Multilayer Ceramic Capacitors: Mitigating Rising Failure Rates

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Abstract
The multilayer ceramic capacitor (MLCC) has become a widely used electronics component both for surface mount and embedded PCB applications. The MLCC technologies have gone through a number of material and process changes such as the shift from precious metal electrode (PME) configurations which were predominantly silver/palladium to base metal electrodes (BME) dominated by nickel. Each of these changes were accompanied by both quality and reliability problems. The MLCC industry is now in the midst of an unprecedented set of challenges similar to the Moore's Law challenges being faced by the semiconductor industry. While capacitor failures have historically been responsible for a significant percentage of product field failures (most estimates are ~30%) we are seeing disturbing developments in the low voltage (<250V) commodity part infant mortality and wearout failure rates.

Introduction
Seven decades after its discovery, the ferroelectric material, barium titanate ($BaTiO_3$) has established itself as the most widely used dielectric material used in the construction of multilayer ceramic capacitors (MLCCs) both because of its intrinsic properties and its amenability to property modification with dopant materials and process variants [1].

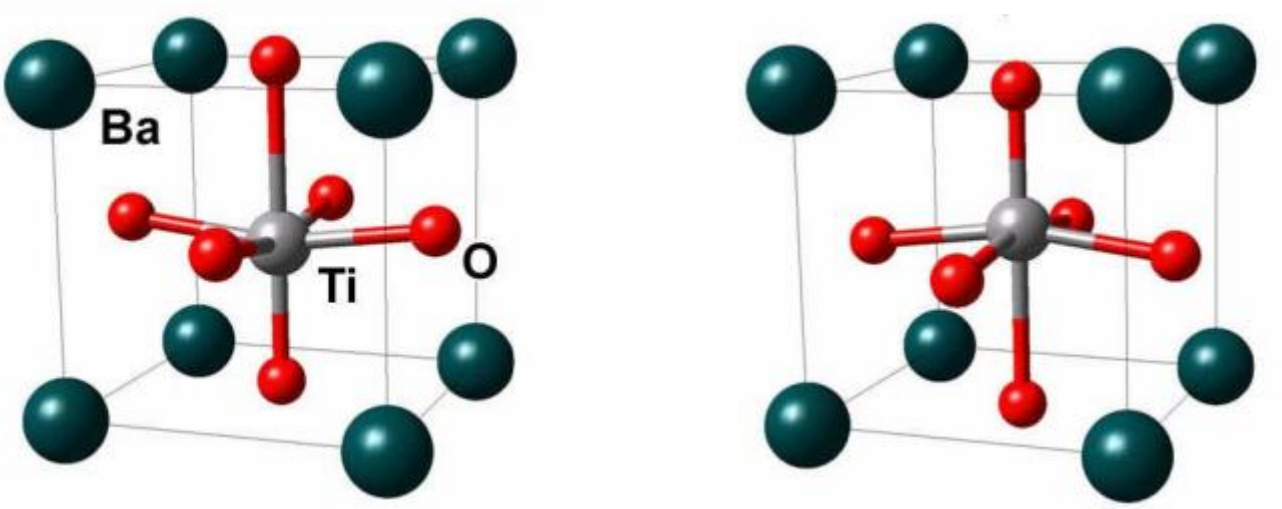

Figure 1 – Electric Field Polarity Driven Displacement of Ti Cation within $BaTiO_3$ Unit Cell Structure [2]

Scaling up from the cell to the ferroelectric domain and crystal structure, the dielectric properties of $BaTiO_3$ are dominated by the polarization versus electric field (P vs. E) hysteresis responses.

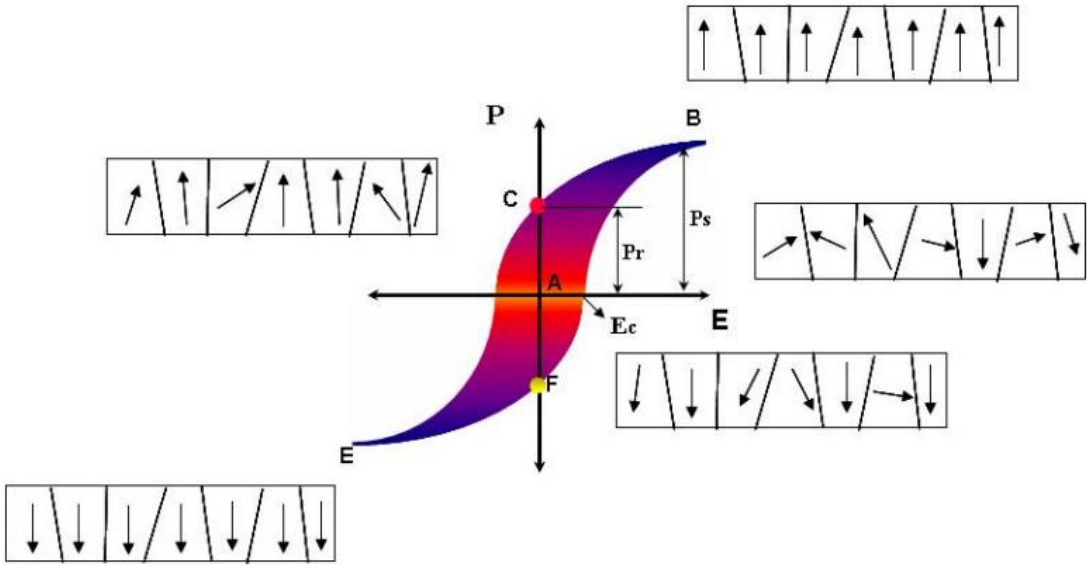

Figure 2 – Polarity Domain Structures and P vs. E Hysteresis [3]

The unit cell structure of $BaTiO_3$ shifts with temperature into different crystalline phases, each having different electrical and mechanical properties. Of particular interest for the performance of MLCCs is the shift at the T_C Curie point (~120°C) from <100> polarized tetragonal at room temperature to non-polar cubic.

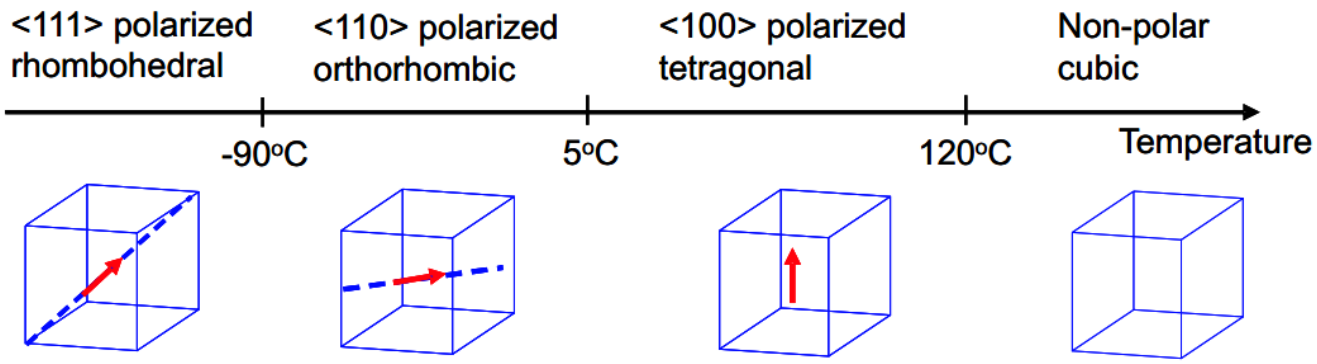

Figure 3 – Various Phases of $BaTiO_3$ Unit Cell Structure [4]

The MLCC electrical performance is dramatically affected at temperature transitions above and below the Curie point because the capacitor's $BaTiO_3$ dielectric constant is likewise dramatically changed.

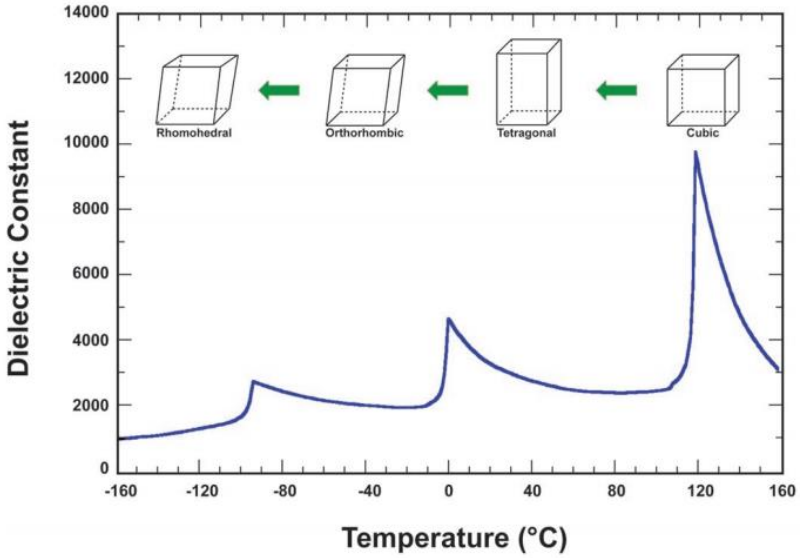

Figure 4 – Various Phases of $BaTiO_3$ Unit Cell Structure and Resultant Changes in Dielectric Constant [5]

MLCC Configuration and Production

Capacitors consist of two or more conductive plates (also called internal electrodes) separated by a dielectric material. As clearly denoted by the term 'multilayer ceramic capacitor' the dielectric material for MLCCs is a ceramic. The structure is shown in Figure 5.

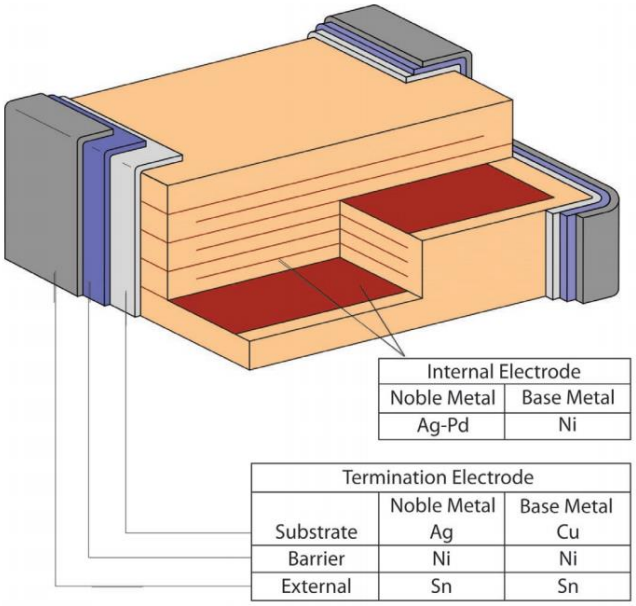

Figure 5 – MLCC Structure and Material Sets [5]

Most MLCCs are produced by a co-firing process where the internal electrodes and the ceramic materials are heated simultaneously. In such a process, the material integrity of the metallic and ceramic substances must be maintained which means choosing materials that do not substantially interact. Early MLCC conductive plates were made from precious metal electrode (PME) materials.

Previous work [6] introduced the CPS (conceptual product space) reliability model (Figure 6) as a practical visual representation of how the driving forces of technology, cost, and performance have merged to affect product reliability. These first MLCC parts, which had PME material sets, were suitable for harsh environment and long product lifetime applications. As the revenue center of gravity (RCG) shifted to consumer electronics and the PME materials, particularly palladium, became more expensive, demand rose for base metal electrode (BME) configurations.

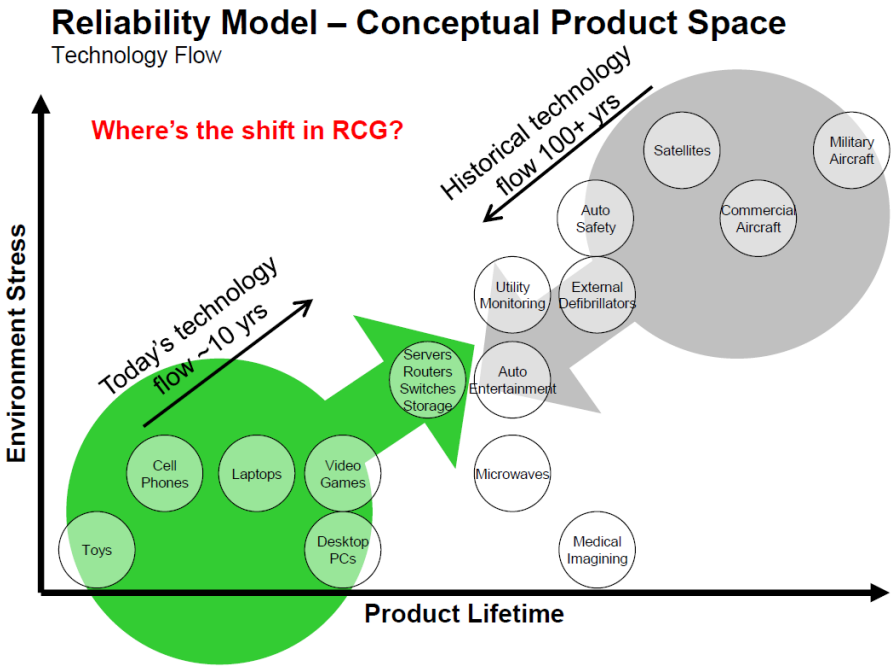

Figure 6 – Conceptual Product Space Reliability Model [6]

The production process for MLCCs typically begins with casting the dielectric from a ceramic slurry; the inner electrode materials are then printed onto the dielectric, which is stacked, laminated, cut into shape, the placed in an oven for binder burn out and sintering.

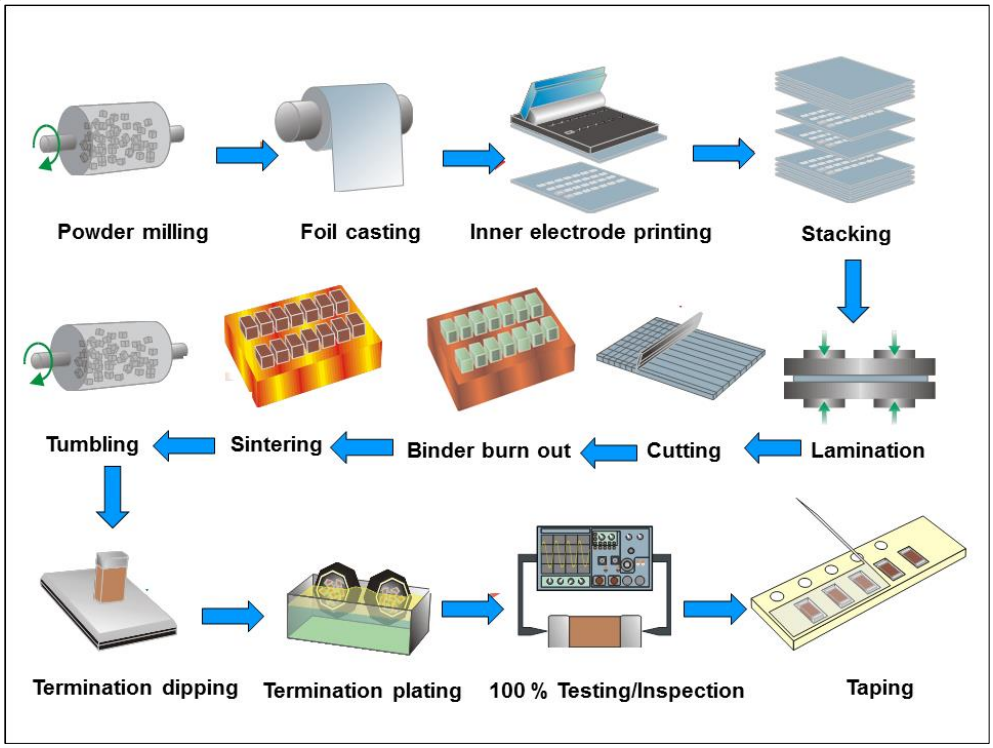

Figure 7 – Simplified MLCC Manufacturing Process [7]

With the move from PME to BME configurations, new binder burn out and sintering processes were required. Whereas the PME parts required temperatures ~1100°C, BME parts required temperatures ~1300°C. The nickel in the BME electrodes readily oxidized during firing. This required changing the sintering atmosphere, see Table 1, in the processing kilns from the previous standard nitrogen/oxygen to a controlled chemically reducing atmosphere [8].

Table 1 – Kiln Environment MLCC Manufacturing

Operation	PME Atmosphere & Heating	BME Atmosphere & Heating
Sintering	Air at 1150°C	Nitrogen and hydrogen with PO_2 $<10^{-8}$ atmosphere, 1350°C
Re-oxidation	Not required	Nitrogen and hydrogen with PO_2 10^{-8} to 10^{-4} atmosphere, 1000°C

Oxygen Vacancies: Migrations and Effects

The chemically reducing kiln atmosphere doesn't just remove the oxygen from the BME structure; it also removed some of the oxygen from the $BaTiO_3$ dielectric leaving oxygen vacancies behind. These oxygen vacancies not only disrupt the dielectric properties of the ceramic, but also induce a PN junction behavior and create asymmetrical insulation resistance.

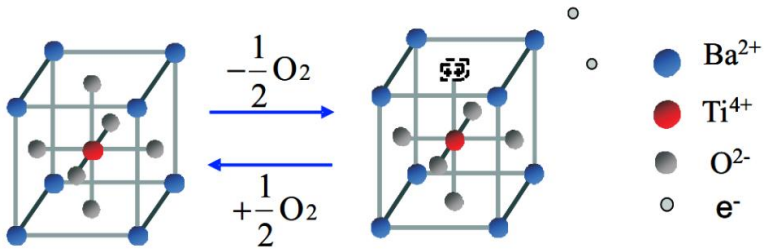

Figure 8 – Creation of Oxygen Vacancies in $BaTiO_3$ Unit Cell Structure [4]

The re-oxidation operation noted in Table 1 is not 100% effective in returning the missing oxygen to the $BaTiO_3$ dielectric and even after its successful completion, oxygen vacancies remain.

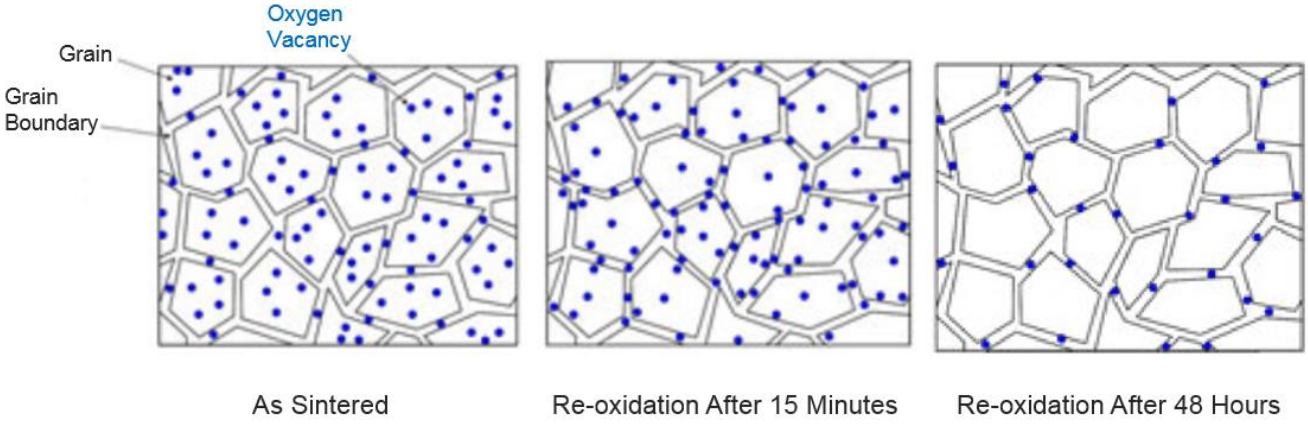

Figure 9 – Effect of Re-oxidation Time on Oxygen Vacancy Distribution [9]

Under the influence of time and voltage, those remaining oxygen vacancies migrate and preferentially collect at the interfaces of the inner electrodes and dielectrics.

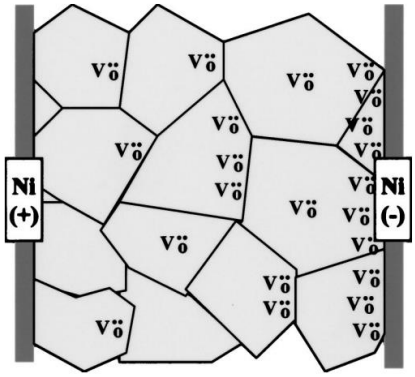

Figure 10 – Schematic Representation of Oxygen Vacancies (Vö) Collecting at Ni- Electrode [10]

Industry Concerns

At the 2010 Capacitor and Resistor Technology Symposium (CARTS) industry concerns were raised about the effect of oxygen vacancy migration exacerbated by higher capacitance MLCCs appearing in smaller and smaller packages.

"Up until recently, failure due to dielectric wear out was not a concern for the capacitors used to support CPUs. Our reliability models showed that the capacitors could be used for thousands of years before the insulation resistance would begin to degrade. In the last five years, we have noticed a disturbing trend, as the capacitance density has increased; the usable life has reduced to hundreds, then tens of years and now even less than five years.

Going forward, we see reduced reliability margins impacting capacitor supplier roadmaps and posing an increased risk for applications using decoupling MLCCs. Many users don't truly understand the risk they are taking because the industry standard Life Test is inadequate for describing the expected reliability of MLCCs." [11]
This was followed by similar concerns. [12] [13]

Failure Confirmation of Production MLCCs

Recent test and field failures of MLCCs have confirmed those concerns. All these failures have been loss of insulation resistance (IR) also described as DC leakage.

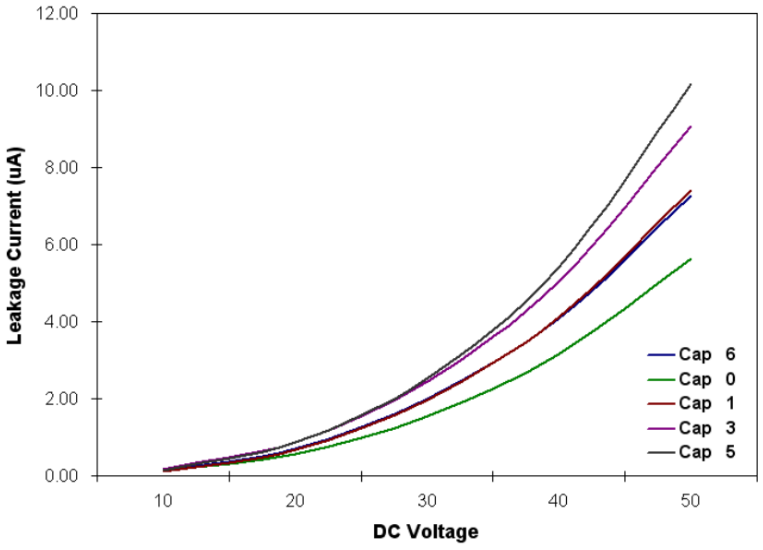

Figure 11 – Confirmation of Oxygen Vacancy Migration Failure

Field failures have been confirmed for MLCC applications where DC leakage fell substantially below the manufacturer's datasheet specification in 14 months, far below the 5 to 8 years projected in [11]. One conclusion in that 2010 CARTS paper was, "given the complexity of today's electronic devices and the reduced reliability margins of high CV capacitors, designers must pay special attention to reliability requirements of their system and the long term reliability of the capacitors . . ." To mitigate rising MLCC failure rates, that was advice worth heeding in 2010 and remains valid today.

References

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