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# Influence of the cryogenic temperature and the BIAS voltage on the spontaneous polarization effect of X5R dielectric capacitors.

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***ABSTRACT:*** *In this work the sensitivity of X5R dielectric capacitors to temperature and to DC BIAS voltage are presented, at Room (296K) and Liquid Nitrogen (77K) temperatures, from -6V to +6V of DC BIAS voltages. Experimental results show a cumulative effect derived from these two sources, generating a spontaneous polarization in the dielectric and providing a very specific behavior profile. Through theoretical and experimental analysis, each one of the factors that leads to the achieved CxV (capacitance-voltage) profile is analyzed, as well as it is provided a mathematical model that for this behavior. Capacitance results showed a 70% capacitance decrease for the unbiased components and an additional capacitance variation due to DC biasing, from 12% to 4.6%. This work improve and update the previous ones, once it presents the behavior of SMD X5R dielectric ceramic capacitor not only at positive but also at negative bias, highlighting the ferro-electric effect, hysteresis and its consequences at different temperatures. The implemented experimental setup allows, as well, measurements in a dry environment, avoiding thermal shocks and allowing measuring in the vicinities of the target temperature (77K).*

***Keywords*** *- Devices characterization, spontaneous polarization effect, capacitors, cryogenics, hysteresis.*

## I. INTRODUCTION

There is a great lack of information for the designing and implementation of circuits operating at cryogenic temperatures. The qualitative and quantitative behaviours of electronic components below -55ºC are not accessible to circuit designers, increasing, even more, the difficulties for the designing of special purposes devices.

High performance infrared image sensors need to operate at Low Temperatures in order to increase the Signal to Noise Ratio (SNR). Particularly for embedded missile sensors, advanced electronic systems must be designed for operating at cryogenic temperatures and must be efficient and reliable under this hostile environment [1]. Quantum-Well Infrared Photodetectors (QWIPs), as an example, shows to be highly susceptible to the temperature, demanding not only a stable cryogenic system operation [2] but also additional cryogenic components in the biasing circuits. A proper design of these devices, and their peripherals, will greatly simplify the thermal system, avoiding additional heating units and, thereby, reducing the size and the weight of the overall system.

In this context, capacitors are a basic block for circuit design and must be studied and modelled for this range of temperatures, once they can be used not only as an energy storage component, but also in power conditioning, signal coupling, signal decoupling, by-pass, noise filters, tuned circuits and so on. Although their importance for circuit designers, there is only some literature reporting their dielectric behaviour at cryogenic temperatures [2-7], all of them examining the low field dielectric properties, and none addressing the effects of DC BIAS [8][10], at which the component is generally subjected in the devices [1].

Depending on the DC bias voltage on which a capacitor works, its capacitance will show a variance, influencing the performance of the system as a hole. When these components are subject to low temperatures, these changes are even more evident.

Through experimental results, this work presents the performance of ceramic SMD capacitors (X5R dielectric) and the concepts of temperature and BIAS voltage dependence, explaining their physical behavior and the cumulative effects that these two sources provide on this kind of components. This component was chosen once it is a good option for cryogenic sensors and spatial applications, showing low Effective Series Resistance and Inductance (ESR and ESI), good mechanical performance under shake and vibration conditions (good for missile embedded circuits) and medium ratio of capacitance/volume [9], besides showing a spontaneous polarization effect, what implies a hysteresis behavior.

The achieved results corroborate and improve previous works [8] [10], once it considers and models the ferro-electric effect (spontaneous polarization effect) not only at liquid nitrogen temperature (77K) but also at its vicinities (84K and 70K), showing a quadratic voltage dependent behavior of the capacitance. Another

improvement to previous works shows an analysis of the behavior under negative and positive bias, highlighting the ferro-electric effect and hysteresis, as well as its consequences at different temperatures, what shows to be cumulative to temperature effect. The use of a dry chamber in the experimental setup avoids thermal shocks in the components, approach used in [10], still allowing the variation of the temperatures in the vicinities of 77K, with high accuracy (0.1K). A detailed collection of points (0.1V step), instead of 10% of the total range (0.6V) in [10] is also a feature that leads to the detailed modeling of the studied phenomena.

## II. THEORETICAL CONCEPTS

Amongst their multiple applications, capacitors are able to provide a low-impedance supply for a component, or group of components, in order to minimize the noise present in power supply lines [11], being therefore highly used in noise filtering circuits. For these cases, ceramic capacitors are a standard choice, especially when high capacitance and low volume are necessary. Currently, the surface mounting capacitors are ideal in providing the lowest inductance, being preferred in practical implementations [11]. The adopted three-symbol code to which the capacitors are denominated indicates their temperature characteristics, where the first one relates to the lower limit of the operating temperature range, the second is the upper limit of the operating temperature range, and the third relates to the maximum capacitance change [12]. X5R capacitors are typically composed of Barium Titanate modified with dopants in order to provide high dielectric constant ($\varepsilon R \approx 1000 – 4000$) and temperature stability [13]. Although being considered stable in the specified range, their lower limit operation temperature is -55ºC, which does not guarantee its stability under this temperature. There are not validated models or datasheets that reveal their performance below -55ºC.

Capacitance is highly affected by variations in temperature. This variation depends mainly upon the specific dielectric formulation once the insulation resistance decreases with increasing temperature [12]. Moreover, high dielectric constant ceramic capacitors may show variation in capacitance relating to different levels of applied AC and DC voltages, once the electric field strength across the dielectric changes the effective dielectric constant of the material [14]. Therefore, when a DC bias is applied to a high dielectric ceramic capacitor, a change occurs in its capacitance value. This phenomenon is called "spontaneous polarization", occurring in ferro-electric ceramics and being observed in all high dielectric constant ceramic capacitors.

Furthermore, decreasing the temperature below the Curie point (temperature of maximum dielectric constant), one of the axes (C axis) of the element lattice stretches and the other ones shrink, causing a change in the crystalline structure and, consequently, in dielectric constant (see Fig. 1) [14]. Therefore, when a ceramic capacitor operates at cryogenic temperatures, there are other two phenomena happening at the same time and cumulatively to the effects of the BIAS voltage: a spontaneous polarization caused by asymmetry in the crystalline lattice (with or without a DC bias application) and a reduction in the relative dielectric constant, leading to a lower capacitance. Both phenomena representation can be illustrated by Fig. 1.

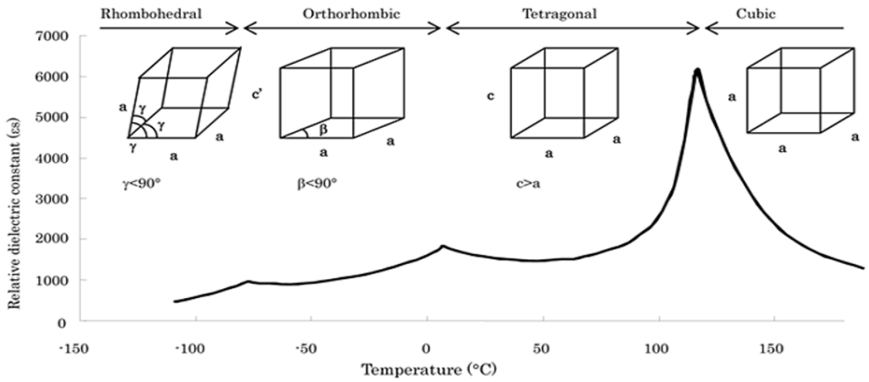



Fig.1: Relative dielectric constant relation to temperature in ºC [14].

If a capacitor is unbiased, the reversal of its spontaneous polarization can be easily achieved through the application of an opposite external electric field. However, with the application of an external bias on the same direction of the previous polarization, the spontaneous polarization can be even increased, making the free reversal of the spontaneous polarization more difficult, leading to a lower capacitance than the unbiased one [14].

The spontaneous polarization effect of a ferro-electric material implies an hysteresis effect, which can be used in a high variety of applications (as a memory function, tuneable capacitance and ferro-electric RAM) and must be dimensioned and characterized [15] not only for these goals but also for many other applications. Electrical hysteresis typically occurs in ferro-electric material, where domains of polarization contribute to the

total polarization. For the chosen capacitor (X5R dielectric), the temperature dependent capacitance and the hysteresis behaviour are both unknown below -55ºC.

## III. EXPERIMENTAL SETUP

Three samples of a ceramic 100nF capacitor (X5R dielectric) were chosen randomly in a commercial batch and positioned in a test bench for this study. The presented results show the mean of these three measurements and the specifications of the used capacitors can be found in [16].

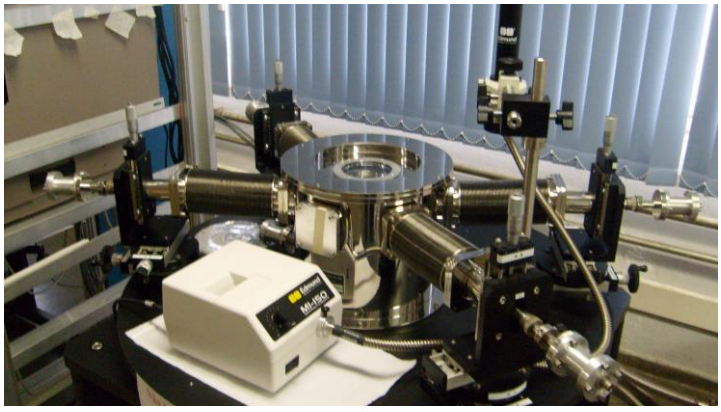
A base plate was prepared and the samples fixed with a special resin, in order to avoid short-circuits between terminal leads and provide good temperature stability.

A Cryogenics Equipment (Janis Research Co., Inc – Model nº CCR10-2(4TX-6)) and a Semiconductor Device Analyzer (Agilent B1500A) were used in the experimental setup, as seen in Figure 2a and 2b.

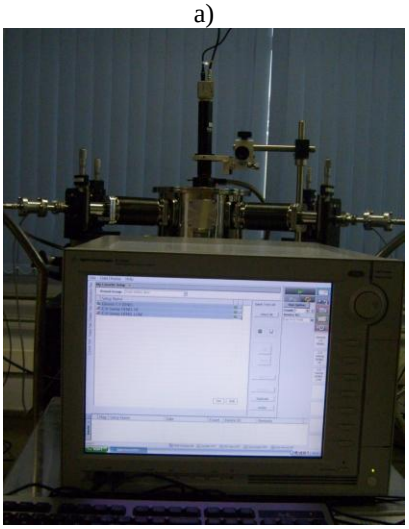
The Cryogenics Equipment allows dry measurements of the component characteristics, avoiding thermal shocks provided by a liquid nitrogen bath. Besides this feature, it provides an accurate temperature control (0.01K) in a wide range of temperatures from 10K to Room temperatures, allowing measurements not only at the focus temperature (77K) but also in its vicinities and allowing the determination of the pattern behaviour.

The components were inserted in a vacuum chamber (Figure 2c) where it was found $10^{-7}$ Torr. This level of vacuum allows a temperature decrease up to 10K, without humidity condensing interference. The temperature transport is provided "by contact" through a copper-gold axis, in contact with the base plate and the samples.

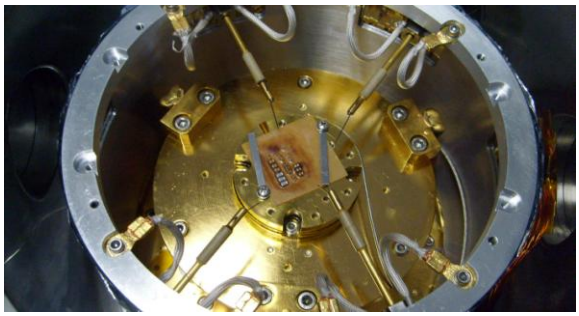
The measurements were performed using cryogenic microprobes (Figure 2c), allowing up to four points of measurements. All the operations and the positioning of the probes can be followed from a monitor.



a)



b)



c)

Fig.2: Experimental setup: (a) Cryogenics Equipment; (b) Semiconductor Device Analyzer – B1500; and (c) Base plate and samples inside the Cryogenics Equipment.

The C-V sweep measurements were performed with a Multi-Frequency Capacitance Measurement Unit (MFCMU), which forces an AC signal, performs staircase sweep output of DC bias voltage and measures impedance for each sweep step. It was also used a SMU/CMU Unify Unit (SCUU) for IV/CV switching, and allowing, if necessary, additional measuring of IV curves without the necessity of changing cables or the setup. Before performing the capacitance (impedance) measurement under different BIAS voltages, it was performed the phase compensation (correcting errors caused by extending measurement cables), the open correction (correcting for stray admittance) and the short correction (correcting for residual impedance), providing data correction and accurate measurements. Relating to these measurements, it was used a medium integration time, a single sweep (from -6V to +6V), a LOG sweep, a VAC of 10KHz and a mean time of 40 minutes between measurements for temperature equalization.

Adequate shielding and guarding were also provided, preventing electrostatic noise and leakage currents, enabling low-current measurements. High-resolutions Source/Monitor Units (HRSMU) with 1fA were used, providing high accuracy to all measurements.

## IV. EXPERIMENTAL RESULTS AND ANALYSIS

As a standard for comparisons, the samples were first characterized at room temperature in order to verify their behaviors and understand the physical concepts that influence their response. After that, measurements were done at the focus temperature (77K) and at its vicinities (84K and 70K) in order to verify the impact of a Liquid Nitrogen temperature environment in its behaviour.

The results are compared with the previously published data of [10], besides to those of [8], complementing them. All the measurements hereon report a wide range of bias voltages (from -6V to 6V), in order to evaluate the ferro-electric effect polarization.

Figure 3 depicts an experimental and typical response of X5R dielectric capacitors. It is in accordance with the results obtained by [10], for the positive measured range. Once it was measured at 296K, the lattice shows a tetragonal structure according to Fig.1, indicating a low spontaneous polarization, what is confirmed by the small shift in the maximum capacitance peak. On the other hand, Fig.1 also presents a high dielectric constant (and a relatively high capacitance), what is confirmed in Fig.3, once the capacitance is almost the nominal capacitance of the component (from the datasheet). The small difference is related to the experimental temperature and frequency of the VAC. Nominal capacitance could be achieved in a lower frequency (VAC) or at a higher temperature [10].

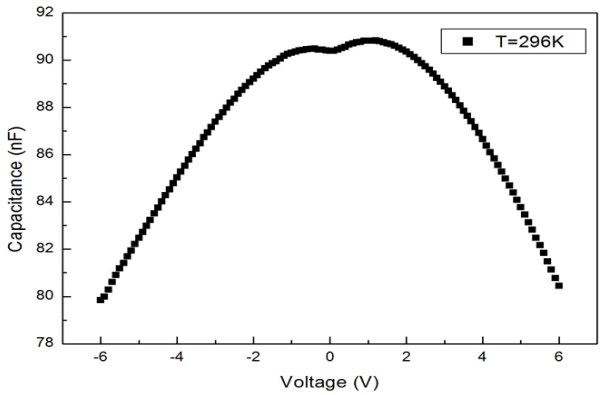
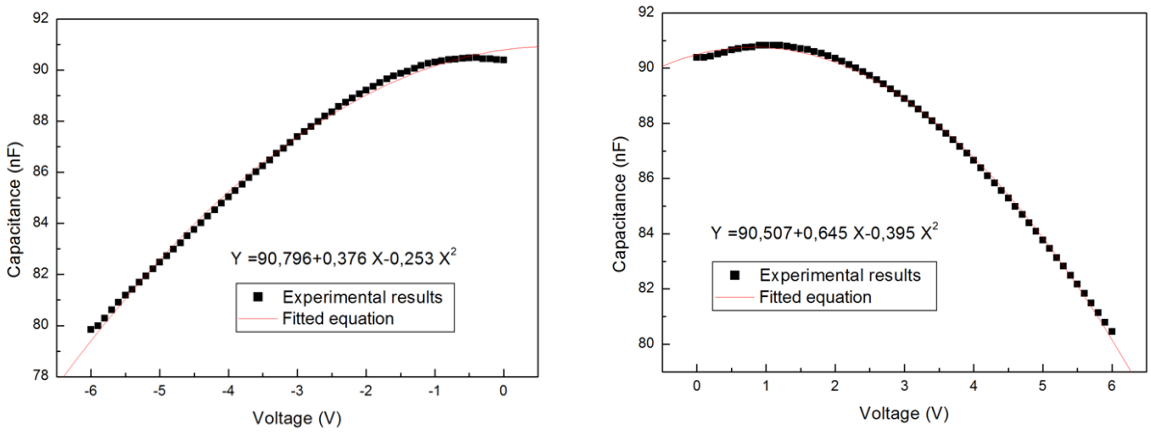



Fig.3: Experimental results of a 100nF SMD X5R dielectric capacitor at 296K.

Another important feature of the experimental curve seen in Figure 3 is the "DC bias characteristic". It shows a polarization of ferro-electric ceramics, being observed in all high dielectric constant type ceramic capacitors. This phenomenon is cumulative to the previous ones and is a consequence of the electric field generated by the bias applied to the capacitor, leading to a decrease in the capacitance of the component, when submitted to a specific BIAS voltage. In this case, it was perceived a decrease of approximately 12% in the capacitance for both biasing (positive and negative), what is a considerable feature to be considered by designers.

Concerning to the small shift perceived in both peaks of the curve due to the changing in the lattice from cubic to tetragonal, this small spontaneous polarization is a consequence of the small difference to the Curie point of pure Barium Titanate that is approximately 130ºC. It leads to the conclusion that just a small electric field is necessary to cancel the spontaneous polarization at this temperature once "easier is the reversal of the spontaneous polarization, higher is the capacitance" [14]. The positive biasing behavior is in accordance with the one previously presented by [10], but this graph shows the negative biasing as well. According to this curve, once the bias goes from -6V to 0V, the spontaneous polarization of the dielectric becomes smaller showing a higher capacitance and finding a maximum close to 0V.

Based on the previous graph, it was possible to fit the curve for both positive and negative bias, modeling it and showing the ferro-electric effect. Figures 4 a) and b) present the curves and their fitted equations. One can see that the behavior of the capacitor is mainly quadratic, for both directions of biasing. At room temperature, little differences can be seen on the peak capacitance, once the ferro-electric effect is very small.




a) b)

Figure 4: Experimental results and fitted equations at 296K under a) negative bias and b) positive bias.

Based on the previous analysis, and taking it as a standard pattern for further comparisons, the same measurements were done at cryogenic temperature (77K) and at its vicinities. In Figure 5 it is possible to perceive the behaviour of the X5R capacitors when exposed to a cryogenic and dry environment. In Fig.5, a big variation on the nominal capacitance can be achieved relating to the room temperature measurements, due to a much lower dielectric constant (Fig.1), explaining the high capacitance variation achieved (70%). The peak capacitance is almost one third of the previously measured (approximately 30nF), presenting an important parameter deviation from the nominal one and influencing highly the designing.

On the other hand, once at 77K the lattice changed to a Rhombohedral structure (according to Fig.1), it will show a higher shift relating to the results at room temperature, due to the higher spontaneous polarization and the longer distance from the Curie point.

Relating to the "DC bias characteristics", it was perceived an asymmetrical derivative of the capacitance behaviour for positive and negative biasing, consequence of the higher spontaneous polarization to which the dielectric is submitted under BIAS voltage. Both positive and negative bias lead to a 4.6% and 3.3% decrease in capacitance, showing also a difference in the peak of the curves. While the positive bias presented a similar shape to that verified at room temperature, the negative bias presented a peak at zero volts.

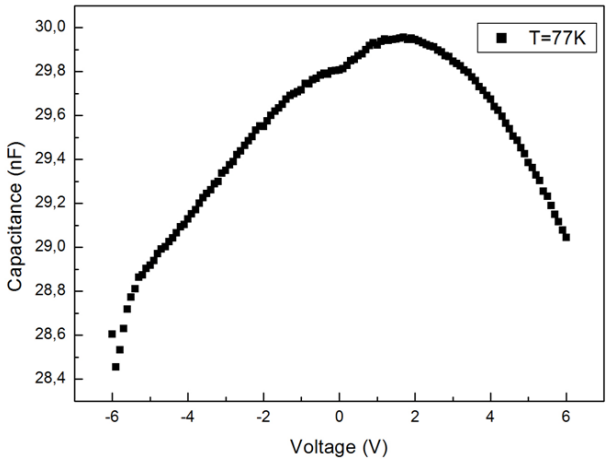
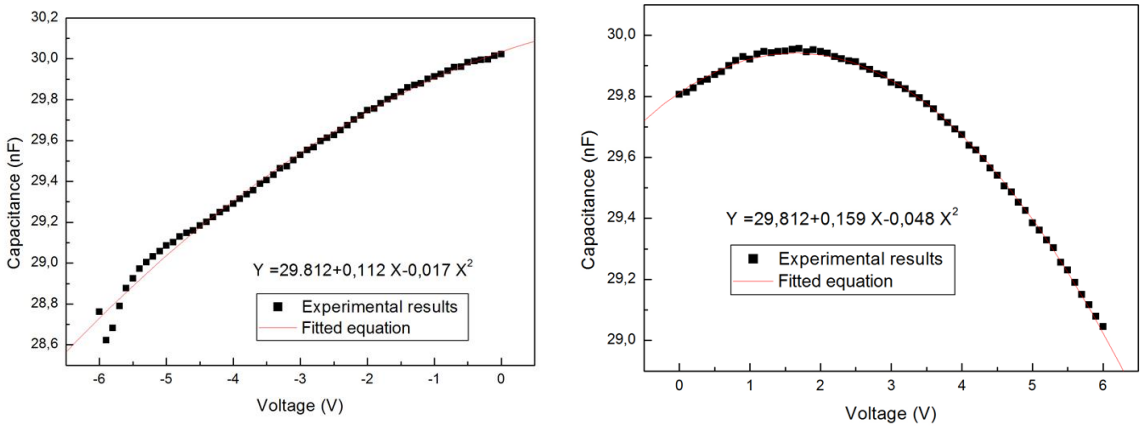



Fig.5: Experimental results of a 100nF SMD X5R dielectric capacitor at 77K.

Once again, the positive BIAS behavior is in complete accordance with the one previously presented by [10], but the negative biasing shows additional information to this content. For this curve, the negative biasing enforces the spontaneous polarization, becoming it stronger and hampering its cancelling, leading to a lower capacitance. The fitted curves for positive and negative bias showed a higher effect of the ferro-electric effect polarization (see Fig. 6 a and b). One can see that the behaviour of the capacitor remains quadratic, for both kind of biasing.




a) b)

Fig.6. Experimental results and fitted equations at 77K under a) negative bias and b) positive bias.

Finally, Fig. 7 shows a brief comparison of the capacitance behavior at 77K and its vicinities. As can be seen, the general behavior of the capacitance is the same in all three curves, showing a similar shape for all of them. Concerning to the peaks of each one of the curves, there cannot be seen a noticeable shift of the peaks (because all of them have the same lattice), for both bias (negative and positive), while a noticeable difference in the capacitance can be seen (the dielectric constant varies). Therefore, one can conclude that the effects of the temperature are much more decisive to the capacitor behavior at this range of temperatures than the spontaneous polarization effect. Also based on Fig.7, it can be seen that the capacitance steps between each one of the curves is not constant, although the difference in temperature is the same (7K). This measurement demonstrates the previously presented behavior of the dielectric that is not constant (shown in Fig.1). Once the dielectric can be approximated to linear in a short range around the target temperatures, it is expected that the capacitance behavior shows bigger steps, higher the temperature is. The only exceptions would be for those temperatures that present inflection points in Fig.1.

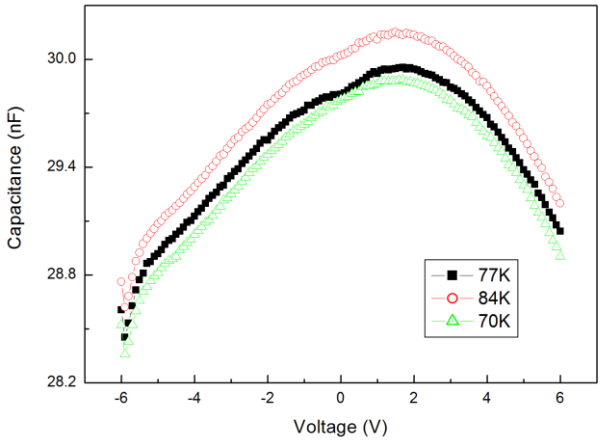



Fig.7. Experimental results for the experimental curves in the vicinities of the 77K.

Finally, through a comparison between the general behavior of the four curves at different temperatures (296K, 84K, 77K and 70K), it can be seen that even with a big decrease in capacitance due to the low temperature, the capacitance behavior concerning to the bias showed to be much more stable, once it is achieved a difference of approximately 3% in capacitance for the full range, instead of the 12% perceived at room temperature. These results indicate that it is possible to substitute a capacitor (designed for room temperature) for another one with three times the capacitance, reaching better performance, once the capacitance will be the same, but the sensitivity to bias will be decreased.

## V. CONCLUDING REMARKS

Characterization of 100nF SMD X5R dielectric ceramic capacitors are presented and discussed at room and cryogenic temperatures. Based on experimental results, these behaviors are physically analyzed, explaining the sensitivity of the capacitance to Voltage BIAS and temperature. Experimental results allow, as well, the modeling of their behavior for each one of the temperatures, at positive and negative BIAS, including the hysteresis.

A broader approach than previous works was presented, once it models the behavior of capacitors not only for positive bias [10] but also for negative ones, allowing the verification of the ferro-electric effect of the dielectric material and its consequences, like the hysteresis and difference in the minimum capacitances.

The used test bed allowed verifying the behavior not only in the Liquid nitrogen temperature, but also in its vicinities with high accuracy, making possible to understand the general behaviour of the capacitor and its pattern, which was not possible to verify in the previous works in literature. A dry chamber is also important in order to avoid thermal shocks in the components.

The three samples set of X5R ceramic capacitors showed similar performances and a strong temperature dependence due to their ferro-electric nature. When cooled from room temperature to 77K, this type of capacitors showed a 70% decrease in capacitance. The application of a DC bias causes further decrease in capacitance, as the bias voltage tends to hold the domains in place. It was presented, however, that although the decreasing in capacitance, a lower variation through the voltage range was achieved, tending to reach more "stable" capacitors in relation to bias condition. The achieved results allow the generalization of the model for X5R dielectrics, since the capacitors were chosen and placed randomly in the test bed. Additionally, a further understanding of the processes involved in dielectric and its consequences in the capacitor behaviour were provided.

It is believed that improvements in this area could result in additional enhancing in the capabilities of using capacitors as cryogenic devices, supporting sensor design knowledge. This would be a considerable advantage to sensor designers and manufacturers.

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