## Workshop on Quantum Materials Epitaxy
## Room Ballroom A - Session QME-SaM1

### Oxides I

**Moderator:** Bharat Jalan, University of Minnesota

8:00am **QME-SaM1-1 Hunting for New Oxide Superconductors using MBE**, ***Darrell Schlom,*** Cornell University **INVITED**

Most oxide superconductors have been discovered through bulk synthesis.In this talk I will describe our efforts to use strain engineering, epitaxial stabilization, and interface engineering—all strengths of MBE—to hunt for new oxide superconductors.

* This work was performed in collaboration with the coauthors listed in the references below.


1. J.P. Ruf, H. Paik, N.J. Schreiber, H.P. Nair, L. Miao, J.K. Kawasaki, J.N. Nelson, B.D. Faeth, Y. Lee, B.H. Goodge, B. Pamuk, C.J. Fennie, L.F. Kourkoutis, D.G. Schlom, and K.M. Shen, "Strain-Stabilized Superconductivity," *Nature Communications* **12** (2021) 59.
2. F.V.E. Hensling, M.A. Smeaton, V. Show, K. Azizie, M.R. Barone, L.F. Kourkoutis, and D.G. Schlom, "Epitaxial Growth of the First Two Members of the $Ba_{n+1}In_nO_{2.5n+1}$ Ruddlesden-Popper Homologous Series," *Journal of Vacuum Science and Technology A* **40** (2022) 062707.


†schlom@cornell.edu [mailto:schlom@cornell.edu]

8:30am **QME-SaM1-3 Advanced Epitaxial Growth of Quantum Materials Using Thermal Laser Epitaxy**, ***Jochen Mannhart,*** Max Planck Institute for Solid State Research, Germany **INVITED**

Molecular Beam Epitaxy (MBE) and Pulsed Laser Deposition (PLD) are the primary techniques employed for the epitaxial growth of thin films and heterostructures of quantum materials [1]. Each technique has its own set of advantages and drawbacks. Thermal Laser Epitaxy (TLE) is an innovative epitaxial growth technique that aims to combine the benefits of both MBE and PLD. TLE utilizes laser-induced thermal evaporation of ultra-pure sources, facilitated by practically unlimited evaporation temperatures. Moreover, also the substrate temperatures are virtually unrestricted, as is the gas atmosphere applied throughout the entire process.

In this presentation, I will discuss the state-of-the-art in the growth of quantum materials using thermal laser epitaxy and the opportunities this advanced technique offers for the epitaxial growth of complex films and heterostructures.


[1] H. Boschker and J. Mannhart, 'Q*uantum Matter Heterostructures*', Annu. Rev. Condens. Matter Phys. 8, 145 (2017)
[2] W. Braun and J. Mannhart, '*Film Deposition by Thermal Laser Evaporation'*, AIP Advances 9, 085310 (2019)


The work that will be presented has been conducted together with W. Braun, H. Boschker, B. Faeth, F. Felden, F.V.E. Hensling, M. Jäger, D.-Y. Kim, L.N. Majer, and T. Smart.

9:00am **QME-SaM1-5 Superconductivity at Interfaces of $KTaO_3$ and its Possible Origins**, ***Anand Bhattacharya,*** Argonne National Laboratory **INVITED**

Superconductivity in materials with broken inversion symmetry and strong spin-orbit coupling can lead to unconventional pairing states that may be of interest in quantum science and technology. In this seminar I will discuss a recently discovered superconducting electron gas formed at interfaces of a 5*d* transition metal oxide $KTaO_3$ (KTO) that combines these attributes intrinsically, and whose unique properties provide strong clues about the origin of its superconductivity. KTO, like its widely studied 3*d* cousin $SrTiO_3$ (STO), is a 'quantum paraelectric', where the onset of ferroelectricity at low temperatures is believed to be thwarted by quantum fluctuations, giving rise to a very large dielectric constant. However, unlike STO, no evidence of superconductivity has been found to date in electron-dopedKTO in the bulk. Recently, we discovered that electron gases formed interfaces of KTO are robust two-dimensional superconductors[1] over a wide range of carrier densities, with $T_c$ as high as 2.2 K, about an order of magnitude higher than those found at STO interfaces. Furthermore, there is a striking dependence of $T_c$ on the crystalline facet of KTO at which the interfacial electron gas is formed – in our samples the maximum $T_c$ values at the KTO (111) and (110) interfaces are 2.2 K and ~ 1 K respectively, while the KTO (001) interface remains normal down to 25 mK. For the KTO (111) interface, a remarkable non-saturating *linear* dependence of $T_c$ on the areal carrier density ($n_{2D}$) is observed, over nearly an order of magnitude of $n_{2D}$. The superconductivity can also be tuned by gate electric fields, which elucidates the role of the interface in mediating pairing and allows for reversible switching of superconductivity at $T$ = 2 K. Based on these findings, we propose a mechanism[2] for pairing via inter-orbital interactions induced by inversion-breaking transverse optical (TO1) phonons, the same mode that softens in the quantum paraelectric phase, that explains several key aspects of superconductivity at KTO interfaces. Our results may provide insights into the pairing mechanism in other doped quantum paraelectrics, which has remained an open question for decades. Looking further, KTO interfaces are also a promising platform for exploring novel devices[3] for quantum science, and I will present some initial results in this direction.

*References:*


1. C. Liu et al., *Science* (2021). https://www.science.org/doi/abs/10.1126/science.aba5511
2. C. Liu et al., *Nature Communications* (2023).https://doi.org/10.1038/s41467-023-36309-2
3. M. Yu et al., *Nano Lett.* (2022). https://doi.org/10.1021/acs.nanolett.2c00673


9:30am **QME-SaM1-7 Synthesis of Electronic-Grade Quantum Heterostructures by Hybrid PLD**, ***Chang-Beom Eom,*** University of Wisconsin-Madison **INVITED**

Modern quantum materials are inherently sensitive to point defects, and require a new synthesis route to produce epitaxial oxide thin films and interfaces clean enough to probe fundamental quantum phenomena. The recent discovery of robust superconductivity at $KTaO_3$ (111) and $KTaO_3$ (110) heterointerfaces on $KaTaO_3$ bulk single crystals offers new insights into the role of incipient ferroelectricity and strong spin-orbit coupling.Electronic grade epitaxial thin film platforms will facilitate investigation and control of the interfacial superconductivity and understanding the fundamental mechanisms of the superconductivity in $KTaO_3$. The major challenge of research on $KTaO_3$ system is that it is difficult to grow high-quality $KTaO_3$ epitaxial thin films due to potassium volatility. Recently, we have developed the hybrid PLD method for electronic grade $KTaO_3$ thin film growth, which successfully achieves this by taking advantage of the unique capabilities of PLD to instantly evaporate $Ta_2O_5$ in a controlled manner and evaporation of $K_2O$ to maintain sufficient overpressure of volatile species. We successfully synthesized heteroepitaxial $KTaO_3$ thin films on 111-oriented $KTaO_3$ bulk single crystal substrates with a $SmScO_3$ template by hybrid PLD, followed by a $LaAlO_3$ overlayer. Electrical transport data show a superconducting transition temperature of ~ 1.35K. We anticipate that the ability to synthesize high-quality epitaxial complex oxides such as $KTaO_3$ that contain volatile elements will provide a new platform for exploring new physics and technological applications arising from unique characteristics such as large spin-orbit coupling.

This works has been done in collaboration with Jieun Kim, Jungwoo Lee, Muqing Yu, Neil Campbell, Shun-Li Shang, Jinsol Seo, Zhipeng Wang, Sangho Oh, Zi-Kui Liu, Mark S. Rzchowski, Jeremy Levy.

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# Author Index

## Bold page numbers indicate presenter