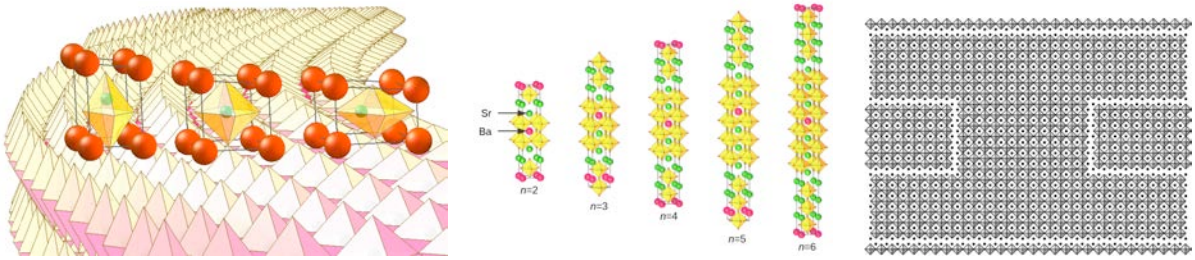
# Thin-Film Alchemy:
# Engineering Oxide Films to Unleash their Hidden Properties

Darrell G. Schlom
*Department of Materials Science and Engineering and*
*Kavli Institute at Cornell for Nanoscale Science*
*Cornell University*

Guided by theory, unparalleled properties—those of hidden ground states—are being unleashed by engineering oxides at the atomic level. This engineering includes strain engineering, dimensional confinement, and defect engineering. Using these thin-film tricks, materials that are not ferroelectric or ferromagnetic in their unstrained state can be transmuted into ferroelectrics, ferromagnets, or materials that are both at the same time. Similarly, new tunable dielectrics with unparalleled performance have been created. Our studies reveal details about the microscopic growth mechanism of these phases, which are relevant to preparing multicomponent oxide heterostructures with atomic precision. A new era for engineering functional oxide thin films for electronics is upon us: oxides by design. This work was performed in collaboration with the coauthors listed in the references below.




Strain engineering, dimensional confinement, epitaxial stabilization, and defect engineering applied to make today's best tunable dielectric even better in new $(SrTiO_3)_{n-m}(BaTiO_3)_mSrO$ tunable dielectrics.

## References

C.H. Lee, N.D. Orloff, T. Birol, Y. Zhu, V. Goian, E. Rocas, R. Haislmaier, E. Vlahos, J.A. Mundy, L.F. Kourkoutis, Y. Nie, M.D. Biegalski, J. Zhang, M. Bernhagen, N.A. Benedek, Y. Kim, J.D. Brock, R. Uecker, X.X. Xi, V. Gopalan, D. Nuzhnyy, S. Kamba, D.A. Muller, I. Takeuchi, J.C. Booth, C.J. Fennie, and D.G. Schlom, "Exploiting Dimensionality and Defect Mitigation to Create Tunable Microwave Dielectrics," *Nature* **502** (2013) 532–536

C.H. Lee, V. Skoromets, M.D. Biegalski, S. Lei, R. Haislmaier, M. Bernhagen, R. Uecker, X.X. Xi, V. Gopalan, X. Martí, S. Kamba, P. Kužel, and D.G. Schlom, "Effect of Stoichiometry on the Dielectric Properties and Soft Mode Behavior of Strained Epitaxial $SrTiO_3$ Thin Films on $DyScO_3$ Substrates," *Applied Physics Letters* **102** (2013) 082905.

Y.F. Nie, Y. Zhu, C.-H. Lee, L.F. Kourkoutis, J.A. Mundy, J. Junquera, P. Ghosez, D.J. Baek, S. Sung, X.X. Xi, K.M. Shen, D.A. Muller, and D.G. Schlom, "Atomically Precise Interfaces from Non-Stoichiometric Deposition," *Nature Communications* **5** (2014) 4530.

V. Goian, S. Kamba, N. Orloff, T. Birol, C.H. Lee, D. Nuzhnyy, J.C. Booth, M. Bernhagen, R. Uecker, and D.G. Schlom, "Influence of the Central Mode and Soft Phonon on the Microwave Dielectric Loss near the Strain-Induced Ferroelectric Phase Transitions in $Sr_{n+1}Ti_nO_{3n+1}$," *Physical Review B* **90** (2014) 174105.

A.M. Hagerstrom, X. Lu, N.M. Dawley, H.P. Nair, J. Mateu, R.D. Horansky, C.A.E. Little, J.C. Booth, C.J. Long, D.G. Schlom, and N.D. Orloff, "Sub-Nanosecond Tuning of Microwave Resonators Fabricated on Ruddlesden-Popper Dielectric Thin Films," *Advanced Materials Technologies* (2018) 1800090. https://doi.org/10.1002/admt.201800090

N.M. Dawley, E.J. Marksz, A.M. Hagerstrom, M.E. Holtz, G.H. Olsen, J. Zhang, C.J. Long, J.C. Booth, C.J. Fennie, D.A. Muller, N.D. Orloff, and D.G. Schlom, "Applying Chemistry to Make Today's Best Tunable Millimeter Wave Dielectric even Better" (unpublished).