Materials for Neuromorphic Circuits

Conference | 2023

UNIVERSITY OF CAMBRIDGE

MAN:C
Materials for Neuromorphic Circuits

Magdalene College,
University of Cambridge, UK

26 - 30 JUNE 2023

Contents

About

MANIC

The scientific aim of MANIC is to synthesize materials that can function as networks of neurons and synapses by integrating conductivity, plasticity and self-organization. Successes in deep learning show that the paradigm of neuromorphic computing is very attractive. However, current technology is based on the Turing/von Neumann architecture, requiring extensive communication and an excessive amount of energy for computing. The human brain performs pattern recognition tasks with a fraction of the power needed by supercomputers for similar tasks. In this multidisciplinary project, new (memristic) materials and architectures for neuromorphic computing have been investigated in order to develop materials that can learn. This work has been carried out by fifteen early stage researchers (ESR's) and their supervisors coming from many universities across Europe.

Final NWE

The final MANIC conference is the last formal meeting we will have as a network, and for many, marks the end of their PhD. It was Alexander Graham Bell who said:

> "When one door closes another door opens; but we often look so long and so regretfully upon the closed door that we do not see the ones which open for us".

In that spirit, do not not look so long and regretfully at the door closing. Rather, let us look toward the future and be thankful for the collaborators and friends we have made along the way.

Organizing committee

Jack Eckstein	Felix Risch	Michael Carpenter
Beatriz Noheda	Jasper van der Velde	Valeria Bragaglia

Timetable

ESR: Attendance is expected for ESRs only. ALL: Everyone is encouraged to attend. PI: Attendance is expected for MANIC students, their supervisors, and invited speakers. SB: Supervisory Board only

Monday, 26 of June

9:00–17:00	**Arrival and Check in at Robinson College**		
16:00–17:00	ESR	**ESR workshop** Who gets to do research? Equity in STEMM viewed through a funding lens	Prof Rachel A. Oliver
18:00–19:00	PI	**Buffet Dinner Robinson College** (If you responded "yes" to survey	Garden Restaurant Supper

Tuesday, 27 of June

8:00–9:00	**Coffee and Registration in Magdalene**		
9:00–9:45	ALL	**Ekhard K.H. Salje** University of Cambridge	Neuromorphic devices and ferroelastic domain walls
9:45–10:00	ALL	**Panagiotis Koutsogiannis** Consejo Superior de Investigaciones Cientificas	Atomic characterisation of Pb(Zr, Ti)O_3 conductive domain walls by STEM
10:00–10:15	ALL	**Johannes Hellwig** RWTH Aachen University	Diffusive memristive $SrTiO_3$ devices
10:15–11:00	ALL	**Pavan Nukala** Centre for Nanoscience and Engineering, IISc Bengaluru	Neuromorphic materials: electromechanical neuristors and critical networks
11–11:20	**Coffee**		
11:20–11:50	ALL	**Jack Eckstein** University of Cambide	Domain wall dynamics in WO_3
11:50–12:35	ALL	**Valeria Bragaglia** IBM Research – Zurich	Materials and Devices for Unconventional Computing Approaches
12:35–13:05	ALL	**Nele Harnack** IBM Research – Zurich	Quantitative temperature measurment of self-heating in non-linear devices using scanning thermal microscopy
13:05–14:00	**Lunch**		
14:00–14:45	ALL	**Dennis Meier** Norwegian University of Science and Technology	Ferroelectric domain walls – functional electronic properties and opportunities for unconventional computing
14:45–15:15	**Coffee**		
15:15–16:00	ALL	**Marin Alexe** University of Warwick	Ferroelectric Tunnel Junctions
17:45–18:45	PI	**Chauffeur punting on the river Cam** Location →	Jesus Green Mooring

Wednesday, 28 of June

8:30–9:30	**Coffee and Registration in Magdalene**		
9:30-10:00	ALL	**Romar Angelo Avila** University of Twente	Studying the effect of cation stoichiometry and thickness gradients on epitaxial $BaTiO_3$ films using off-center PLD
10:00–10:45	ALL	**Gustau Catalan** Catalan Institute of Nanoscience and Nanotechnology	Polarization and domain walls in antiferroelectric $PbZrO_3$
10:45–11:00	ALL	**Tomasso Stecconi** IBM Research – Zurich	Title TBD

11:00–11:30	**Coffee break and scientific discussion**		
11:30–11:45	ALL	**Jan Rieck** University of Groningen	Ferroelastic domain walls in $BiFeO_3$ as memristive networks
11:45-12:00	ALL	**Felix Risch** EPFL (Swiss Federal Polytechnical Institute)	Title TBD
12:00–12:30	ALL	**Evgenios Stylianidis** University College London	Straining the usual suspect: phase transitions in $SrTiO_3$ films
12:30–14:00	**Lunch**		
14:00–14:45	ALL	**Yigit Demirag (online)** University of Zurich	On-chip (meta) learning strategies for spiking neural networks with emergent memory technologies
14:45–15:00	ALL	**Mian Li** University of Groningen	Image processing in c-AFM images
15:00–15:45	ALL	**Neil Mathur** University of Cambridge	Electrocaloric effects in epitaxial films of $SrTiO_3$
15:45–16:05	**Coffee break and scientific discussion**		
16:05-16:20	ALL	**Davide Cipollini** University of Groningen	Modeling domain walls network in $BiFeO_3$ with stochastic geometry and entropy based similarity measure
16:20–17:05	ALL	**Adnan Mehonic** University College London	Resistance Switching in Silicon Oxide for Memory and Computing Applications
	End of talks: walk to Sedgwick Museum		
18:00-19:00	ALL	**Evening reception** Sedgwick Museum	Nibbles provided

Thursday, 29 of June

8:30–9:30	**Coffee and Registration in Magdalene**		
9:30–10:15	ALL	**Merlyne De Souza** University of Sheffield	A “delay system” reservoir based on a nano-ionic solid electrolyte FET
10:15-10:30	ALL	**Dimitris Spithouris** RWTH Aachen University	Volatile STO memristive devices
10:30–11:15	ALL	**Eleni Vasilaki** University of Sheffield	Learning in Networks of Mathematically Agnostic "In Materio" Neurons
11:15–11:45	**Coffee break and scientific discussion**		
11:45–12:30	ALL	**Ahmed Nejim** Silvaco Europe Ltd - St. Ives	Device and circuit design tools role in developing neuromorphic technology
12:30–13:15	ALL	**Markus Hellenbrand** University of Cambridge	Multilevel Resistive Switching in Amorphous Oxides
13:15–14:15	**Lunch**		
14:15–15:00	ALL	**Pedro L. Galindo** University of Cádiz	Digital Image Processing applied to the Characterization of Nanomaterials

15:00–15:30	ALL	**Michael Wilkinson** University of Groningen	Mystery talk
15:30–16:00	ALL	**Beatriz Noheda** University of Groningen	Summary and conference close
	Conference Closed		
16:00 – 17:00	SB	**Supervisory Board Meeting** Magdalene College	
18:45–close	PI	**Formal Hall Magdalene** Dress Code: Smart Casual	Email Michael Carpenter (mc43@cam.ac.uk) with dietary concerns.

Friday, 30 of June

8:30–11:00	**Check out of Robinson accommodation**

List of Abstracts – Invited Talks

Neuromorphic devices and ferroelastic domain walls

Ekhard K.H. Salje

University of Cambridge, UK

Neuromorphic device applications commonly involve memristive switching. I will discuss a scenario where ferroelastic domain walls are the key elements for carrier transport because they, in almost all cases, contain four fundamental properties which can lead to memristive conductivity. The first is that ionic and electronic conductivity is largely enhanced in twin walls as compared with the bulk. The second is that they possess very large polarities of the same order of magnitude as archetypal ferroelectric materials such as BaTiO3. This can lead to driven pattern formation under electric fields. The third fundamental property is that twin walls are often, but not always, highly mobile. The fourth is their ability to attract and transport dopants.

In a simple thought experiment, we consider needle domains with two twin walls joint at the needle tip. This needle tip can then be driven towards a perpendicular wall which remains immobile under dielectric driving. Transport will occur when the needle tip is close enough to the immobile wall, the current is highly sensitive to the distance between the needle tip and the immobile wall. This simple geometry is akin to the action of Josephson junctions if the walls are superconducting. I will discuss the 'loading' of twin walls with dopants and their transport and advocate the use of WO3 as a possible template material for neurotrophic devices.

Ferroelectric Tunnel Junctions

Marin Alexe

University of Warwick, UK

Recently a new dimension was added to quantum tunnel junctions by replacing the insulator with a ferroelectric barrier obtaining ferroelectric tunnel junction (FTJ). The main effect in FTJ, called tunnel electroresistance (TER), is based on the modulation of metal-semiconductor barrier at the metal-ferroelectric interface and implicitly of the tunnelling probability by ferroelectric polarisation. TER is in many ways similar to a resistive switching, but it is a genuine electronic and not an ionic effect. It can be as high as 105 ratio as large as 1000 at room temperature. [1] The use of ferromagnetic metal electrodes converts FTJ in an artificial multiferroic tunnel junction (MFTJ), which not only combines both TER and tunnelling magnetoresistance (TMR) effects, but also show novel magneto-electric effects including electric control of spin polarisation. [2] The obtained MFTJ becomes a four states non-volatile memory device: two ruled by the ferroelectric polarization and the other two by magnetization alignment of the electrodes. Furthermore, by replacing the ferroelectric barrier with an antiferroelectric barrier, obtaining in this way antiferroelectric tunnel junction (AFTJ), TER can reach values as high as 109 , at current densities exceeding 10 A/cm2 . [3] Whilst AFTJ does not retain information, it can play the role of a complementary resistive switching (CRS) device which usually is obtained by anti-serially stacking two classical resistive switching layers. Besides, I will also show recent developments related to flexible MTJs and tunnel junction comprising the ferroelectric incommensurate spin crystal. [4]

References

[1] D. Pantel, S. Goetze, D. Hesse and M. Alexe, ACS Nano 5, 6032 (2011).

[2] D. Pantel, S. Goetze, D. Hesse and M. Alexe, Nature Mater. 11, 289 (2012)

[3] G. Apachitei, J. J. P. Peters, A. M. Sanchez, D. J. Kim, M. Alexe, Adv. Electron. Mat. 3, 1700126 (2007).

[4] D. Rusu et al., Nature 602, 240 (2022).

Polarization and domain walls in antiferroelectric $PbZrO_3$

Gustau Catalan

Catalan Institute of Nanoscience and Nanotechnology, Spain

Antiferroelectric materials are defined by having an antiparallel but switchable arrangement of dipoles. The fact that the ground state is antipolar makes them, a priori, unsuitable for memory devices. On the other hand, antipolar cancellation is seldom perfect, and the archetypal antiferroelectric, PbZrO3, often presents a small remnant polarization, the origin of which remains unclear. In this work, we have investigated one potential source of polarization that is inherent to all antiferroelectrics: antiphase boundaries. Antiphase boundaries are a particular case of so-called translational boundaries, whereby the antipolar sequence shifts its phase along the crystal lattice, from, say, up-down-up-down to down-up-down-up. In PbZrO3, we have seen that such translational boundaries can cluster together, forming extended domains that are polar – ferrielectric, in fact. I will present our study of the structure of these incipient ferrielectric domains and their implications for the appearance and stability of polarization in antiferroelectric PbZrO3.

Ferroelectric domain walls – functional electronic properties and opportunities for unconventional computing

Dennis Meier

Norwegian University of Science and Technology, Norway

Ferroelectric domain walls are a paradigmatic example for the rich physics and application opportunities of topological defects. The research on ferroelectric domain walls has revolutionized the way we understand polar structures and triggered the development of conceptually new devices for nanotechnology.[1]

In my talk, I will discuss how ferroelectric domain walls can be used to emulate the behavior of key electronic components, such as digital switches and diodes. Furthermore, I will show the importance of the three-dimensional (3D) nanoscale structure for the response of both individual domain walls and domain-wall networks. By combining tomographic microscopy techniques and finite element modelling, we studied the spreading of electrical currents in the complex 3D network of domain walls and topologically protected vortices in ferroelectric ErMnO3.[2] Our measurements demonstrate the impact of curvature effects, which represent an additional degree of freedom for controlling the resistance of ferroelectric domain walls. The results expand previous work into the third dimension and give new opportunities for domain-wall based multi-level resistance control and unconventional computing.

[1] Ferroelectric domain walls for nanotechnology, D. Meier and S. M. Selbach, Nat. Rev. Mater. 7, 15 (2022)

[2] The third dimension of ferroelectric domain walls, E. D. Roede, K. Shapovalov, T. J. Moran, A. B. Mosberg, Z. Yan, E. Bourret, A. Cano, B. D. Huey, A. T. J. van Helvoort, and D. Meier, Adv. Mater. 34, 2202614 (2022)

Neuromorphic Computing with Coupled Oscillators

Aida Todri-Sanial

Eindhoven University of Technology, Netherlands

With the ever-increasing number of edge devices and the amount of data to process at the edge requires innovation in hardware implementation that not only is energy efficient but also enables continuous online learning capability. Current AI algorithms such as deep learning are power-hungry to be deployed at the edge and most of the current research efforts are focused on training algorithms while hardware implementations remain a major challenge. Recently, neuromorphic computing inspired by biological neural networks presents a viable opportunity to implement not only energy efficient architecture but also enable online learning by emulating biological plasticity. Oscillatory neural networks are a promising neuromorphic computing paradigm that intertwines the dynamics of a physical system based on coupled oscillators with neural networks. Oscillatory neural networks (ONNs) are a promising neuromorphic computing paradigm for AI at the edge. ONNs are networks of coupled oscillators using their natural synchronization behavior to compute. The main computing element is an oscillator and information are encoded in the phase difference among oscillators, which allows to reduce drastically supply voltage amplitude resulting in low-power computing. In this talk, I will cover aspects of both analog circuit design and digital design implementation for ONNs. I will also present the current progress and challenges with respect to novel materials, devices and computing architectures for ONN implementation – ongoing efforts in the frameworks of EU H2020 NeurONN and Horizon EU PHASTRAC projects.

Neuromorphic materials: electromechanical neuristors and critical networks

Pavan Nukala

Centre for Nanoscience and Engineering, IISc Bengaluru, India

Neuromorphic hardware can be thought of as a bottom-up assembly of individual building block such as neurons and synapses. The memristor crossbars (enabling novel computing strategies) are classic examples of such architectures. However, real biological neural networks have a very complex architectures with $\sim 10^{15}$ interacting elements. To emulate such a behaviour, it is worth exploring self-assembled materials networks that behave globally like biological neural networks, and strategies to train these networks.

In this talk, I'll discuss our recent progress on both these aspects: individual computing elements such as neuristors, and self-assembled network of Ag nodes and filaments hosted in a 2D hBN matrix.

In the first part, I'll draw analogies between a biological neuron (in a pig gut) that exhibits gel to solid-like phase transition about the body temperature, and correlated Mott insulators (VO_2, $NdNiO_3$) that also exhibit a volatile phase transition with current. I'll show at least three different self-oscillatory behaviors from such systems (tonic spiking, bursting and phasic spiking), and present simple electrothermal models that will model these systems effectively. A traveling action potential in a neuron is also a sound wave, and thus is electromechanical in nature. I'll clearly show through interferometry experiments that even in VO2, the self-oscillations are both electromechanical and electrooptical in nature, opening up the applications of these neuristors in MEMS and optics.

In the next part, I'll show that in Ag-hBN (large area, CVD grown) systems, we could stabilize two different networks: (a) a percolative tunnel network of Ag clusters intercalated between vdW BN layers, and (b) a physically percolating filamentary Ag network. Critical exponents of various order parameters will be shown, and I'll discuss how both these networks exhibit avalanche dynamics of a system poised at criticality. I'll also discuss how we are attempting to model these systems.

Ferroelectric gating of 2D devices for the co-integration of energy efficient steep slope switches and neuromorphic electronics

Adrian Ionescu

EPFL (Swiss Federal Polytechnical Institute), Switzerland

Edge Artificial Intelligence (AI) will rely on energy efficient computing in autonomous systems with various form factors. To satisfy the requirements of such emerging applications, various electronic devices based on new physical principles and novel architectures are explored, aiming to improve information processing performances. The co-integration of logic and neuromorphic units is considered as a promising approach. In this context, enhanced functionalities of field effect devices by material innovations is the key to create a multi-functional hardware platform. Due to the excellent electrostatic control and free dangling bonds properties, two-dimensional (2D) material could be used to fabricate versatile heterostructure and scaled devices with reconfigurable circuit elements. 2D/2D material system offers the potential to demonstrate tunneling field-effect transistor (TFET)s with alternative carrier-injection mechanism for achieving a sub-60 mV/dec subthreshold slope (SS) and reducing power consumption. Furthermore, it can be used to develop hybrid complementary metal-oxide-semiconductor (CMOS)-TFET architecture, known as a platform with advantageous trade-offs between performance, speed and low power. Negative capacitance (NC) of ferroelectric (FE) materials can effectively boost the performance of FET and tunnel FET transistors by offering a step-up voltage transformer. Moreover, the strong proximal coupling of FE materials with 2D materials allows the realization of 2D material-based FeFETs for constructing synaptic devices with low power consumption, fast operation and good data retention. In this talk we will present recent design and experimental results on co-integrated von Neumann 2D steep slope switches and neuromorphic synaptic devices built on a same technology platform, using doped high-k ferroelectric gating. We will explore the benefits and the performance of such designs. Moreover, we will show that the proposed ferroelectric material system can be used to co-integrate supercapacitors for on-chip energy storage on the same technological ferroelectric/2D platform.

A ”delay system” reservoir based on a nano-ionic solid electrolyte FET

Merlyne De Souza

University of Sheffield, UK

Spintronic oscillators, photonic modules, and two-terminal memristors are some of the most widely examined options in hardware implementations of Reservoir computing systems. These implementations may typically be considered as ”delay systems”, rather than fully connected networks of non-linear neurons, whose dynamics is affected by its own history a time τ in the past [1]. We achieve higher learning efficiency by training the readout network by sampling the output of the reservoir after every input pulse rather than after a sequence of pulses [2]. The advantages of our three terminal ZnO/Ta2O3 Thin Film Transistor, is the ease with which the time constant τ of the reservoir may be manipulated, simply from the applied gate voltage, or reset pulse, or read voltage. Reading the device in the off-state helps reduce power consumption [3].

References:

[1]L. Appeltant, M. Soriano, G. Van Der Sande, J. Danckaert, S. Massar, J. Dambre, B. Schrauwen, C. R. Mirasso, I. Fischer 2, 468 (2011)

[2] Ankit Gaurav, Xiaoyao Song , Sanjeev Manhas , Aditya Gilra , Eleni Vasilaki , Partha Roy and Maria Merlyne De Souza Frontiers in Electronics, doi: 10.3389/felec.2022.869013

[3] A. Gaurav, Xiaoyao Song, Sanjeev Kumar Manhas, Partha Pratim Roy and Maria Merlyne De Souza, Proc of EDTM 2023

Resistance Switching in Silicon Oxide for Memory and Computing Applications

Adnan Mehonic

University College London, UK

The increasing demand for computing power has brought to light the limitations of current CMOS-based technologies and Von Neumann architecture. To address this, alternative paradigms like memristor-based accelerators have emerged. In this presentation, I will discuss resistance switching in silicon oxide (SiOx)-based ReRAM devices and explore pathways for improving device performance. Additionally, I will present the rationale and challenges associated with utilising memristive crossbar arrays as analogue hardware accelerators. Two algorithmic approaches are presented to tackle inherent issues in memristor-based systems. The first approach involves utilising committee machines during inference, while the second approach explores non-ideality-aware training of memristor-based artificial neural networks (ANNs).

Learning in Networks of Mathematically Agnostic "In Materio" Neurons

Eleni Vasilaki

University of Sheffield, UK

Material-based computing, a promising paradigm for low-power computation, frequently grapples with network construction challenges due to the absence of accurate mathematical models for the component devices. This limitation typically confines such systems to reservoir architectures, where learning is restricted solely to the output layer.

We tackle this hurdle by training recurrent networks to serve as emulators for devices operating as "complex neurons" in a feedforward system. We achieve this by employing the well-established Neural Ordinary Differential Equations (NeuroODEs) techniques, resulting in differentiable emulators. This development facilitates the application of advanced training methodologies, such as backpropagation through time, to optimise network interconnectivity.

Furthermore, we demonstrate the successful transferability of connecting weights computed using an emulator to a physically fabricated nano-ring device by our team. This accomplishment significantly broadens the potential for the application of gradient-based learning rules in the field of material-based computing.

Digital Image Processing applied to the Characterization of Nanomaterials

Pedro L. Galindo

University of Cádiz, Spain

Characterization of nanomaterials can be achieved using electron microscopy, to determine the size, shape, crystal structure, chemical composition, optical and magnetic properties of structures, in some cases at the atomic level.

Z-contrast imaging is particularly useful because, with the use of aberration and chromatic corrected microscopes, the probe size is in the order of a few angstroms (probe sizes under one angstrom have been recently reported), and there is a direct correlation between the local contrast and local mass-thickness, which depends on the atomic number Z, enabling the interpretation of the image.

In this talk, a set of useful tools developed in our research group for characterizing nanomaterials using Z-contrast images will be presented, including strain analysis, superresolution, the great potential of using Gabor filters for nanoparticle localization and analysis and some applications of neural networks (Generative Adversarial Networks, Deep Learning, etc.) in the Electron Microscopy field.

Materials and Devices for Unconventional Computing Approaches

Valeria Bragaglia

IBM Research – Zurich, Switzerland

Neuromorphic computing is a promising paradigm of artificial intelligence (AI) systems that aims at developing an efficient computing architecture thatresemblesthe biological brains. The development of novel materials and devices with neural and synaptic functions incorporated into unique architectures will allow the implementation of a computing system that can efficiently perform the heavy vector - matrix manipulation inherent to AI workloads with O(1) time complexity.[1] In this talk I will focus on the role of materialscience in the development of various devices based on Phase Change Materials and Oxide Resistive Random Access Memories, key building blocks for the realization of the artificial neural and synaptic function in neuromorphic computing.[2,3] These devices rely on diverse physical mechanisms and materials and their understanding via experimental and theoretical means is pivotal to the device optimization and coupling to the higher layers of the computer architecture. The device rich switching and oscillating behaviours are dictated by a combination of factors including material compositions, fabrication processes, device morphologies and many others, and therefore provide a high degree of design freedom to tailor a device under specific application requirements. We will see examples of how material and device engineering can lead to breakthroughs in device performance. Nonetheless, device variability among other nonidealitiesstill hinders the hardware scaling to large networks required to solve more complex AI tasks. Challenges at device and hardware level may also be overcome through a complementary research effort to develop more robust, hardware-friendly algorithms and computational models that could compensate for the variability issues of devices.

[1] A. Sebastian et al., "Memory devices and applications for in-memory computing", Nature Nanotechnology, 15, 529-544, 2020.

[2] From: https://spectrum.ieee.org/analog-ai.

[3] G. Csaba and W. Porod, "Coupled oscillators for computing: A review and perspective," Applied Physics Review, 3 January 2020.

Device and circuit design tools role in developing neuromorphic technology.

Ahmed Nejim

Silvaco Europe Ltd, St. Ives, UK

An overview of the work developing Electronic Design Automation (EDA) models for neuromorphic devices and circuits will be presented. The advantage of producing a multiscale flow that leverages all the automation features offered by EDA tools will be showcased. This will enable future technology designers to “discover” best compromise with the least computational overhead without loosing sight of the underlying physical phenomena.

Multilevel Resistive Switching in Amorphous Oxides

Markus Hellenbrand

University of Cambridge, UK

The rapid and continued growth of power consumption due to Information and Communications Technology requires new forms of memory and computing paradigms, as a large part of the power consumption explosion is due to inefficient memory and its separation from data processing in the von Neumann architecture. One of the main competitors for such novel memory is the mechanism of resistive switching, whereby information can be stored in the (non-volatile) resistance state of a device instead of volatile charge. For large-scale industrial implementation, resistive switching in amorphous oxides is of great interest. However, in such materials, the switching mechanism typically based on the reversible filamentary electrical breakdown of the oxide layer faces challenges of uniformity and reproducibility. Here, we present our recent advances of addressing these challenges and demonstrate gradually tuneable (as opposed to abrupt filamentary) multiple (up to >500) resistance levels in individual cells by spatially restricting the switching process inside the amorphous layers. In one approach, this is achieved by creating self-assembled hafnium-oxide-based amorphous phase-separated nanocomposite films, and in a second approach by self-assembly of a thin epitaxial interlayer in a sodium bismuth titanate thin film during an otherwise non-epitaxial process. Both materials are deposited at 400 °C by pulsed laser deposition and demonstrate gradual multi-level resistive switching with switching endurances of >10 000 cycles. Based on this multilevel performance, basic synaptic functionality is demonstrated, too.

Electrocaloric effects in epitaxial films of $SrTiO_3$

Neil Mathur

University of Cambridge, UK

I will describe electrocaloric effects near the 243 K ferroelectric phase transition in epitaxial films of SrTiO3 on DyScO3 substrates. Results will be compared with (1) bulk SrTiO3 and (2) the canonical Landau description of this system.

List of Participants

Beatriz Noheda	University of Groningen
Jasper van der Velde	University of Groningen
Jan Rieck	University of Groningen
Felix Risch	EPFL (Swiss Federal Polytechnical Institute)
Igor Stolichnov	EPFL (Swiss Federal Polytechnical Institute)
Romar Avila	University of Twente
Evgenios Stylianidis	University College London
Pavlo Zubko	University College London
Panagiotis Koutsogiannis	Consejo Superior de Investigaciones Cientificas
César Magén	Consejo Superior de Investigaciones Cientificas
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Michael Wilkinson	University of Groningen
Iurii Tikhonov	University of Picardie
Davide Cipollini	University of Groningen
Lambert Schomaker	University of Groningen
Nele Harnack	IBM Research Zurich
Siegfried Karg	IBM Research Zurich
Yigit Demirag	University of Zurich
Giacomo Indiveri	University of Zurich
Elisabetta Chicca	University of Groningen
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Regina Dittmann	RWTH Aachen University
Dimitris Spithouris	RWTH Aachen University
Marty Gregg	Queen's University Belfast
Jack Eckstein	University of Cambridge
Michael Carpenter	University of Cambridge
Ekhard Salje	University of Cambridge
Marin Alexi	University of Warwick
Gustau Catalan	Catalan Institute of Nanoscience and Nanotechnology
Dennis Meier	Norwegian University of Science and Technology
Aida Todri-Sanial	Eindhoven University of Technology
Pavan Nukala	Centre for Nanoscience and Engineering
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Xavier Moya	University of Cambridge
Gertjan Koster	University of Twente