

Defect Engineering of BaTiO₃ Thin Films for High-Energy-Density Capacitor Applications

Dylano van Grinsven

Department of Electrical Engineering and Computer Science, University of Missouri,
Columbia, MO, USA.

vangrinsvendylano@missouri.edu

Shaurya Sami

Department of Electrical Engineering and Computer Science, University of Kansas, Lawrence,
KS, USA.

shauryawork@ku.edu

Abstract

Defect engineering in barium titanate thin films has become a central materials strategy for increasing the energy density, efficiency, and reliability of capacitors used in electrified transport, pulsed power, renewable energy conversion, and distributed grid infrastructure. This paper examines BaTiO₃ thin-film capacitors as socio-technical systems rather than isolated materials problems. It analyzes how oxygen vacancies, acceptor and donor doping, grain boundaries, interface states, strain, and nanodomain configurations influence permittivity, leakage current, breakdown strength, fatigue, and thermal stability. The discussion emphasizes structural trade-offs: strategies that increase permittivity often reduce breakdown strength or accelerate degradation, while defect passivation that improves reliability may lower effective polarization. Processing pathways, including chemical solution deposition, physical vapor deposition, atomic layer deposition, and aqueous tape casting for ultrathin multilayer ceramic capacitors, are compared in terms of defect control, scalability, and environmental burden. The paper then links materials architecture to manufacturing infrastructure, metrology, standards, supply-chain governance, critical raw materials, and policy. It argues that high-energy-density BaTiO₃ capacitors require coordinated innovation across defect chemistry, interface engineering, quality assurance, and responsible materials governance. Robust deployment depends not only on laboratory energy density but also on accelerated lifetime prediction, thermal management, recyclability, fair access to critical materials, and transparent standards. The conclusion identifies research priorities for balancing performance, reliability, sustainability, and equity in next-generation capacitor systems.

Keywords

defect engineering; barium titanate; thin films; high-energy-density capacitors; dielectric reliability; manufacturing infrastructure; materials governance; sustainability.

1. Introduction

The accelerating electrification of energy systems has made dielectric capacitors critical components in power electronics, pulsed-power supplies, electric vehicles, renewable-energy inverters, medical devices, and defense platforms. Ferroelectric ceramics have long occupied a central position in this landscape because their high permittivity permits compact charge storage and rapid discharge [1]. Modern ferroelectric applications extend across memory,

sensing, actuation, and energy conversion, but capacitor applications impose particularly stringent demands on breakdown strength, leakage current, thermal stability, and fatigue resistance [2]. Within this context, barium titanate thin films are attractive because they combine a perovskite structure, high intrinsic polarization, and compatibility with multilayer architectures that can be integrated into dense electronic packages [3]. However, the same defect chemistry that makes BaTiO₃ versatile also creates reliability hazards, especially when films are scaled below several hundred nanometers and subjected to high electric fields.

Multilayer ceramic capacitors have evolved through base-metal electrode systems, refined powder processing, and thin dielectric layers, enabling enormous volumetric capacitance in commercial devices [4]. Yet the pathway from laboratory-scale BaTiO₃ films to deployable high-energy-density capacitors is not merely a matter of maximizing permittivity. Ceramic capacitors must balance capacitance, breakdown strength, dielectric loss, insulation resistance, temperature coefficient, and lifetime under bias, humidity, and thermal cycling [5]. Energy storage in ceramic dielectrics depends on the interplay between polarization response and electrical breakdown, and early studies already recognized that useful energy density is constrained by nonlinear dielectric behavior and defect-mediated conduction [6]. Defect engineering therefore becomes a system-level design discipline: it must coordinate thin-film deposition, interface control, electrode chemistry, packaging, testing, and supply-chain realities.

BaTiO₃ thin films are especially sensitive to oxygen vacancies, cation nonstoichiometry, grain boundaries, and interfacial dead layers. These defects can enhance permittivity through domain-wall mobility and local field amplification, but they can also increase leakage, lower breakdown strength, and promote fatigue. The central challenge is not to eliminate defects entirely, since complete defect elimination is often impractical and sometimes undesirable in ferroelectrics, but to distribute and stabilize defects in ways that improve energy density without compromising reliability. This paper argues that defect engineering for high-energy-density BaTiO₃ capacitors should be understood as an infrastructure problem. It involves architectural choices at the device level, governance choices at the manufacturing level, and policy choices at the materials-system level. The following sections examine defect chemistry, processing pathways, system-level trade-offs, manufacturing infrastructure, sustainability, fairness, and policy implications.

2. Defect Chemistry and Thin-Film Architecture in BaTiO₃ Capacitors

The defect chemistry of BaTiO₃ is dominated by oxygen vacancies, acceptor impurities, donor dopants, and cation vacancies. Oxygen vacancies are mobile under high electric fields and elevated temperatures, and their migration can lead to resistance degradation, electrode interface reduction, and local stoichiometric imbalance [3]. In thin films, the density of such defects is strongly affected by deposition atmosphere, annealing temperature, oxygen partial pressure, and electrode materials. Acceptor doping can immobilize oxygen vacancies and improve insulation resistance, but it may also pin domain walls and reduce permittivity. Donor doping can enhance conductivity and domain-wall response, yet excessive donor states may increase leakage and undermine high-field reliability. The design problem is therefore not a simple optimization of one defect species but a multi-objective balancing of polarization, conduction, breakdown, and aging.

Grain boundaries and interfaces add another layer of complexity. In bulk ceramics, grain boundaries often act as barriers to charge transport and as regions of space-charge segregation. In thin films, the surface-to-volume ratio is much higher, so film-electrode interfaces,

substrate-film interfaces, and columnar grain boundaries dominate electric-field distribution. Interfacial dead layers can reduce effective permittivity, while locally reduced regions can concentrate field and initiate breakdown. Defect dipoles and trapped charges near interfaces may contribute to imprint, fatigue, and asymmetric leakage. Consequently, defect engineering must be integrated with interface engineering. The goal is to create internal fields and chemical gradients that stabilize oxygen sublattices, suppress electronic trap-assisted conduction, and preserve polarization switching under repeated cycling.

Comparisons with polymer and nanocomposite dielectrics clarify the uniqueness of BaTiO₃ thin films. Polymer dielectrics can offer high breakdown strength, low loss, and graceful failure, and they have achieved impressive energy densities in laboratory systems [8]. Polymer nanocomposites attempt to combine high permittivity fillers with flexible matrices, but they often suffer from agglomeration, interfacial defects, and reduced breakdown strength [11]. BaTiO₃ ceramics offer higher permittivity and thermal stability, but they are brittle and defect-sensitive. BaTiO₃-based solid solutions and multilayer architectures have demonstrated improved energy storage by tuning relaxor behavior and reducing remnant polarization [12]. The lesson is that defect engineering in BaTiO₃ is not solely about suppressing defects; it is about designing a defect landscape that favors high polarization with low hysteresis, high resistivity, and delayed breakdown.

Thin-film architecture also matters at the level of strain and crystallographic orientation. Lattice mismatch with substrates can impose biaxial strain that alters polarization, domain stability, and phase transitions. Strain can enhance ferroelectricity in some orientations but can also generate misfit dislocations and vacancy sinks. Columnar grains may provide vertical pathways for leakage, whereas equiaxed grains may distribute field more uniformly but introduce more grain-boundary volume. Multilayer stacks with alternating dielectric compositions can block treeing and redistribute field, but they introduce interdiffusion and thermal expansion mismatch. Thus, defect chemistry must be considered together with microstructure, texture, and stack design. The most promising films are likely to be those in which point defects, grain boundaries, and interfaces are co-designed rather than treated as independent variables.

3. Processing, Interfaces, and Defect Control Across Length Scales

Processing determines which defects exist, where they reside, and how they evolve during operation. Chemical solution deposition offers compositional flexibility and low capital cost, but it can leave organic residues and porosity that seed leakage and breakdown. Physical vapor deposition provides dense films and precise thickness control, yet it may introduce point defects and stress gradients. Atomic layer deposition enables exceptional conformality and interface control, but its throughput and cost remain challenging for thick high-energy-density layers. Each route creates a distinct defect signature, and the same post-deposition annealing step may heal one defect while activating another. A broad review of dielectric materials for energy storage emphasizes that energy density, efficiency, and reliability are coupled through processing history rather than determined by composition alone [13].

For high-energy-density capacitor films, the most important processing objective is often not maximum crystallinity but controlled defect passivation. Oxygen annealing can reduce oxygen vacancies, yet it may oxidize base-metal electrodes and create interfacial phases. Reducing atmospheres protect electrodes but can increase vacancy concentration. Rapid thermal processing can limit interdiffusion but may leave residual strain. Thickness scaling increases capacitance per unit area but also increases the probability of a critical defect within

the active volume. Consequently, reliability engineering must treat defect populations statistically. A film with excellent average properties may still fail if a small fraction of regions contains connected vacancy clusters, pores, or interfacial protrusions. Metrology that captures rare defects is therefore as important as average dielectric characterization [14].

Recent work on aqueous tape casting of BaTiO₃ films for ultrathin multilayer ceramic capacitors illustrates how processing architecture can address both performance and manufacturability [15]. Aqueous systems reduce the use of volatile organic solvents, but they require careful control of binder chemistry, slurry stability, drying stresses, and burnout profiles. The resulting green bodies must densify uniformly while avoiding carbon residues, porosity, and compositional segregation. When successful, such approaches can produce thin dielectric layers with improved uniformity and lower environmental burden, which is essential for scaling high-energy-density capacitors into commercial multilayer formats. The broader implication is that defect engineering begins before deposition or sintering, in the formulation and drying stages that determine particle packing and interface chemistry.

Beyond single-layer films, interface engineering across the entire stack is critical. Electrode materials influence Schottky barriers, oxygen exchange, and interfacial resistance. Buffer layers can block cation diffusion and reduce dead-layer effects. Nanodomain engineering can lower switching barriers and improve energy efficiency by promoting reversible polarization rather than irreversible domain wall motion [16]. Lead-free perovskite dielectrics have also advanced through compositional design and defect compensation, offering pathways to avoid toxic elements while maintaining high energy storage [17]. Antiferroelectric thin-film capacitors demonstrate that phase transitions can be harnessed for high energy density and fast discharge, but they also require precise control of switching fields and fatigue [18]. These examples show that processing, interfaces, and defect chemistry form a single integrated design space.

4. System-Level Trade-Offs: Energy Density, Efficiency, Reliability, and Thermal Management

At the system level, high energy density is never an isolated figure of merit. Capacitors must deliver charge rapidly, recover efficiently, and survive repeated charge-discharge cycles without excessive heating. A film with high permittivity may store more charge at low field, but if its breakdown strength is low, the usable energy density may be modest. Conversely, a film with very high breakdown strength may store less charge per unit volume if its permittivity is low. The practical optimum depends on converter topology, voltage rating, cooling strategy, and lifetime requirements. Defect engineering can shift this trade-off, but it cannot eliminate it. For example, acceptor doping may improve resistivity and breakdown strength while reducing permittivity; donor doping may restore polarization but increase leakage. The system designer must therefore evaluate capacitor films as part of a power electronic architecture rather than as standalone materials.

Efficiency is another critical constraint. Dielectric loss generates heat, and heat accelerates defect migration, oxidation-reduction reactions, and fatigue. In high-power applications, even modest losses can create thermal runaway if heat cannot be removed from a dense multilayer stack. Defect states near interfaces and grain boundaries often contribute to loss through hopping conduction, space-charge relaxation, and domain-wall pinning. Reducing these losses may require lower defect concentrations, but it may also require different electrode interfaces and packaging materials with high thermal conductivity. The trade-off between energy density and thermal management becomes especially severe in embedded capacitors, where

the dielectric is surrounded by organic boards and other heat-sensitive components. Materials innovation must therefore be paired with thermal architecture and reliability modeling.

Reliability under field, temperature, humidity, and cycling is governed by defect kinetics. Oxygen vacancies can migrate toward cathodes, alter local stoichiometry, and initiate resistance degradation [3]. Fatigue can arise from domain-wall pinning, charge trapping, and microcracking. Breakdown can be initiated by pores, second phases, or electrode asperities, and it can propagate through connected defect networks. Because failure is often stochastic and defect-limited, reliability prediction requires accelerated testing and statistical lifetime models. The most useful defect engineering strategies are those that increase the time to critical defect accumulation rather than merely improving initial properties. In this sense, defect engineering is a reliability discipline as much as a performance discipline.

System robustness also depends on graceful degradation. A capacitor that fails short can destroy a converter, whereas a capacitor that loses capacitance gradually may be tolerated until maintenance. BaTiO₃ thin films tend to fail abruptly when breakdown occurs, so protection circuits, fuses, and distributed capacitor banks are often used to limit damage. Defect engineering can contribute to robustness by designing films with self-limiting conduction, high thermal stability, and resistance to filament formation. However, robustness cannot be guaranteed by materials alone. It requires architecture-level redundancy, fault detection, and standards that account for aging. The integration of defect-tolerant films with fault-tolerant power electronics is a promising direction for high-reliability systems.

5. Manufacturing Infrastructure, Metrology, and Deployment Pathways

Scaling defect-engineered BaTiO₃ thin films from laboratory demonstrations to industrial production requires manufacturing infrastructure that can reproduce defect populations with high fidelity. Thin-film deposition tools, annealing furnaces, electrode patterning, and multilayer lamination must all be qualified for yield and repeatability. In multilayer ceramic capacitors, base-metal electrode processing has enabled cost reduction and high volumetric efficiency, but it imposes strict oxygen partial pressure constraints during sintering [4]. These constraints interact with defect chemistry because the same atmosphere that protects electrodes may stabilize oxygen vacancies. Manufacturing therefore becomes a coupled chemical, thermal, and mechanical process that must be controlled across large substrates and long production runs.

Metrology is a central bottleneck. Average permittivity and loss measurements are necessary but insufficient. Defect engineering requires spatially resolved characterization of vacancy concentrations, grain-boundary chemistry, interface states, strain, porosity, and local breakdown precursors. Techniques such as impedance spectroscopy, transmission electron microscopy, X-ray diffraction, electron energy loss spectroscopy, and scanning probe methods each provide partial information. The challenge is to integrate these measurements into process control systems that can detect drift before it causes field failures. In this sense, the deployment of high-energy-density capacitors depends on a metrology infrastructure that treats defects as critical quality attributes rather than incidental imperfections [14].

Deployment also depends on standards and qualification protocols. Capacitor manufacturers and original equipment manufacturers must agree on accelerated test conditions, failure criteria, and data reporting. Without common standards, materials innovations cannot be compared reliably, and system designers may over-specify or under-specify capacitors. Standards can also support fairness by ensuring that smaller suppliers and new entrants can

demonstrate compliance without proprietary testing pipelines. Policy instruments such as precompetitive research consortia, shared testbeds, and open reference materials can reduce duplication and accelerate learning. The integration of BaTiO₃ thin films into embedded passives and power modules further requires co-design with board materials, thermal interfaces, and packaging reliability [19].

Supply-chain governance is equally important. High-energy-density capacitors may require barium, titanium, rare earth dopants, nickel, copper, and other materials with concentrated production or geopolitical risks. The European Commission's critical raw materials framework emphasizes resilience, circularity, and diversification [20]. Defect engineering can contribute to supply-chain resilience by reducing reliance on scarce dopants, enabling lower-temperature processing, and improving material utilization. However, it can also increase complexity if it requires multiple high-purity precursors or exotic characterization tools. Deployment pathways should therefore compare not only technical performance but also manufacturability, material intensity, and infrastructure compatibility.

6. Sustainability, Critical Materials, Fairness, and Governance

Sustainability in BaTiO₃ thin-film capacitors encompasses energy consumption, water use, solvent emissions, waste generation, and end-of-life recovery. Aqueous tape casting reduces organic solvent use, but it still requires energy for drying, burnout, and sintering. Vacuum deposition has high capital intensity and energy demand, though it may enable thinner layers and lower material waste. The environmental burden of capacitor manufacturing is distributed across mining, purification, synthesis, deposition, packaging, and disposal. Defect engineering can reduce burden by improving yield, lowering annealing temperatures, and extending lifetime. A capacitor that lasts twice as long may have a lower life-cycle impact even if its initial manufacturing footprint is higher.

Critical materials governance intersects with defect engineering through dopant selection and electrode design. Some dopants improve reliability but rely on scarce elements; others are abundant but less effective. Research should prioritize abundant, recyclable, and low-toxicity alternatives where possible. Circular economy strategies for capacitors include recovery of metals from electrodes and packaging, but ceramic dielectrics are difficult to separate and recycle. Designing multilayer capacitors for disassembly and material recovery is a socio-technical challenge that involves product architecture, business models, and regulation. Policy can support extended producer responsibility, design-for-recycling standards, and public procurement that rewards lower life-cycle impacts.

Fairness is also relevant. Access to high-energy-density capacitors affects the affordability and reliability of electric vehicles, renewable energy systems, and medical devices. If advanced defect-engineered films are protected by narrow patents or require exclusive manufacturing infrastructure, benefits may concentrate in a few firms or regions. Open standards, licensing frameworks, and publicly funded pilot lines can broaden access. At the same time, intellectual property protection can incentivize investment in risky materials research. Governance must balance incentives for innovation with equitable diffusion. This balance is particularly important for technologies tied to climate mitigation and public infrastructure, where delays and disparities have social costs.

Policy implications extend to safety and environmental regulation. Thin-film capacitors may contain barium, lead in some legacy formulations, and organic solvents. Even lead-free BaTiO₃ systems require responsible handling of nanoparticles and process chemicals.

Regulations should be based on life-cycle evidence rather than material categories alone. Governments can fund shared facilities for hazard testing, environmental assessment, and worker safety. They can also support international standards for defect characterization and lifetime prediction. The goal is not to slow innovation but to ensure that performance gains do not transfer risks to workers, communities, or ecosystems. Sustainable defect engineering must therefore be evaluated through both technical and social metrics.

7. Robustness, Policy, and Future Research Directions

Future research should integrate defect chemistry with reliability physics and system architecture. One priority is predictive modeling that links processing conditions to defect populations, and defect populations to lifetime under realistic mission profiles. Such models require data from multiple length scales and must account for stochastic failure. Another priority is interface engineering that stabilizes oxygen sublattices while preserving polarization. Buffer layers, electrode alloys, and graded compositions may offer pathways to higher breakdown strength and lower leakage. Nanodomain and relaxor-like designs can reduce hysteresis and improve efficiency, but their long-term stability under bias and temperature must be established [16]. Antiferroelectric and lead-free systems provide alternative design spaces, yet they face similar challenges in fatigue, field cycling, and manufacturing reproducibility [17][18].

Policy can accelerate progress by funding precompetitive research, open data, and shared metrology. It can also support demonstration projects that test capacitors in real power electronic systems rather than only in laboratory fixtures. Standards bodies should develop test protocols for defect-sensitive properties, including leakage evolution, breakdown statistics, and thermal runaway thresholds. Supply-chain policies should encourage diversification and recycling without creating new bottlenecks. International cooperation is essential because capacitor supply chains and climate goals are global. The most robust strategy is one that treats defect engineering as a public-interest technology, where performance, safety, environmental impact, and equitable access are evaluated together [20].

8. Conclusion

Defect engineering of BaTiO₃ thin films offers a powerful route to high-energy-density capacitors, but its success depends on coordinated design across materials, interfaces, processing, manufacturing, and governance. Oxygen vacancies, dopants, grain boundaries, and interfaces can enhance or degrade performance depending on how they are distributed and stabilized. The most promising approaches balance permittivity, breakdown strength, efficiency, and reliability rather than optimizing a single metric. Processing innovations such as aqueous tape casting and advanced deposition methods can improve uniformity and reduce environmental burden, while interface and nanodomain engineering can improve energy storage efficiency. However, laboratory performance must be translated into reproducible, testable, and sustainable products. This requires metrology for rare defects, standards for lifetime prediction, supply-chain resilience, and policies that promote fair access to critical materials. High-energy-density BaTiO₃ capacitors should therefore be viewed as socio-technical systems. Their future depends not only on defect chemistry but also on the infrastructure and governance that determine whether advanced materials can be deployed safely, sustainably, and equitably at scale.

References

1. Haertling, G. H. (1999). Ferroelectric ceramics: History and technology. *Journal of the American Ceramic Society*, 82(4), 797–818. <https://doi.org/10.1111/j.1151-2916.1999.tb01840.x>
2. Scott, J. F. (2007). Applications of modern ferroelectrics. *Science*, 315(5814), 954–959. <https://doi.org/10.1126/science.1129564>
3. Waser, R., Baiatu, T., & Härdtl, K. H. (1990). dc Electrical degradation of perovskite-type titanates: I, Ceramics. *Journal of the American Ceramic Society*, 73(6), 1645–1653. <https://doi.org/10.1111/j.1151-2916.1990.tb09809.x>
4. Kishi, H., Mizuno, Y., & Chazono, H. (2003). Base-metal electrode-multilayer ceramic capacitors: Past, present and future perspectives. *Japanese Journal of Applied Physics*, 42(1R), 1–15. <https://doi.org/10.1143/JJAP.42.1>
5. Pan, M. J., & Randall, C. A. (2010). A brief introduction to ceramic capacitors. *IEEE Electrical Insulation Magazine*, 26(3), 44–50. <https://doi.org/10.1109/MEI.2010.5482787>
6. Love, G. R. (1990). Energy storage in ceramic dielectrics. *Journal of the American Ceramic Society*, 73(2), 323–328. <https://doi.org/10.1111/j.1151-2916.1990.tb06513.x>
7. Burn, I., & Smyth, D. M. (1980). Energy storage in ceramic dielectrics. *Journal of Materials Science*, 15(9), 2207–2214. <https://doi.org/10.1007/BF00552307>
8. Chu, B., Zhou, X., Ren, K., Neese, B., Lin, M., Wang, Q., Bauer, F., & Zhang, Q. M. (2006). A dielectric polymer with high electric energy density and fast discharge speed. *Science*, 313(5785), 334–336. <https://doi.org/10.1126/science.1127798>
9. Wang, Y., Zhou, X., Chen, Q., Chu, B., & Zhang, Q. (2010). Recent development of high energy density polymers for dielectric capacitors. *IEEE Transactions on Dielectrics and Electrical Insulation*, 17(4), 1036–1042. <https://doi.org/10.1109/TDEI.2010.5539672>
10. Khanchaitit, P., Han, K., Gadinski, M. R., Li, Q., & Wang, Q. (2013). Ferroelectric polymer networks with high energy density and improved discharged efficiency for dielectric energy storage. *Nature Communications*, 4, 2845. <https://doi.org/10.1038/ncomms3845>
11. Prateek, Thakur, V. K., & Gupta, R. K. (2016). Recent progress on ferroelectric polymer-based nanocomposites for high energy density capacitors: Synthesis, dielectric properties, and future aspects. *Chemical Reviews*, 116(7), 4260–4317. <https://doi.org/10.1021/acs.chemrev.5b00495>
12. Ogihara, H., Randall, C. A., & Trolier-McKinstry, S. (2009). High-energy density capacitors utilizing 0.7 BaTiO₃–0.3 BiScO₃ ceramics. *Journal of the American Ceramic Society*, 92(8), 1719–1724. <https://doi.org/10.1111/j.1551-2916.2009.03104.x>
13. Hao, X. (2017). A review on the dielectric materials for high energy-storage application. *Journal of Advanced Dielectrics*, 7(1), 1730001. <https://doi.org/10.1142/S2010135X17300016>
14. Palneedi, H., Peddigari, M., Hwang, G. T., Jeong, D. Y., & Ryu, J. (2018). High-performance dielectric ceramic films for energy storage capacitors: Progress and outlook. *Advanced Functional Materials*, 28(42), 1803665. <https://doi.org/10.1002/adfm.201803665>

15. Luan, Saiwei, et al. "Fabrication of High Performance BaTiO₃ Films via Aqueous Tape Casting for ultrathin MLCC applications." *Ceramics International* (2025).
16. Pan, H., Li, F., Liu, Y., Zhang, Q., Wang, M., Lan, S., Zheng, Y., Ma, J., Gu, L., Shen, Y., Yu, P., Zhang, S., Chen, L. Q., Lin, Y. H., & Nan, C. W. (2019). Ultrahigh-energy density lead-free dielectric films via polymorphic nanodomain design. *Science*, 365(6453), 578–582. <https://doi.org/10.1126/science.aaw8109>
17. Yang, L., Kong, X., Li, F., Hao, H., Cheng, Z., Liu, H., Li, J., & Zhang, S. (2019). Perovskite lead-free dielectrics for energy storage applications. *Progress in Materials Science*, 102, 72–108. <https://doi.org/10.1016/j.pmatsci.2018.12.002>
18. Ahn, C. W., Amarsanaa, G., Won, S. S., Chae, S. A., Lee, D. S., & Kim, I. W. (2015). Antiferroelectric thin-film capacitors with high energy-storage densities, low energy losses, and fast discharge times. *ACS Applied Materials & Interfaces*, 7(48), 26381–26386. <https://doi.org/10.1021/acsami.5b08781>
19. Ihlefeld, J. F., Laughlin, B. J., Hunt-Lowery, A., Borland, W., Kingon, A. I., & Maria, J. P. (2005). Copper compatible barium titanate thin films for embedded passives. *Journal of Electroceramics*, 14(2), 95–102. <https://doi.org/10.1007/s10832-005-0867-5>
20. European Commission. (2020). Critical raw materials resilience: Charting a path towards greater security and sustainability (COM(2020) 474 final). Publications Office of the European Union. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474>