4 K		300 K	77 K	4 K
X7R ceramic	21.3 nF	3.4 nF	1 kHz	76 Ω	574 Ω	5.6 MΩ
			10 kHz	1.5 Ω	64 Ω	400 kΩ
			100 kHz	0.3 Ω	7.6 Ω	62 kΩ
Y5V ceramic	1.8 nF	0.9 nF	1 kHz	93 Ω	3940 Ω	3910 Ω
			10 kHz	1.8 Ω	410 Ω	360 Ω
			100 kHz	0.6 Ω	50 Ω	40 Ω
NPO ceramic (NPO/COG/COH)	100.2 nF	99.7 nF	1 kHz	2.1 Ω	2 Ω	3 Ω
			10 kHz	0.3 Ω	0.4 Ω	0.1 Ω
			100 kHz	0.2 Ω	0.02 Ω	0.05 Ω
Polyester	71.8 nF	15.3 nF	1 kHz	42 Ω	37 Ω	340 Ω
			10 kHz	1.8 Ω	40 Ω	36 Ω
			100 kHz	0.8 Ω	19 Ω	18 Ω
PPS	92 nF	83.2 nF	1 kHz	21 Ω	4.4 Ω	3.1 Ω
			10 kHz	1.1 Ω	0.2 Ω	0.25 Ω
			100 kHz	0.2 Ω	0.02 Ω	0.3 Ω

4. Results

A synthesis of all measurements is given on Table 1. It is an average of all the measurements normalized at 100 nF at 300 K. This averaging/normalization is made on 6 PPS of 100 nF and 220 nF; 3 Polyester of 220 nF; 6 X7R of 10 nF and 100 nF; 9 Y5V of 10 nF and 100 nF; and 14 NPO of 100 nF. Capacitance does not show significant frequency dependence in the range of 1 kHz to 100 kHz. For this reason, Table 1 only shows an average value of capacitances measured at 1 kHz, 10 kHz and 100 kHz.

A. Capacitance

Except NPO, all capacitors show a clear capacitance decrease at cryogenic temperature (Fig. 2); particularly for Y5V and X7R ceramic capacitor that lose more than 95 % in capacitance at 4 K. This strong temperature dependence is due to the ferroelectric nature of dielectrics [2]. These dielectric materials are optimized to exhibit a very high dielectric constant K (2), larger than 1000, at the middle of the specified temperature range [4].

$$K = \frac{\varepsilon_d}{\varepsilon_0} : \textit{dielectric and free space permittivity ratio} \quad (2)$$

These high-K dielectrics are usually used to get large capacitance (at room temperature) for a small area. Capacitance is related to electrodes area A, dielectric thickness t and permittivity ε_d following equation (3).

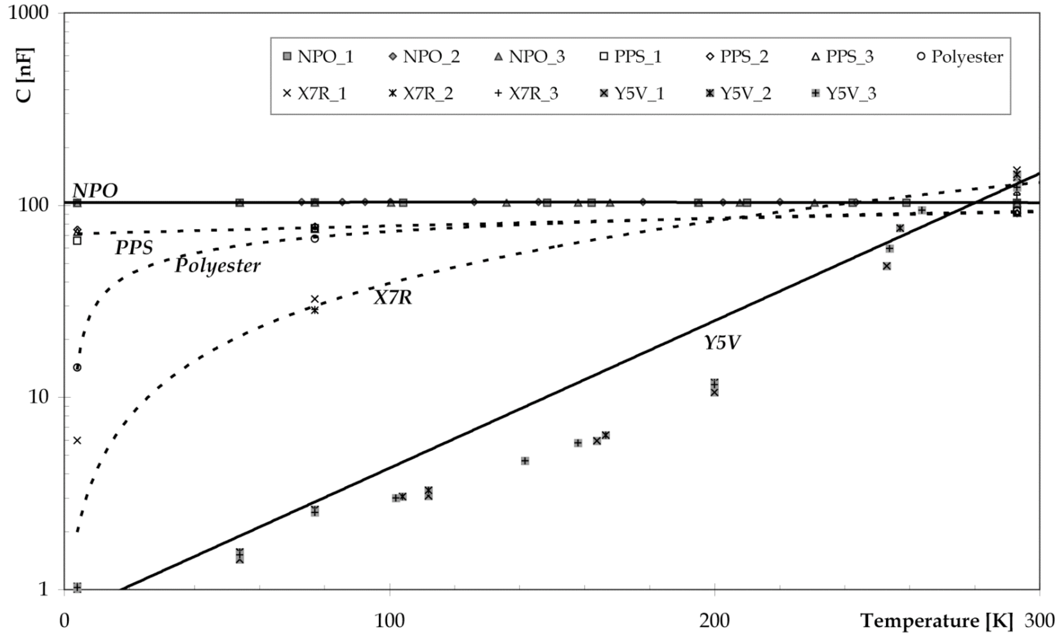

Fig. 2. Capacitance of 100 nF (specified value) capacitors as a function of temperature. For NPO and Y5V, measurement was made at intermediate temperatures in the cold helium gas.

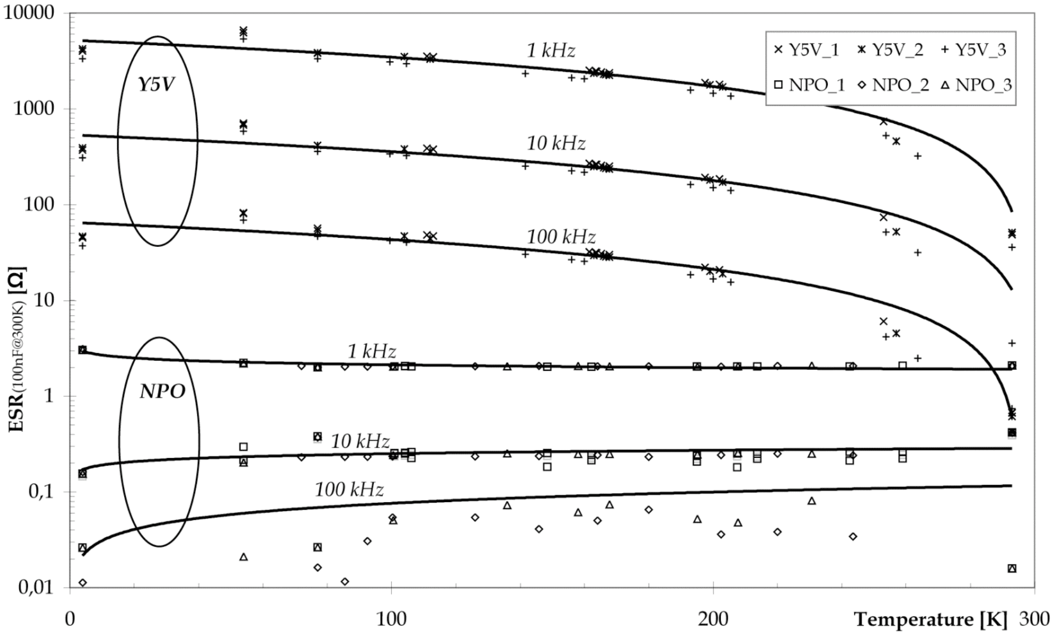

Fig. 3. NPO and Y5V equivalent series resistance (ESR) normalized for 100 nF capacitance at 300 K as a function of temperature. Measurement was made at intermediate temperatures in the cold helium gas.

Thus, capacitance is directly proportional to the dielectric constant *K*:

$$C = \varepsilon_d \frac{A}{t} \propto K \frac{A}{t} \qquad (3)$$

However, this maximization of the dielectric constant accentuates its temperature dependence. Then, this benefit of a large capacitance (at specified range temperatures) contributes to decrease the capacitance at high temperatures, as well as low temperatures [4].

At the opposite of these high-K dielectrics, NPO capacitor dielectric is based on “temperature-compensating” material by using oxides with positive and negative temperature coefficients [4]. This temperature behaviour is always “temperature-compensated” down to 4 K. Results given on Table 1 exhibit fluctuation of NPO capacitance on a temperature range as large as 300 K of only 0.5 %.

For polymer capacitor, the decrease is less dramatic than Y5V and X7R even if polyester capacitor lost 85 % in capacitance at 4 K. For PPS technology the loss is “only” of the order of 20 %.

B. Equivalent Series Resistance

ESR is a very critical parasitic component of a capacitor used to AC-voltage bias a superconducting device. A superconducting bolometer biasing [5] typically requires ESR less than 100 mΩ at 100 kHz (for a typical 100 nF capacitance).

Averaged/normalised ESR values are reported on Table 1 at 300 K, 77 K and 4 K up to 100 kHz. Figure 3 shows ESR of few Y5V and NPO capacitors (normalized at 100 nF at 300 K) measured at intermediate temperatures in the cold helium gas.

ESR is strongly frequency dependent due (for a large part) to the leakage dielectric resistance, which is in parallel to the capacitor (Rp on figure 4). The influence of this part on the ESR value is strongly dependant of the capacitor impedance and then frequency dependant.

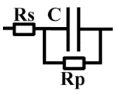

Fig. 4. Simplified schematic of real capacitor: access parasitic resistance Rs in series and leakage dielectric resistance Rp in parallel.

The impedance expression Z of the capacitor equivalent circuit represented on figure 4 comprising a real $\Re\{Z\}$ and imaginary $\Im\{Z\}$ part (4). These two parts are respectively the measured ESR (5) and the invert of the measured capacitance multiplied by ω (6).

$$Z = Rs + C\,//\,Rp = \Re\{Z\} + i\Im\{Z\} = Rs + \frac{Rp}{1 + jRpC\omega} \qquad (4)$$

$$measured\ ESR \approx \Re\{Z\} = Rs + \frac{Rp}{1 + Rp^2C^2\omega^2} \qquad (5)$$

$$measured\ C \approx \frac{1}{\omega \times \Im\{Z\}} = \frac{1}{\omega\left(\dfrac{Rp^2C\omega}{1 + Rp^2C^2\omega^2}\right)} \qquad (6)$$

These two expressions of the ESR (5) and the capacitance (6) of the parasitic model (Fig. 4) allow to represent on figure 5 the evolution of their values as a function of the frequency (numerical application: C = 100 nF, Rp = 1 MΩ and Rs = 0.1 Ω).

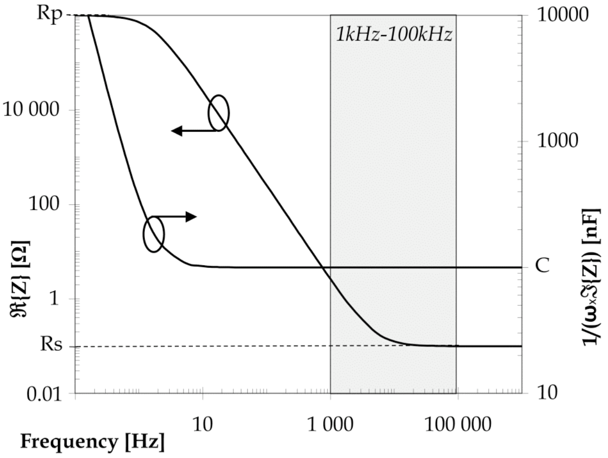

Fig. 5. Evolution of the ESR (5) and Capacitance (6) following a first approximation parasitic model of capacitor given on figure 4 (numerical application: C = 100 nF, Rp = 1 MΩ and Rs = 0.1 Ω).

On figure 5, one can graphically determine a decreasing of the ESR slower than a simple $1/\omega^2$ law and with a constant capacitance over the frequency range of 1 kHz to 100 kHz.

Table 1, shows systematically this decrease of ESR value from 1 kHz to 100 kHz.

Concerning the temperature evolution, like for capacitance, ESR has best (*i.e.* small) value with PPS capacitors and especially for NPO, which is the only technology that has an ESR smaller than 100 mΩ at 4 K.

5. Conclusions

This study presented above shows clearly predisposition of NPO capacitor for cryogenic applications even if this kind of commercially available SMD capacitor is only specified (in the better case) for an operating temperature range from -55 °C to 125 °C (220 K to 400 K).

This collection of data gives a good idea of the ESR value for a sample of popular SMD capacitors where ESR is rarely indicated on datasheet, especially at cryogenic temperature.

The frequency dependence of the ESR is illustrated by using a simple parasitic model with parallel resistance. This gives an idea of the influence of the leakage resistance on the decreasing of the ESR values at high frequency. This frequency dependence is similar at cryogenic temperature and shows that it could be interesting to operate at 100 kHz (and more) in order to benefit of an optimum ESR.

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