# High Field Capacitance-Temperature Behavior of $BaTiO_3$ Ceramic Disc Capacitors

C. K. CAMPBELL, FELLOW, IEEE, JACOBUS DANIEL VAN WYK, FELLOW, IEEE,
MAX FRIEDRICH KARL HOLM, AND JURGENS JOHANNES SCHOEMAN

*Abstract*—**Experimental and theoretical studies are reported on the capacitance-temperature (CT) characteristics of an undoped $BaTiO_3$ high voltage (1000 V) nonlinear ceramic disc capacitor with 3.6:1 capacitance ratio over the dc bias voltage range, for application to power electronic snubbers. CT responses for both the zero bias and 1000-V bias conditions are modeled, in terms of the polarization of permanent dipole moments. High field modeling employed a modified Langevin function, incorporating an empirical domain sensitivity parameter, together with a smeared Curie temperature.**

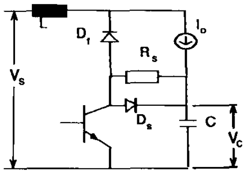


Fig. 1. Outline of an *RCD* turn-off snubber circuit, with stray inductance *L* included.

## I. INTRODUCTION

THIS PAPER is concerned with a study of the capacitance-temperature (CT) characteristics of high voltage **nonlinear** barium titanate ($BaTiO_3$) ceramic disc capacitors, under high field dc bias conditions. Such nonlinear capacitors have previously been investigated for their use in dissipative resistance-capacitance diode (*RCD*) snubber circuits [1] for power electronics circuits employing bipolar junction transistors (BJT's) or gate turn-off thyristors (GTO's) as the switching elements. *RCD* snubbers act to dampen the switching transient, to limit the excessive power dissipation peaks that can otherwise occur in these switch elements during the turn-off period [1]. Because a large snubber capacitance $C$ is required for good snubbing, the use of dissipative snubbers with linear capacitors becomes impractical at high voltage levels and high repetition frequencies, due to the large average power loss $P_r$ in the snubber resistor. This leads to the use of so-called regenerative snubbers to recover the capacitively stored energy, resulting in complicated and expensive circuit schemes [1]. Since the problem of dissipating or storing energy in the switching process is directly related to the amount of stored energy in the capacitor, an expensive alternative technique is to use a nonlinear capacitor in the snubber circuit [2]–[4]. In this application the nonlinear ceramic capacitor should satisfy the following criteria: i) a capacitance ratio of 3:1 or larger, in terms of initial-to-final dc bias voltage, ii) breakdown voltage in excess of 1000 V, iii) voltage excursions from 0 up to 500 V at repetition rates up to ultrasonic frequencies, iv) high current carrying capacity, v) acceptable power losses at these voltages, currents, and repetition rates, vi) long lifetime, with good reliability and very slow degradation, and vii) good CT stability—especially in the high biased state up to about 100°C. This last aspect is the focus of this paper.

A brief review is first given of *RCD* snubber essentials, with the rationale for using nonlinear snubber capacitors. This is followed by details of the fabrication of the undoped $BaTiO_3$ ceramic disc capacitors employed, together with CT measurements of device performance under zero bias and 1000-V bias. Modeling of these responses is then carried out, assuming the capacitance variation as a function of temperature is principally due to polarization of the ferroelectric permanent dipole moments. For the high bias field characteristics the modeling incorporates an empirical domain sensitivity parameter in the describing Langevin function, as well as a smearing of Curie temperatures for the individual microregions.

## II. *RCD* SNUBBER HIGHLIGHTS

Fig. 1 outlines the general form of an *RCD* snubber, where the ideal aim of capacitor $C$ is to provide zero voltage across the transitor when the current turns off. Energy stored in $C$ during the turn-off period by current flow through diode $D_s$ is subsequently dissipated in $R_s$ during the turn-on period. In the absence of stray inductance $L$, freewheeling diode $D_f$ will clamp the charged capacitor voltage $V_c$ to source voltage $V_s$ at the end of turn-off. Stray inductance $L$ will, however, cause $V_c$ to rise above $V_s$. Assuming that none of the stored energy $W_c$ is lost in the switch during the subsequent turn-on process interval, the energy loss $W_r$ in the resistor $R_s$ equals the stored energy $W_c$ in the capacitor:

$$W_r = W_c = \frac{1}{2} C_{\text{lin}} V_{\text{co}}^2 \qquad (1)$$

where $V_{\text{co}}$ = final capacitor voltage. Parasitic inductance $L$ in the circuit of Fig. 1 can considerably affect the switching transient during turn-off, giving rise to voltage overshoot (and additional energy storage) during this interval, which

---

Manuscript received February 27, 1990; revised July 16, 1990. This work was supported by the Foundation for Research Development, Pretoria, Republic of South Africa.

The authors are with the Energy Laboratory, Faculty of Engineering, Rand Afrikaans University, Johannesburg, 2000, Republic of South Africa.

IEEE Log Number 9039048.

0148-6411/90/1200-1124$01.00 © 1990 IEEE

can be detrimental to circuit rating and switch performance. Since a large snubber capacitance $C$ is required for good snubbing, the use of dissipative snubbers with linear capacitors $C_{\text{lin}}$ becomes impractical at high voltage levels and high repetition frequencies $f_s$, due to the large average power loss $P_r$ in the snubber resistor,

$$P_r = \left[\frac{1}{2} C_{\text{lin}} V_{\text{co}}^2\right] \cdot f_s. \tag{2}$$

A regenerative snubber, which recovers some of the stored energy, can be used as an alternative to the above mentioned dissipative linear snubber [5], [6], but this can be a complex and costly method.

With a nonlinear capacitor in the snubber circuit, its capacitance is initially relatively large at the start of the turn-off period, so that good snubbing is obtained. As the transistor switches off, however, the rising switch voltage $V_c$ causes $C$ to decrease as

$$C(V_f) \approx C_f + C_i \exp\left[-\frac{V_c}{\gamma V_s}\right] \tag{3}$$

where $C_f$ = final saturated capacitance, $C_i$ = initial capacitance of the exponential term, $\gamma$ = a curve factor, and $V_s$ = specified voltage of capacitor [3]. With such a nonlinear capacitor it has been shown that the same degree of snubbing at turn-off can result, although the stored energy is now reduced by about the ratio of initial-to-final capacitance [2]. When parasitic inductance is present in *RCD* snubber circuitry, it is important that the minimum capacitance of the biased nonlinear capacitor voltage be relatively insensitive to temperature variations, as this could lead to an undesirable increase in voltage overshoot across the transistor switch with rising temperature.

## III. EXPERIMENTAL

### *A. Fabrication*

$BaTiO_3$ ceramic disc capacitors were fabricated from undoped $BaTiO_3$ powder with about 1-$\mu$m grain size, as prepared by a wet oxalate process at 900°C [7]. Undoped powder was used so that normal operation would be well below the Curie–Weiss temperature [$\approx$ 128°C]. It was cold-pressed, without any binding flux, at a force of 50 kN in an Instron Type 1195 mechanical press. Typically, 1.5-g powder was employed in a die of 30-mm diameter, to yield after sintering thicknesses of about 1 mm. With the discs placed on an alumina surface [8], sintering was carried out in air for 20 h at 1100°C, with the furnace temperature raised by 200°C/h to the sintering temperature. Following natural cooling fo 24 h after furnace shut-down, thin-film aluminum electrodes (of 20-mm diameter, to minimize fringing flux inhomogeneities) were evaporated on both sides, to prevent migration of the subsequently applied silver contact paste applied [8].

### *B. Measurements*

Capacitance-voltage-temperature (CVT) measurements were carried out at 1 kHz, with an ac bridge operating under small signal ($\approx$0.5 V) conditions. The bridge itself was coupled to the test capacitor through two 2.2-$\mu$F series-connected high voltage linear capacitors, to isolate the dc supply source. DC bias up to 1000 V was applied to the test capacitor through two 2.2-M$\Omega$ protective series resistors.

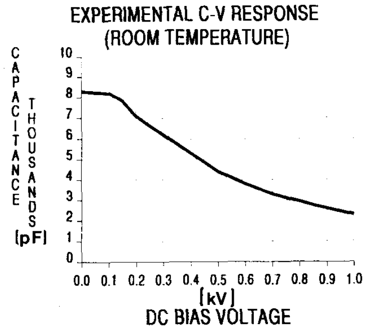
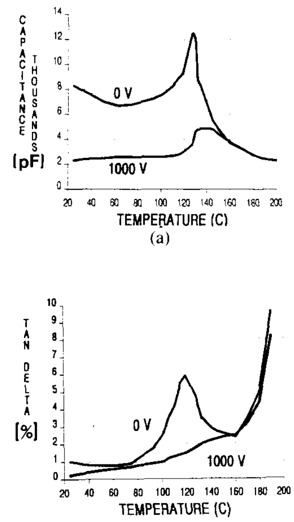


Fig. 2. Measured room temperature $C$–$V$ response of $BaTiO_3$ capacitor up to 1000-V bias.



(a)

(b)

Fig. 3. (a) Measured CT responses for capacitor under zero bias and 1000-V bias, from 20 to 200°C. (b) Corresponding tan $\delta$ responses.

### *C. Results*

Fig. 2 shows the measured room temperature (24°C) capacitance of a sample $BaTiO_3$ disc capacitor, as a function of dc bias up to 1000 V. The capacitance decreased from 8300 to 2300 pF under this bias, for a capacitance ratio of 3.6:1. The effective dielectric constant $K \approx 2800$ at maximum capacitance at room temperature. Also, the dissipation factor tan $\delta$ decreased from 1 to 0.2% over this bias range. Fig. 3(a) shows the measured CT response of this specimen at test temperatures from 20 to 200°C, for bias voltage extremes of 0 and 1000 V. As shown, the minimum capacitance remained essentially, and desirably, constant up to about 100°C. Fig. 3(b) shows the corresponding dissipation factor, tan $\delta$, for these two bias voltage values. A discussion of these responses, with a view to modeling the CT characteristics, is given in the following.

## IV. Analysis and Modeling

### *A. Overall Characteristics*

The overall capacitance of these $BaTiO_3$ ceramic disc capacitors may be attributed to a combination of space charge capacitance across grain boundaries [9]-[12], together with ferroelectric capacitance contributions from the ceramic grains themselves. The donor states at grain boundary interfaces should, however, be fairly completely excited at room temperature. Thus while the $C-V$ response will be due to a combination of a) space charge polarization at grain boundaries and b) grain ferroelectricity, the CT responses of Fig. 3(a) and Fig.3(b) may be attributed principally to ferroelectric effects in the ceramic grains, with an initially pseudorandom distribution of domains under zero bias. We thus postulate that these CT responses are principally due to the polarization of permanent dipole moments.

In Fig. 3(a) the fact that the peak of the dielectric constant is not coincident with the peak of the dielectric loss is consistent with the presence of a diffuse phase transition in the Curie range, associated with structural disorder and compositional fluctuations. This result is generally encountered in ceramics and materials with mixed phases [12]. Moreover, the temperature difference between the peak dielectric constant and the peak dielectric loss is an outcome of the Kramers-Kronig relations where there is a temperature dependent relaxation at temperatures close to the Curie temperature of the individual microregions in the polycrystalline ceramic [8], [12]. As well, since the Curie temperature of a mixed system is sensitive to compositional changes and stress, the shift of the peak dielectric constant to higher temperatures under a dc bias, as shown in Fig. 3(a), is not unexpected. This field dependent phenomenon is also encountered in conventional Devonshire ferroelectrics with first-order phase transitions at the Curie temperature [12]. In the analysis of the zero field and high field capacitance characteristics given in the following, we assume that a) the grain boundary capacitance is large compared with the grain capacitance, and b) the ferroelectric gain capacitance variations are primarily due to the polarization of permanent dipoles in the pseudorandomly oriented grain and domain structure in the polycrystalline material.

### *B. Zero Bias Response*

The decrease of the zero bias capacitance in Fig. 3(a) over the temperature range from 20 to 70°C is indicative of a temperature dependent relaxation process. For a pure compound with permanent electric dipoles under low-field excitation, the Debye equations yield the complex molar polarizability $[\hat{P}]$ in the form [13], [14]

$$[\hat{P}] = \frac{N_a}{3\epsilon_0}\left[\frac{p^2}{3kT}\,\frac{1}{1+j\omega\tau^*}\right] \tag{4}$$

where $N_a$ = Avogadro's number, $p$ = permanent dipole moment, $\tau^*$ = intrinsic relaxation time, $\epsilon_0$ = permittivity of free space, $\omega$ = angular frequency, $T$ = temperature, and $k$ = Boltzmann constant. In applying (4) to the polycrystalline ceramic, we assume that $p = p_d$, for a pseudorandom ordering of individual domains of equal total moment $p_d$. From (4) we see that effective permittivity $K$ should decrease linearly with $T$; in agreement with the initial slope of the zero bias curve in Fig. 3(a) up to about 70°C—before being masked by the phase transition permittivity change, with Curie temperature $T_c \approx 128°C$. Here, the permittivity change for the phase transition around the Curie temperature is approximated as proportional to $G/(A + |T - T_c|)$, where $A$ and $G$ are constants, so that the average permittivity $K$, and capacitance $C$, under zero dc bias is appoximately proportional to

$$K(T, V=0) \approx \frac{1}{(B+T)}\left[\frac{G}{(A+|(T-T_c)|)}\right] \tag{5}$$

where $B$ = constant. This response is modeled in Fig. 4, with constants $A = 22$ and $B = 22$, and $G$ chosen to scale the upper curve in Fig. 3(a).

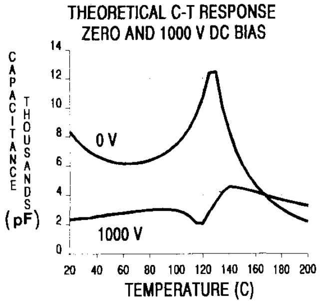


Fig. 4. CT modeling of the experimental responses of Fig. 3(a).

### *C. High Field Response*

In characterizing the CT response under high dc bias field excitation we employ a modified Langevin function $L(a)$ for permanent dipole polarization:

$$L(a) = \coth(a) - \frac{1}{a} \tag{6}$$

where the normal Langevin parameter $a = p \cdot E/kT$ is replaced here by $a = \alpha_d \cdot p \cdot E/k \cdot T_c^*$, to include a domain sensitivity factor $\alpha_d$ catering for the increased sensitivity of the Curie range to external influences such as electric fields—as well as a smeared Curie temperature $T_c^*$ for individual microregions [12]. Thus the polarization well below the Curie range is

$$P = N_d p_d L(a) \tag{7}$$

where $N_d$ = domain density. When the permittivity change over the Curie range is included in (7), we obtain an expression for the high field CVT dependence as

$$C(V,T) \approx \frac{FC_0}{D + |T - T_c^*|} \cdot \left[1 - \coth\left(\frac{\alpha_d pE}{kT_c^*}\right) + \frac{kT_c^*}{\alpha_d pE}\right] \tag{8}$$

where $F$ and $D$ are constants and $C_0$ is the zero-bias capacitance at room temperature. In relating (8) to the experimental high field CT response in Fig. 3(a) we employ an empirical domain sensitivity parameter $\alpha_d$ in the form

$$\alpha_d = \frac{T}{H + |T - T_c^*|} \tag{9}$$

where $H$ = a constant. It may be considered as reflecting the sensitivity of the phase transition to parameters such as electric field. Its inclusion was empirically necessary here, in order to approximate the relatively constant experimental CT response in Fig. 3(a), up to about 100°C. The lower curve in Fig. 4 shows a plot of (8) thus obtained with $D = 75$, $F = 60$, $H = 10$, and $T_c^* = T_c \pm 10°$ with $T_c = 128°$. Scaling factor $F$ is included here, to cater for both the grain-boundary capacitance and grain ferroelectricity contributions to the $C-V$ response at constant temperature. Note that the temperature shift of the capacitance peak, relative to that for the zero-bias condition, is in reasonable agreement with the experimental result in Fig. 3(a).

## V. DISCUSSION

Experimental and theoretical studies have been conducted on undoped high voltage BaTiO$_3$ ceramic disc capacitors with nonlinear $C-V$ characteristics, for possible application of these devices to $RCD$ snubbers in power electronic switches. In this application it is desirable that the minimum capacitance under high field bias remain relatively constant over a wide temperature range, as is indeed observed here. In an analysis of these experimental responses a Langevin function modeling approach was used in the determination of the polarization of the ferroelectric grains, to which these CT characteristics were principally attributed. This function was originally derived to treat the ordering of noninteracting dipoles in an ordering electric field. In applying this methodology here, it was tacitly assumed that while the ferroelectric domains within the individual grains have strong interaction and coupling, the collective system of grains in the ceramic allowed for an electric field alignment of initially pseudorandomly oriented domains, with weak coupling between those in adjacent grains. Moreover, the high field model incorporated an empirical domain sensitivity parameter, as well as a smeared Curie temperature, that yielded good agreement with experiment.

It has been pointed out that since these ceramics were sintered on alumina substrates, the introduction of alumina impurities cannot be excluded: even at the relatively low sintering temperature employed here. Such impurities, segregating at grain boundaries, could influence the polarization mechanisms significantly. To this end, the alternative use of zirconia substrates is under examination.

## ACKNOWLEDGMENT

The authors are indebted to Dr. G. Overbeek of the Anglovaal Research Laboratory, Florida, South Africa, for providing ceramic materials, as well as analytical and electron microscope facilities.

## REFERENCES

[1] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power Electronics: Converters, Applications and Design.* New York: Wiley, 1989, ch. 20, pp. 522-532.

[2] C. G. Steyn and J. D. van Wyk, "Optimum nonlinear turn-off snubbers: Design and application," *IEEE Trans. Indust. Appl.*, vol. 25, pp. 298-306, Mar./Apr. 1989.

[3] ——, "Study and application of nonlinear turn-off snubber for power electronic switches," *IEEE Trans. Indust. Appl.*, vol. IA-22, pp. 471-477, May/June 1986.

[4] A. G. K. Lutsch, J. D. van Wyk, and J. J. Schoeman, "On the evaluation of ferroelectric nonlinear capacitors for application in power circuits," *IEEE Trans. Comp., Hybrids, Manuf. Technol.*, vol. 12, pp. 352-357, Sept. 1989.

[5] A. Ferraro, "An overview of low-loss snubber technology for transistor converters," in *IEEE PESC'82 Rec.*, June 1982, pp. 466-467.

[6] F. C. Zach, K. H. Kaiser, J. H. Kolar, and F. J. Haselsteiner, "New loss-less turn-on and turn-off (snubber) networks for inverters, including circuits for blocking voltage limitation," *IEEE Trans. Power Electron.*, vol. PE-1, pp. 65-75, Apr. 1986.

[7] W. S. Clabaugh, E. M. Swiggard and R. Gilchrist, "Preparation of barium titanate oxylate tetrahydrate for conversion to barium titanate of high purity," *J. Res. Nat. Bur. Stand.*, vol. 56, research paper 2677, pp. 289-291, 1955.

[8] J. C. Burfoot and G. W. Taylor, *Polar Dielectrics and Their Applications.* London, UK: Macmillan, 1979, ch. 2, p. 31.

[9] W. Heywang, "Semiconducting barium titanate," *J. Mat. Sci.*, vol. 6, pp. 1214-1226, 1971.

[10] H. D. Park and D. A. Payne, "Characterization of internal boundary capacitors," in L. M. Levinson and D. C. Hill, Eds., *Grain Boundary Phenomena in Electronic Ceramics, Advances in Ceramics, vol. 1.* Columbus, OH: American Ceramic Society, 1981, pp. 242-253.

[11] G. H. Jonker, "Equilibrium barriers in PTC thermistors," in L. M. Levinson and D. C. Hill, Eds., *Grain Boundary Phenomena in Electronic Ceramics, Advances in Ceramics, vol. 1.* Columbus, OH: American Ceramic Society, 1981, pp. 155-166.

[12] M. E. Lines and A. M. Glass, *Principles and Applications of Ferroelectrics and Related Materials.* Oxford, UK: Clarendon, 1977, ch. 8, pp. 285-292.

[13] C. J. F. Bottcher, *Theory of Electric Polarization.* New York: Elsevier, 1952, ch. 10, pp. 355-363.

[14] J. C. Anderson, *Dielectrics.* London, UK: Chapman and Hall, 1964, ch. 6, pp. 67-82.