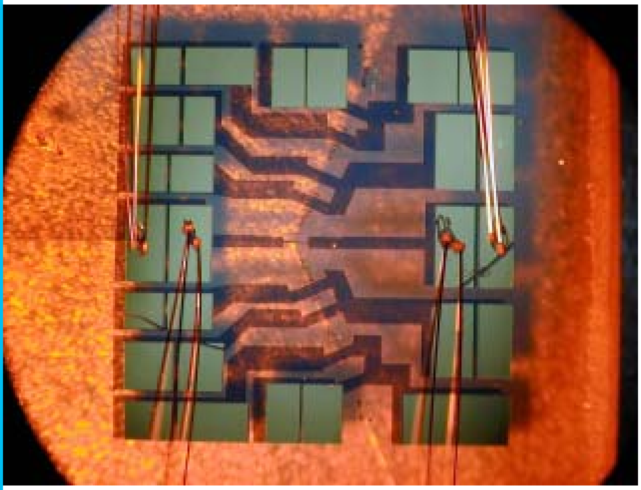
Thin Films for Novel Oxide Devices (THIOX)

An ESF scientific programme



Oxide materials show a rich spectrum of physical properties, encompassing ferroelectricity, dielectricity, ferromagnetism, colossal magnetoresistance, anti-ferromagnetism, and superconductivity. Therefore, thin films of these oxide materials have a high potential for device applications. A large number of materials is under investigation to be employed in future devices, for example in electric field-effect devices, superconducting Josephson junctions, in magnetic tunnel junctions, as exchange bias layers in GMR heads, and in tuneable high-frequency devices.

The potential of these materials for device applications is excellent, but some of the key factors controlling the physics, for instance the doping level and the structural order, are often difficult to control. Moreover, the compatibility of different oxides in terms of interface structure and electronic properties is a poorly understood issue, as are the effects of (substrate-induced) strain. In all cases, structural and electronic properties depend on deposition method and growth conditions, which have to be well understood and controlled. Advanced devices and fine-tuning of the electronic properties of these materials require further research in these areas.

The large amount of parameters and the machinery required for fabrication and analysis make it impossible for any single research group to get a firm grip on these issues, especially since these problems are strongly interdisciplinary in nature. What is needed, and what is aimed for, is more interaction between groups working on physical properties, on growth studies, and on structural/chemical analysis at the atomic level. The groups involved in this programme all play a leading international role in their subfields. However, they realise a need for stronger awareness of all aspects of the materials science, if tailoring of multilayered oxide structures for specific applications is to be successful. This is not a specific European but rather a worldwide problem, and a concerted European action will strongly aid in putting European groups at the forefront of this technologically promising research area. This programme, positioned at the intersection between condensed matter physics, chemistry, and materials science, aims at establishing a European network of groups working on different aspects of thin oxide films and oxide hybrids (combinations of films with different functionalities) with possible compatibility with standard semiconductor technology.

The European Science Foundation acts as a catalyst for the development of science by bringing together leading scientists and funding agencies to debate, plan and implement pan-European initiatives.

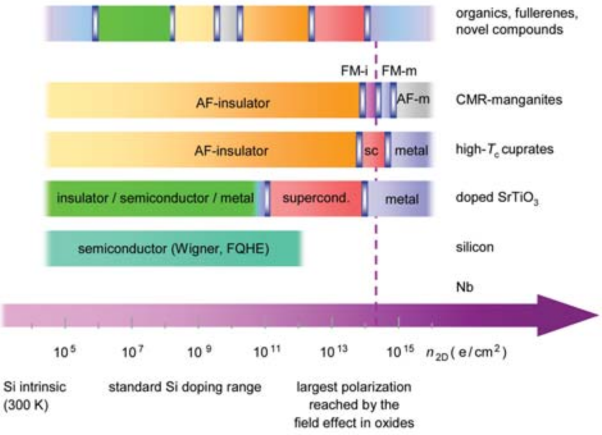


Illustration of the zero-temperature behaviour of various correlated materials as a function of sheet charge density. Silicon is shown as a reference. The examples for high-T_c superconductors and for colossal magnetoresistive (CMR) manganites reflect $YBa_2Cu_3O_{7-\delta}$ and (La,Sr)MnO_3, respectively. The top bar has been drawn to illustrate schematically the richness of materials available for field-effect tuning and the spectrum of their phases. AF, antiferromagnetic; FM, ferromagnetic; I, insulator; M, metal; SC, superconductor; FQHE, fractional quantum Hall effect; Wigner, Wigner crystal.

Introduction

Artificially layered complex oxide structures may well play a key role in the development of novel devices and device concepts. The potential of oxide thin films in device applications has already been demonstrated by the use of Bi-Sr-Ta-oxides in ferroelectric memory elements. Equally interesting and innovative combinations are superconductors with ferromagnets (spin injection) or superconductors/ ferromagnets with ferroelectrics (allowing a change in the doping level upon electric polarisation reversal). However, the possibilities are still limited by insufficient knowledge of the combinatorial possibilities of the different oxides, of the physics at the interfaces, of limitations set by strain effects or layer thickness, or of the possible compatibility with Si-technology. Although success has been obtained in the last years with heterostructures employed for electric field-effect studies, most efforts in the last years (worldwide) have gone into investigating single films of the different classes of materials (superconducting, ferroelectric, ferromagnetic/ magnetoresistive) and simple combinations involving an insulating (tunnelling) barrier oxide with one type of material on both sides. In the latter case, the example of manganite-based ferromagnetic tunnel junctions, which perform much less well at high temperatures than might be expected, already shows that the materials science and the interface physics are not fully understood. To come to a comprehensive understanding of these issues, the THIOX programme focuses on five topics:

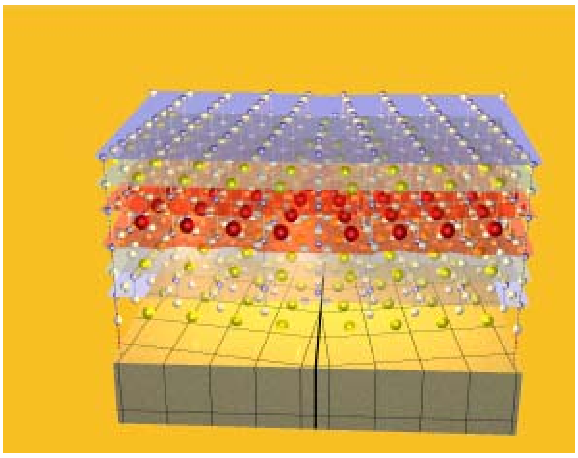
- Electronic and magnetic junctions
- Interface properties (structure and electronic)
- Hybrid structures
- Epitaxial growth, strain effects, defects, and pattern technology
- New materials.

The focus topics are used to break down barriers between different areas of expertise. It should allow groups working on junctions to also produce samples dedicated for growth studies; or groups working on magnetic layers to become familiar with ferroelectrics. Especially, it should allow increased collaboration in structure analysis of samples by transmission electron microscopy, electron energy loss, and synchrotron radiation. In addition, it allows availability of well-characterised substrates, the combination of the advantages of different growth techniques for special purposes, and comparison of samples made with different deposition techniques. These techniques (pulsed laser deposition, molecular beam epitaxy, sputtering) have seen rapid improvements with increased possibilities for in situ characterisation, making growth of high-quality heterostructures much more feasible. Finally, it should allow easier access to and testing of submicron pattern technologies either for device applications or for the creation of artificial defects.

Scientific background

The properties of oxide films are critically dependent on parameters such as deposition conditions, composition, intrinsic structure, doping, and strain. These parameters are studied within the different research themes.

In the research theme *junctions*, magnetic tunnel junctions based on manganites (both trilayer and ramp-type) are studied, while work has started on ruthenates and “double perovskites”. For these junctions, it is of great importance to obtain well defined, and the most favourable, epitaxial films in an all-in situ process. A new development here is the use of ferromagnetic insulating barriers as spin filters. Joint efforts should yield optimised junctions, functioning at the highest possible temperatures and especially elucidate the role of the interface, namely the terminating layer on the metal side. In the case of superconducting Josephson junctions, the investigation of the interface is a major task. The challenge is to change the carrier concentration and to modulate the electronic properties of the superconducting layer without introducing any chemical or microscopic structural disorder.

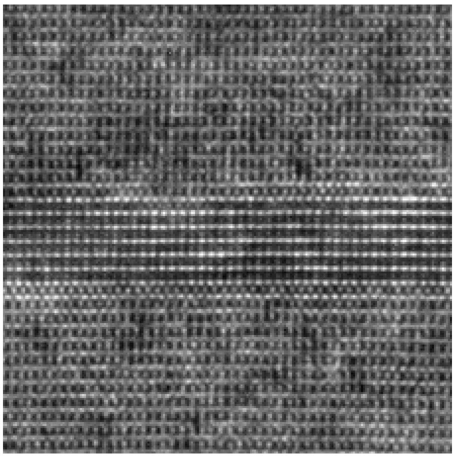


Bicrystalline junction

In the theme of *hybrid structures*, superconductor/ferromagnet combinations (especially YBCO/manganite) are deposited in order to investigate spin injection effects. In addition, ferroelectric/superconductor (PZT/YBCO) or ferroelectric/ferromagnet combinations (PZT/manganite) are produced. The above figure (grain junction) illustrates the behaviour of various materials as a function of sheet charge density. Chemical doping, which is the most commonly used technique to change the carrier density, invariably introduces disorder, and often magnetic scattering, rendering the interpretation of measurement data difficult. The ferroelectric field effect in heterostructures based on a superconducting layer and a ferroelectric layer is to electrostatically modulate in a reversible and non-volatile fashion the hole carrier density of the superconducting layer. With this approach, reversible switching behaviour between insulating and superconducting behaviour in underdoped high T_c superconductors has been demonstrated.

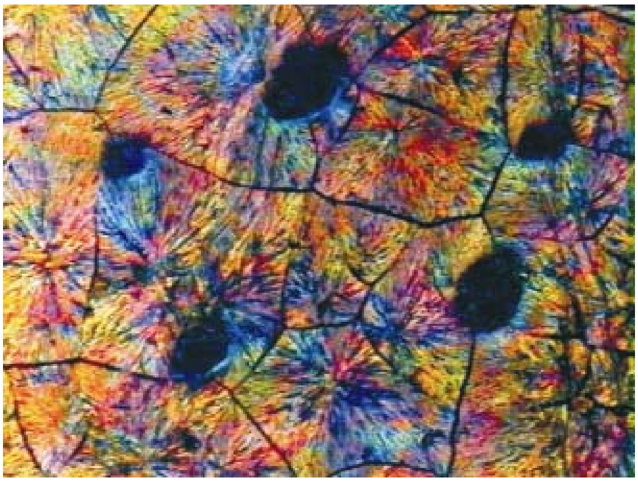
Furthermore, ferromagnet/antiferromagnet (manganite/manganite) combinations are grown for exchange biasing, and dielectric/superconductor hybrids (STO/YBCO) for the development of gate oxides. The need for smaller and faster devices pushes the materials science to its limits. It is already known that scaling of silicon devices (gate electronics, memories) is limited by material and interface properties of the thin SiO_2 gate dielectric. Metal-Oxide-Silicon (MOS) transistors with gate dimensions of 130 nm and a silicon-oxide gate dielectric thickness less than 2.5 nm are currently used in advanced integrated circuits. Going to smaller dimensions, the thickness of the conventional SiO_2 gate-dielectric has to be reduced. For sub-100 nm CMOS technologies, SiO_2 layers with thickness less than 1.7 nm would be needed. For such thin layers the tunnelling current is too high, while the intrinsic reliability prohibits further scaling. Hence, the gate dielectric technology is a major roadblock for scaling of CMOS technologies below 100nm dimensions. Thicker gate dielectric layers with higher relative dielectric constant (ε_r » 20-30) need to be introduced to replace SiO_2. Metal oxides such as zirconium oxide, tantalum oxide, hafnium oxide, and titanium oxide are proposed and investigated as exploratory gate dielectric materials.

The themes of *growth, strain, defects* and *patterning* are concerned with growth studies on single films for the other parts of the community. As one example, it can elucidate the role of the substrate. For a simple and much-used substrate such as $SrTiO_{3,}$ it was recently shown that a Sr- or a Ti-termination yields superconducting YBCO films with different morphology and relaxation behaviour. Such effects need to and will be studied for other materials. As a fringe benefit, well-characterised single-termination substrates should become available for the whole oxide community. A more general aim is to understand defect formation in pseudomorphic growth, which allows the growth of strained material and control over the amount of defects. Layered structures, mostly cuprates, are at the focus of these studies, but will be extended to layered manganites, which are beginning to be of interest for example for tunnel junctions. A final example is the study of growth on Si, of evident importance for devices. Close collaboration with electron microscopy groups is prerequisite and will be clearly stimulated by the programme; especially important here will be the development of electron energy loss spectroscopy (EELS) as a research tool for element-specific investigations. Pattern technology deserves special mentioning, since many groups cannot afford dedicated research on this topic and having access to specialised knowledge will be greatly beneficial.



HREM image of $SrRuO_3$-$SrTiO_3$-$SrRuO_3$ tri-layer magnetic tunnel junction. The $SrTiO_3$ barrier is 6 unit cells (approximately 2 nm) thin.

New materials, finally can for example be artificially layered structures, or new bulk materials. The importance of this research theme within the programme is to quickly disseminate information on new bulk materials which are of interest for the thin films community – most film efforts are on existing (thermodynamically stable) bulk compounds. As one example, the non-intermetallic superconductor MgB_2 is mentioned, which was announced with a record-high T_c for a conventional superconductor of 39 K, and which might well be of interest for combining with oxides.



Optical micrograph of a thin films produced by PLD from PTFE/$BaTiO_3$ composite target (University Linz)

Aims and objectives

The THIOX programme aims to deepen the understanding of the physics and materials science underlying oxide devices: a critical appraisal of the influence of the growth parameters and deposition methods, and to transfer such knowledge to application-oriented areas (devices). The envisaged achievements will be both general and specific. Generally, we like to be able to fabricate complex oxide heterostructures for devices in a controlled way, which includes the understanding of strain and interface effects. THIOX aims at establishing a European network for groups working on different aspects of oxide thin films and oxide heterostructures. THIOX would like to build a strong European community with its own profile, support the European research in this important field, and strengthen the links with the oxide electronics community in the USA and Japan.

The field of oxide electronics is developing very fast, especially in Japan. A European effort, bringing together various research groups and techniques, is needed to strengthen the European position and to create an “epitaxial oxide community” in Europe. The added value derives from the fact that most of the mentioned issues overlap so strongly in their materials science aspects, that it would be more efficient to try to benefit from the expertise available in the different groups. The community should be strong enough to work on fundamental research of oxides, and simultaneously transfer and translate this knowledge to the level of devices. This should result in providing new technological concepts for electronics, which is of great interest for science as well as European society. Equally important, by stimulating these cross-correlations, students and young researchers will be made aware of the interrelated problems in materials science research, which will lead to a substantial strengthening, in the long run, of the European capacity to sustain a high level in this research area. A significant part of the budget is used to support the exchange of young scientists and to enable tutorial meetings.

In addition, we know that being able to host the International Workshop for Oxide Electronics is significant in increasing the visibility of the field for young European researchers. THIOX brought this important workshop to Europe in 2003 and would like to do so again in 2006. The workshop would typically last three days and cover the whole scope (and all our themes) on oxide electronics. Previous workshops have mainly taken place in Japan (this year for the fourth time) and USA (three times). In 2000, this workshop was held in Europe for the first time and immediately showed its importance by the number of contributions which came from all over Europe – it was there that the idea of a European Oxide community was first discussed.

The THIOX ESF programme

During the next five years, workshops will be organised on each research theme. New challenges and opportunities as well as knowledge transfer and R&D are guiding principles. These R&D workshops will be open for those European researchers (in universities, research institutes and industry) who are internationally respected and can bring an added value to this community. This type of meeting is very common in the USA and Japan, and has proved its importance. Apart from these workshops/conferences, meetings of a more tutorial nature will be organised. These meetings will especially be for young scientists (in research institutes as well as industry) entering this field. In addition, special grants for young scientists will become available. These grants are given primarily to broaden the view of excellent students through visits to other laboratories for up to a period of six months, to become aware of new research activities and to learn new preparation and analysis techniques by making use of advanced equipment in the partner laboratories.

Finally, short scientific visits will be supported. The budget also foresees the support of joint publications. A website with all information and activities of this ESF programme is available.

THIOX main activities are:

- Support for the International Workshop on Oxide Electronics (WOE) in 2003 and 2006
- Support participation of young European scientists to participate in the WOE of 2004, 2005, and 2007
- Organisation of five topical workshops on different research themes, focusing on specific problems of critical importance for the oxide community
- Organisation of three tutorial meetings for young scientists (institutes and industry)
- Support short scientific visits of world experts
- Grants for young scientists (up to six months)
- Use THIOX to facilitate the access to large facilities (for example synchrotrons) or the specific (analysis) equipment (for example TEM) for the network members
- Support joint publications and a THIOX website
- Prepare the launching of a Network of Excellence on Oxide Electronics.

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THIOX Steering Committee

Prof. Dave Blank (Chair)
MESA+ Research Institute
Faculty of Science
and Technology
University of Twente
P.O. Box 217
7500 AE Enschede
Netherlands
Tel: +31 53 489 3121
Fax: +31 53 489 4683
E-mail:
d.h.a.blank@utwente.nl

Prof. Giuseppe Balestrino
Facoltà di Ingegneria
Dipartimento di Scienze
e Tecnologie Fisiche ed
Energetiche
Università di Roma
"Tor Vegata"
Roma
Italy
Tel: +39 0672597221(off.)
or 72597245 (lab.)
E-mail: balestrino@uniroma2.it

Prof. Dieter Bäuerle
Institut für Experimental
Physik, Abteilung für
Angewandte Physik
Johannes Kepler
Universität Linz
Alternbergerstrasse 69
4040 Linz
Austria
Tel: +43 732 2468 9244
Fax: +43 732 2468 9242
E-mail: dieter.baeuerle@jku.at

Prof. Mark Blamire
Dept of Materials Science
Cambridge University
Pembroke Road
Cambridge CB2 3QZ
United Kingdom
Tel: +44 1223 334 359
Fax: +44 1223 334 567
or 373
E-mail: mb52@cam.ac.uk

Dr. Jose Maria de Teresa
Instituto de Ciencia de
Materiales de Aragon
Universidad de Zaragoza-
CSIC
Calle Pedro Cerbuna 12
50009 Zaragoza
Spain
Tel: +34 976 76 24 63
Fax: +34 976 76 12 29
E-mail:
deteresa@posta.unizar.es

Dr. Karol Frohlich
Slovak Academy of Sciences
Institute of Electrical
Engineering
Dubravska cesta 9
841 04 Bratislava
Slovak Republic
Tel: +421 2 54 77 58 06
Fax: +421 2 54 77 58 16
E-mail: elekfroh@savba.sk

Prof. Jochen Mannhart
Institute of Physics
EKM
University of Augsburg
Universitätsstrasse 1
86135 Augsburg
Germany
Tel: +49 821 598 3650
Fax: +49 821 598 3652
E-mail: jochen.mannhart
@physik.uni-augsburg.de

Prof. Bernard Mercey
CNRS
CRISMAT/ENSICAEN
6 boulevard du Maréchal Juin
14050 Caen cedex 4
France
Tel: +33 2 31 45 26 08
Fax: +33 2 31 95 16 00
E-mail:
bernard.mercey@ismra.fr

Prof. Victor Moshchalkov
Katholieke Universiteit
Leuven
Lab. voor Vaste-Stoffysica
en Magnetisme
Celestijnenlaan 200 D
3001 Leuven
Belgium
Tel: +32 16 327 184/618
Fax: +32 16 327 983
E-mail: Victor.Moshchalkov
@fys.kuleuven.ac.be

Prof. Eva Olsson
Microscopy and
Microanalysis
Dept of Experimental
Physics
Chalmer's Technical
University
Fysikgrand 3
41 296 Göteborg
Sweden
Tel: +46 31 772 316
or +46 31 772 3247
Fax: +46 31 7723224
E-mail:
eva.olsson@fy.chalmers.se

Prof. Henryk Szymczak
Polish Academy of Sciences
Palace of Culture and Science
room 2314
Plac Defilad 1
00-901 Warsaw
Poland
Tel: +48 22 656 60 63
Fax: +48 22 620 06 97
E-mail: wydz3@pan.pl

Prof. Jean-Marc Triscone
Dépt. de Physique de la
Matière Condensée
Université de Genève
24 quai Ernest-Ansermet
1211 Genève 4
Switzerland
Tel: +41 22 379 6827
Fax: +41 22 379 6869
E-mail: Jean-Marc.Triscone
@physics.unige.ch

Advisory Experts:

Dr. Jan Aarts
Kamerlingh Onnes
Laboratory
Leiden University
P.O. Box 9504
2300 RA Leiden
Netherlands
Tel: +31 71 527 5478
Fax: +31 71 527 5404
E-mail:
aarts@phys.leidenuniv.nl

Prof. Gustaaf van Tendeloo
Electron Microscopy for
Materials Research
University of Antwerp
Gronenborgerlaan 171
2020 Antwerpen
Belgium
Tel: +32 3 2180262
Fax: +32 3 2180257
E-mail: gvt@ruca.ua.ac.be

Prof. Bernard Raveau
Laboratoire de
Cristallographie et
Sciences des Materiaux
ENSICAEN, CRISMAT
UMR 6508/CNRS
6 boulevard du Maréchal Juin
14050 Caen cedex 4
France
Tel: +33 2 31 45 26 16
Fax: +33 2 31 95 16 00
E-mail: bernard.raveau
@ismra.fr

Prof. Tord Claeson
School of Physics and
Engineering Physics
Dept of Microelectronics
and Nanoscience
Chalmers University
of Technology
and University of
Gothenburg
412 96 Göteborg
Sweden
Tel: +46 31 772 33 04
Fax: +46 31 772 3471
E-mail: f4atc@fy.chalmers.se

Prof. Øystein Fischer
Dépt. de Physique de la
Matière Condensée
Université de Genève
24 quai Ernest-Ansermet
1211 Genève 4
Switzerland
Tel: +41 22 379 62 70
Fax: +41 22 379 68 69
E-mail: Oystein.Fischer@
physics.unige.ch

ESF Liaison:

Dr. Patricia Arsene
Science

Ms. Catherine Werner
Administration

European Science Foundation
1 quai Lezay-Marnésia
BP 90015
67080 Strasbourg cedex
France
www.esf.org
Tel: +33 (0)3 88 76 71 28
Fax: +33 (0)3 88 37 05 32
E-mail: cwerner@esf.org

For the latest information on this programme consult the *THIOX* home page: www.esf.org/thiox

Cover picture:
Tetracrystalline grain boundary
device

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