OSEPI
Epitaxy of oxides and semiconductors

May 13-17 2024, villa Clythia, Fréjus (France)

Book of abstracts

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Program overview

Monday may 13th	Tuesday may 14th	Wednesday may 15th	Thursday may 16th	Friday may 17th
	Introduction **Jean-Noël Aqua (INSP - Paris)**	Plenary talk II **Eric Tournié** (IES - Montpellier)	Plenary talk III **Judith Driscoll** (Cambridge university)	**Session V** (continued) : **From properties to devices** Invited 1 **Guillaume Agnus** (C2N - Palaiseau) Invited 2 **Maëva Fagot** (IES - Montpellier) **Regular contributions**
	Plenary talk I **Clément Merckling** (IMEC - Leuven)	**Session II : Structural and functional characterization** Invited 1 **Laura Bocher** (LPS - Orsay) Invited 2 **Julien Barjon** (GEMaC - Versailles) **Regular contributions**	**Session IV : Hybridation** Invited 1 **Valérie Demange** (ISCR - Rennes) Invited 2 **Charles Cornet** (FOTON - Rennes) **Regular contributions**	
	Session I **Growth mechanisms** Invited 1 **Roman Engel-Herbert** (Paul Drude Institute - Berlin)			
	LUNCH AND FREE TIME			
Welcome **(starting 14H)**	Invited 2 **Jean-Christophe Harmand** (C2N - Palaiseau) **Regular contributions**	**Session III : Properties engineering using epitaxy** Invited 1 **Daniele Preziosi** (IPCMS - Strasbourg) Invited 2 **Fabrice Semond** (CRHEA - Valbonne) **Regular contributions**	**Session V : From properties to devices** Invited 1 **Vincent Garcia** (CNRS – Thales - Palaiseau) Invited 2 **Maria Tchernycheva** (C2N - Palaiseau) **Regular contributions**	**Departure** **(14H after lunch)**
	Sponsor session			
	DINNER AND FREE TIME			
	Poster session	**Poster session**	**Poster session**	

Program

Tuesday, may 14th

8H30—8H45 **Introduction: Jean-Noël Aqua (INSP - Paris)**

8H45—9H45 **Plenary talk :**

About the central role of materials exploration and crystal growth in advance and future electronic, photonic and quantum devices

Clément Merckling

IMEC – Leuven

Session I : Growth mechanisms

Chair : Jean-Noël Aqua (INSP – Paris)

9H45—10H30 **Invited 1 :**

Hybrid oxide MBE: possible pathway to achieve semiconductor grade complex oxide thin films?

Roman Engel-Herbert

Paul-Drude-Institute for Solid State Electronics, Berlin

10H30 – 11H00 Break

11H00 – 11H20 Graphene growth mechanisms during propane/hydrogen CVD on SiC

C. Mastropasqua[1,2], A. Michon2, M. Paillet[3], M. Portail[2], M. Koudia[4], M. Abel[3], I. Berbezier[4], A. El Alouani[2]

(1) IM2NP, Marseille
(2) CRHEA, Sophia-Antipolis
(3) Laboratoire Charles Coulomb, Montpellier

11H20 – 11H40 In depth study of the growth mechanism of GaN nanowires by Si-assisted MOVPE

B. Alloing[1], J. Bosch[1], P. Vennégues[1], L. Lymperakis[1]

(1) CRHEA, Sophia-Antipolis

11H40 – 12H00 Nucléation, taille du noyau critique et distributions des zones de capture dans l'épitaxie des semiconducteurs : un aperçu de l'état de l'art

A. Pimpinelli[1]

(1) Institut Pascal, Clermont-Ferrand

12H00 – 12H20 Modeling of InAs nanowire growth using a dual-adatom diffusion-limited approach

D. Mosiiets[1], Y. Genuist[1], J. Cibert[1], E. Bellet-Amalric[2], M. Hocevar[1]

(1) Institut Néel, Grenoble
(2) CEA, PHELIQS, Grenoble

12H20 – 14H00 Lunch and free time

Session I : Growth mechanisms (continued)

Chair : Romain Bachelet (INL – Lyon)

14H00—14H45 **Invited 2 :**

Some mechanisms of III-V nanowire growth

Jean-Christophe Harmand, N. Hong, C. Wei, G. Patriarche, L. Travers, F. Oehler, F. Glas, F. Panciera, C. Tong, A. Scaccabarozzi, A. Catoni

C2N Palaiseau

14H45 – 15H05 Exploring the Impact of Thickness on Epitaxial Growth: A Comparative Study of (001) Oriented CeO2 Thin Films on R-plane sapphire

E. Chaslin[1], Q. Simon[1], A. Borroto[1], M. Himdi[1], X. Castel[1]

(1) IETR, Rennes

15H05 – 15H25 Epitaxial growth and characterization of Potassium Titanyl Phosphate isomorphous thin films by Pulsed Laser Deposition

A. Clavel[1], M. Salaün[1], B; Boulanger[1]

(1) Institut Néel, Grenoble

15H25 – 15H45 Pioneer operando curvature stress measurement during BaTiO3 thin film epitaxy by RF magnetron sputtering

C. Furgeaud[1], R. Rousseau[1], M. Bounab[1], P. Regreny[1], C. Botella[1], A. Danescu[1], R. Bachelet[1], G. Saint-Girons[1]

(1) INL, Lyon

15H45 – 16H15 Break

16H15 – 16H55 Sponsor session

Chair : Jean-Baptiste Rodriguez (IES Montpellier)

16H15 – 16H35 In situ curvature measurement: a great breakthrough for MBE growth monitoring

A. Toujani[1]

(1) RIBER SA

16H35 – 16H55 New FIB and Cryo FIB-SEM by JEOL

L. Vassé[1]

(1) JEOL (EUROPE) SAS, 1 Allée de Giverny, 78290 Croissy-sur-Seine, France

AFTER DINNER : POSTER SESSION

Wednesday, may 15th

8H30—9H30 **Plenary talk :**

Epitaxy of III-V semiconductors: some challenges and evolutions

Eric Tournié

IES - Montpellier

Session II : Structural and functional characterization

Chair : Yvon Cordier (CRHEA – Sophia Antipolis)

9H30—10H15 **Invited 1 :**

How will electron spectromicroscopy reveal "all the secrets" of your oxides down to the atomic scale? … at least their structural, chemical, and electronic features !

Laura Bocher

LPS - Orsay

10H15 – 10H45 Break

10H45—11H30 **Invited 2 :**

Characterisation of defects in wide bandgap semiconductors

Julien Barjon, C. Arnold, I. Stenger, A. Delteil, R. Gillet, S. Hassani, S. Roux, S. Gautam, M.A. Pinault-Thaury

GEMaC - Versailles

11H30 – 11H50 Advanced optical flux monitoring to control thin layer deposition processes

R. Rousseau[1], C. Botella[1], J. Morville[1], L. Berguiga[1], M. Bounab[1], C. Furgeaud[1], R. Bachelet[1], G. Saint-Girons[1]

(1) INL, Lyon

11H50 – 12H10 Electron Channeling Contrast Imaging for epi-layer structural defect characterization

A. Gilbert[1], A. Meguekam[1], E. Tournié[1] and J.B. Rodriguez[1]

(1) IES, Montpellier

12H10 – 12H30 Electrically-driven antiferroelectric-ferroelectric phase transition in epitaxial PbZrO3 thin films studied by in situ X-ray diffraction

T. Cornelius[1], S. Matzen[2], T. Maroutian[2], C. Mocuta[3], A. Zing[2], S. Escoubas[1], O. Thomas[1]

(1) IM2NP, Marseille
(2) C2N, Paris-Saclay
(3) Synchrotron SOLEIL

12H30 – 14H00 Lunch and free time

Session III : Properties engineering using epitaxy

Chair : Maxime Hugues (CRHEA – Sophia Antipolis)

14H00—14H45 **Invited 1 :**

Stabilization of nickelate infinite-layer phase: from 'soft-chemistry' to 'soft-physics'

Daniele Preziosi

IPCMS - Strasbourg

14H45—15H30 **Invited 2 :**

Niobium nitride, a newcomer to the III-nitride semiconductor family: Epitaxy of metal/semiconductor, semiconductor/superconductor hybrid heterostructures

Fabrice Semond

CRHEA - Valbonne

15H30 – 16H00 Break

16H00 – 16H20 Crafting the magnetic anisotropy in highly epitaxial CoV2O4 thin films

L. El Khabchi[1], A. Peña Corredor[1], L. Schlur[1], M. Lenertz[1], J. Robert[1], C. Leuvrey[1], G. Versini[1], F. Roulland[1], D. Preziosi[1], C. Lefevre[1], N. Viart[1]

(1) IPCMS, Strasbourg

16H20 – 16H40 GaN/AlGaN quantum wells grown on bulk GaN substrate in the step-flow or step meandering regime, impact on indirect exciton diffusion

B. Damilano[1], R. Aristegui[1], H. Teisseyre[1], S. Vézian[1], V. Guigoz[1], A. Courville[1], I. Florea[1], D. Lefebvre[1], P. Vennéguès[1], M. Bockowski[1], T. Guillet[1], M. Vladimirova[1]

(1) CRHEA, Sophia-Antipolis

16H40 – 17H00 Phase controlled epitaxy of wurtzite ZnS thin layers by MOCVD

H. Melhem[1], V. Sallet[2], G. Amiri[2], T. Van den Berg[1], G. Hallais[1], G. Patriarche[1], N. Findling[1], L. Largeau[1], P. Hemme[1], C. Renard[1], L. Vincent

(1) C2N, Paris-Saclay
(2) UVSQ, Versailles

17H00 – 17H20 Anisotropic strain-induced single multiferroicity in BiFeO3 thin films

A. Abdelsamie[1,2], P. Dufour[1], A. Finco[2], A. Chaudron[1], J. Fischer[1], N. Jaouen[3], M. Viret[4], K. Bouzehouane1, V. Jacques[2], J.Y. Chauleau[4], S. Fusil[1], V. Garcia[1]

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(2) Laboratoire C. Coulomb, Montpellier
(3) Synchrotron SOLEIL, Gif-sur-Yvette
(4) CEA-SPEC, Gif-sur-Yvette

AFTER DINNER : POSTER SESSION

Thursday, may 16th

8H30—9H30 **Plenary talk :**

The potential for enhanced functional properties offered by vertically aligned nano composite films

Judith MacManus-Driscoll

Cambridge University

Session IV : Hybridation

Chair : Nathalie Lemée (LPMC – Amiens)

9H30—10H15 **Invited 1 :**

Oxide nanosheets as seed layers for growth of complex oxides

F. Baudouin[1], A. Boileau[2], M. Dallocchio[2], B. Bérini[3], S. Ollivier[1], M. Chettab[1], S. Hurand[4], A. David[2], U. Lüders[2], S. Députier[1], W. Prellier[2], M. Guilloux-Viry[1], Y. Dumont[3], A. Fouchet[2], **Valérie Demange**[1]

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(3) GEMaC, Université Paris-Saclay, UVSQ, CNRS, GEMaC UMR8635, 78035, Versailles, France
(4) Pprime, UPR 3346 CNRS-Université de Poitiers, Futuroscope-Chasseneuil

10H15 – 10H45 Break

10H45—11H30 **Invited 2 :**

III-V/Si epitaxial growth and antiphase domains: a matter of symmetry

Charles Cornet[1], S. P. Chandrasekharan[1], A. Gilbert[2], D. Gupta[1], P. Vennéguès[3], F. Semond[3], A. Ponchet[4], L. Cerutti[2], L. Largeau[5], G. Patriarche[5], E. Tournié[2], P. Turban[6], L. Pedesseau[1], N. Bertru[1], J.B. Rodriguez[2]

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(2) IES, Montpellier
(3) CRHEA, Sophia-Antipolis
(4) CEMES, Toulouse
(5) C2N, Paris Saclay
(6) IPR, Rennes

11H30 – 11H50 Strain-relieving mechanism in III-V semiconductors epitaxially grown on Silicon : misfit dislocation networks

A. Gilbert[1], K. Graser[2], A. Trampert[2], M. Ramonda[1], E. Tournié[1], J.B. Rodriguez[1]

(1) IES, Montpellier, (2) Paul-Drude-Institut für Festkörperelektronik

11H50 – 12H10 Vers la localisation bas coût d'hétéroépitaxie de GaAs sur Si

L. Dentz[1], C. Renard[1], F. Hamouda[1], G. Hallais[1], L. Vincent[1], D. Bouchier[1], E. Herth[1], T. Baptiste[1], L. Largeau[1], A. Jaffre[2], J.P. Connolly[2], D. Mencaraglia[2], L. Leroy[1]

(1) C2N, Paris-Saclay, (2) LGEP, Paris-Saclay

12H10 – 12H30 Local epitaxy via CNO nanosheets on glass : effect of thickness on the Vanadate TCO

A. Fouchet[1], M. El rami[1], S. Hurand[2], U. Luders[1], B. Berini[3], A. David[1], C. Labbé[4], J. Cardin[4], M. Guilloux-Viry[5], W. Prellier[1], Y. Dumont[3], V. Demange[5], A. Ruyter[1]

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12H30 – 14H00 Lunch and free time

Session V : From properties to devices

Chair : Laurence Méchin (GREYC – Caen)

14H00—14H45 **Invited 1 :**

Scanning probe microscopy for functional oxide thin films

Vincent Garcia

Laboratoire Albert Fert, CNRS Thales - Palaiseau

14H45—15H30 **Invited 2 :**

Nitride nanowire light emitting diodes: from single wire properties to device applications

Maria Tchernycheva[1], N. Amador[1], S. Vézian[2], B. Damilano[2], J. Bosch[2], B. Alloing[2], J. Eymery[3], C. Durand[3]

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(3) Université renoble Al es, CEA, IRIG, PHELIQS, NPSC, 38000 Grenoble, France

15H30 – 16H00 Break

16H00 – 16H20 Orientation dependence of functional properties in preferentially oriented Bi0.5Na0.5TiO3-BaTiO3 thin films

H. Alaoui[1], A. Lahmar[1], O. Mlida[2], F. Ponchel[3], A. Da Costa[2], F. Le Marrec[1], A. Ferri[2], A. Ysebaert[1], A. Cantaluppi[1], M. H. Chambrier[2], D. Remiens[3], R. Desfeux[2], N. Lemée[1]

(1) LPMC, Amiens
(2) UCCS, Lens
(3) IEMN, Valenciennes

16H20 – 16H40 Ammonia source molecular beam epitaxy of ScAlN/GaN HEMT heterostructures

Y. Cordier[1], C. Elias[1], S. Chenot[1], F. Bartoli[1], P. Vennéguès[1], M. Hugues[1]

(1) CRHEA, Sophia-Antipolis

16H40 – 17H00 Monolithic integration of GaAs based compounds on silicon platform for photonic and optoelectronic devices

L. Mallet-Dida[1], M. Martin[1], J. Moeyaert[1], T. Baron[1], D. Mouloua[1], V. Letka[1], H. Hijazi[1], M. Chobe[2]

(1) LTM, Grenoble
(2) LETI, Grenoble

17H00 – 17H20 InAs/Sn shadow junctions with upgraded superconducting properties

A. Sharma[1], A.H. Chen[2], C. Dempsey[3], A. Purkayastha[1], S. Tan[4], C. Palmstrom[3], S. Frolov[1], M. Hocevar[2]

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(3) Electrical and Computer Engineering, University of California, Santa Barbara
(4) Department of Electrical and Computer Engineering, University of Pittsburgh

AFTER DINNER : POSTER SESSION

Friday, may 17th

Session V: From properties to devices (continued)

Chair : Thomas Maroutian (C2N - Paris)

8H30—9H15 **Invited 1 :**

Oxide thin films processing: some examples on how to take advantage of perovskite properties into devices

Guillaume Agnus, T.Maroutian, S. Matzen, P. Lecoeur

C2N - Palaiseau

9H15—10H00 **Invited 2 :**

Direct epitaxy of lasers on Si substrates: challenges and solutions

Maeva Fagot, D-A Diaz-Thomas, A. Gilbert, M. Ramonda, Y. Rouillard, A.N Baranov, J.B Rodriguez, E. Tournié and L. Cerutti

IES, Univ. Montpellier, CNRS, F-34000 Montpellier, France

10H00 – 10H30 Break

10H30 – 10H50 Infrared GeSn photodetectors: new avenues in monolithic Si photonics

S. Assali[1]

(1) CEA, Grenoble

10H50 – 11H10 Is SCAM a promising oxide material, or a scam?

H. Teisseyre[1,2,3], T. Stefaniuk[4], J. Suffczyński[4], M. Wierzbowska[2], J. Z. Domagała[1], J.Kisielewski[5], A. Kłos[5], A. Korneluk[4]

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(3) CRHEA, Sophia-Antipolis
(4) Faculty of Physics, University of Warsaw, Warsaw, Poland
(1) Łukasiewicz Research Network-Institute of Microelectronics and Photonics, Warsaw, Poland

11H10 – 11H30 Hybrid CVD-MBE Er:Y2O3 thin films for on-chip quantum technologies

A. Blin[1], A. Tallaire[1], D. Serrano[1], I. Balasa[1], P. Goldner[1], A. Kolar[2], A. Kamen[2], Q. Lin[2], X. Liu[2], T. Zhong[2]

(1) IRCP, Paris
(2) Pritzker School of Molecular Engineering at the University of Chicago

11H30 – 11H50 Epitaxial Growth of Fe3O4 on ZnO(000Â±1) Substrates for All-Oxide Spintronic Devices

I. Madaci[1,2], O. Popova[3], P. Vennéguès[2], M. Nemoz[2], B. Berini[1], C. Morhain[2], Y. Dumont[1]

(1) GEMAC, Versailles
(2) CRHEA, Sophia-Antipolis
(3) IPR, Rennes

11H50 – 14H00 Lunch and departure

POSTER LIST

P1: Growth and ferroelectricity of GeTe thin films on nominal and vicinal silicon substrate

L. Meynier[1], F. Verducci[1], B. Croes[1], F. Cheynis[1], S. Curiotto[1], P. Müller[1], F. Leroy[1]

(1) Aix Marseille Université, CNRS, CINAM, AMUTECH, Marseille, France

P2: Selective area growth of InGaAs and InGaN nanowires arrays by hydride vapour phase epitaxy

G. Avit[1], E. Chereau[1,2], E. Semlali[1], A. Sauvagnat[1], G. Gregoire[1], M. Zeghouane[1], J. Jridi[3], C. Bougerol[3], V. G. Dubrovskii[4], E. Gil[1], R. R. Lapierre[2], A. Trassoudaine[1], Y. André[1]

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P3: Growing SiGe nanowires with the hexagonal phase

H. Ameziane[1], H. Melhem[1], G. Patriarche[1], T. Van den Berg[1], G. Hallais[1], C. Renard[1], L. Vincent[1]

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P4: Epitaxial V2O3 films by Reactive Magnetron Sputtering

J. Cordiez[1], V. Demange[3], B. Corraze[1,2], M. Haydoura[1], Z. Khaldi[1], P. Béal[1], M. Guilloux-Viry[3], J. Tranchant[1], M.P. Besland[1], L. Cario[1,2], E. Janod[1,2]

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(3) Univ Rennes, CNRS, ISCR-UMR6226, ScanMAT-UAR2025, F-35000 Rennes, France

P5: CVD Growth of Graphene and Vanadium-Doped SiC for Quantum Hall Resistance Standards

A. El Alouani[1], C. Mastropasqua[1,2], M. Paillet[3], M. Portail[1], Y. Cordier[1], B. Jouault[3], S. Contreras[3], M. Zielinski[4], S. Juillaguet[3], A. Michon[1]

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(3) Université Montpellier 2/CNRS, L2C, Montpellier, France

(4) NovaSiC, 73370, Le Bourget-du-Lac, France

P6: Pulsed laser deposition of La2/3Sr1/3MnO3 thin films: first experiments using a Nd-YAG laser

V. Pierron[1], G. Tarsi[1], J. Blond[1], B. Guillet[1], L. Méchin[1] S.K. Chaluvadi[2], S. Punathum Chalil[2,3], P. Rajak[2,3], P. Orgiani[2] N. Manca[4], L. Pellegrino[4], D. Marre[4]

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(4) CNR-SPIN, Corso Ferdinando Maria Perrone, 24, 16152 Genova GE, Italy

P7: Exploring the epitaxial growth of superconducting β-Sn on Ge

S. Assali[1]

(1) Université Grenoble Alpes, CEA Grenoble

P8: Growth and design of antiferromagnetic (LaVO3)m/(PrVO3)n superlattices

G. Masset[1], M. Martirosyan[1], M. Bugnet[2,3], J. Ghanbaja[1], S. Migot[1], L. Pasquier[1], Q.M. Ramasse[2], S. Andrieu[1], K. Dumesnil[1], and O. Copie[1]

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(2) SuperSTEM Laboratory, SciTech Daresbury Campus, Daresbury, United Kingdom

(3) Univ Lyon, CNRS, INSA Lyon, UCBL, MATEIS, Villeurbanne, France

P9: Determination of the anisotropic dielectric function of epitaxial SrO(SrTiO3)n Ruddlesden-Popper structures (n=1,...5)

M. Bounab[1], C. Furgeaud[1], S. Cueff[1], R. Bachelet[1], M. Bouras[1,2], G. Saint-Girons[1]

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(2) Georgia Tech Lorraine (Georgia Tech-Europe), 2 Rue Marconi, 57070 Metz (France

P10: Complex Oxides by Large Area Pulsed Laser Deposition

M. Rath and U. Lüders

(1) CRISMAT, 6 boulevard Maréchal Juin, 14000 Caen

P11: ELECTRIC AND PIEZOELECTRIC BEHAVIORS OF ZnO NWs GROWN BY MOCVD.

S. Hassani Said[1], G. AMIRI[1], C. SARTEL[1], P. CHRETIEN[3], J. SCOLA[1], N. GOGNEAU[2] and V. SALLET[1]

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P12: Tailoring the metal-insulator transition of rare earth nickelates towards adaptive infrared camouflage

L. Matera[1,2], L. Divay[2], C. Galindo[2], P. Bortolotti[2], M. Bibes[1], L. Iglesias[1]

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P13: Thermoelectric perovskite-oxide solid-solutions epitaxially-grown by MBE for on-chip thermal energy management

D. Han[1], M. d'Esperonnat[1], R. Moalla[1], M. Apreutsei[1], C. Botella[1], C. Furgeaud[1], A. Lamirand[1], M. Bugnet[2], J. Gazquez[3], I. Fina[3], P.O. Chapuis[4], C. Adessi[5], R. Debord[5], V. Giordano[5], S. Pailhès[5], G. Saint-Girons[1] and R. Bachelet[1]

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P14: ZnO : from material growth to quantum cascade devices

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P15: Kinetic Monte Carlo Simulation of Epitaxal Growth of 2D Si

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P16: $[MnO2]^{\delta-}$ 2D Oxides as Templates for Epitaxial Growth of Functional Oxide Films

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P17: Influence of the strain relaxation on the ferroelectric nanodomains in ferroelectric / dielectric superlattices

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Plenary talks

About the central role of materials exploration and crystal growth in advanced and future electronic, photonic and quantum devices

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With the slowing down of Moore's law, related to conventional scaling of integrated circuits, alternative technologies will require research efforts towards new generations of electronic, photonic and ultimately quantum devices. In this context, the integration onto a traditional silicon platform of various materials such as 2D materials as well as perovskites oxides in their single crystalline form would allow to push the limits of devices and technologies.

In this framework, two-dimensional (2D) materials offer prospects of unprecedented advances in device performance at the sub-nanometer scale. Their amazing potential has proven to be a possible solution to overcome the limitations of silicon technology, where the combination of 2D materials with silicon chips promises to surpass the current technological limitations. With that vision, we investigate their integration, in particular for beyond silicon CMOS and advanced memory technologies. However, many challenges remain to unlock their incorporation into the Si-technology, especially the growth, the gate oxide and contact module at the source/drain area in a Field-Effect Transistor device. The quest towards 2D devices is today the focus to boost current device performances.

Perovskite oxides with the ABO_3 chemical formula have a very wide range of interesting intrinsic properties such as metal-insulator transition, ferroelectricity, pyroelectricity, piezoelectricity, ferromagnetic and superconductivity. For the integration of such oxides, it is of great interest to combine their properties with traditional electronic, memory and optical devices on the same silicon-based platform. More especially in the context of high-speed chip-to-chip optical interconnects, compact high-resolution beam steering and video-rate RGB hologram generation require the integration of fast and efficient optical modulators on top of silicon CMOS devices. For these applications the integration of high quality electro-optical materials A defect-free material-stack deposition on silicon wafers is hence required. Among the possible materials options, barium titanate ($BaTiO_3$) is one promising candidate due to its large intrinsic Pockels coefficients that can be obtained. We will then review the different options to integrate $BaTiO_3$ on Silicon substrate though different templates to control the polarization direction and discuss the influence on the physical and more especially electro-optic properties.

Finally, we will discuss the use of perovskite oxides in the field of topological based qubits which is one of the promising methods for realizing fault-tolerant computations. Therefore, the physics at the superconductor/topological insulator heterostructure interface need to be studied further, starting at the material level. In this work, the perovskite structure Barium Bismuthate (BBO) provides opportunity for easily tailored functionality through substitutional doping. Incorporation of potassium into the lattice of BBO results in a superconducting phase with Curie temperature as high as ~ 30K. In addition, BBO is according to DFT based studies, predicted to form topological surface states when doped with Fluorine. In our study, we integrate BBO perovskites on silicon substrates and discuss the structural, chemical and transport properties of the heterostructures.

Part of this work has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreements N^o 864483 and 742299).

Epitaxy of III-V semiconductors: some challenges and evolutions

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III-V semiconductors are compound semiconductors made from chemical elements from the III- (B, Al, Ga, In) and V- (N, P, As, Sb, Bi) columns of the Mendeleev table. Most of them exhibit a number of properties (direct band gaps, effective masses, carrier mobilities) that make them very attractive for high speed/high frequency electronic and/or optoelectronic devices. In particular, the III-V semiconductors have "benefited" from the indirect band gap of Si and Ge, which prevents efficient light emission. The III-V semiconductors allow a large flexibility in terms of band gaps and band alignments, at the expense, however, of large lattice-constant differences (Figs. 1 & 2). Thus, most III-V technologies were initially investigated for the fabrication of light emitting devices, in particular semiconductor lasers. With recent developments in the GaN technology, III-V semiconductors now cover the entire wavelength range from the deep-UV to the far-IR (Fig. 2).

The need for increasingly complex III-V semiconductor heterostructures has been the driving force behind the development of the epitaxy techniques for decades, from early liquid phase epitaxy to today's metal organic vapor phase epitaxy and molecular beam epitaxy, from research lab systems to industrial production systems. In this talk, I will (try to) review the properties of III-V semiconductors and their epitaxy developments, emphasizing the requirements specific to each III-V technology and application, including the mid-IR III-Sb technology developed at Montpellier. Finally, I will give a bird's eye view of the French landscape.

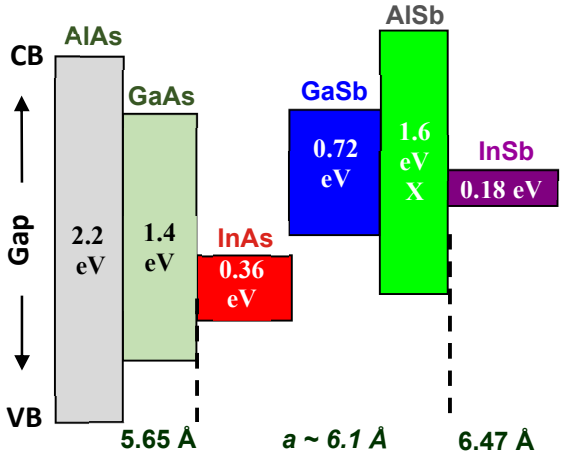

Fig. 1: Band gaps and band alignment for most zinc blende III-V semiconductors.

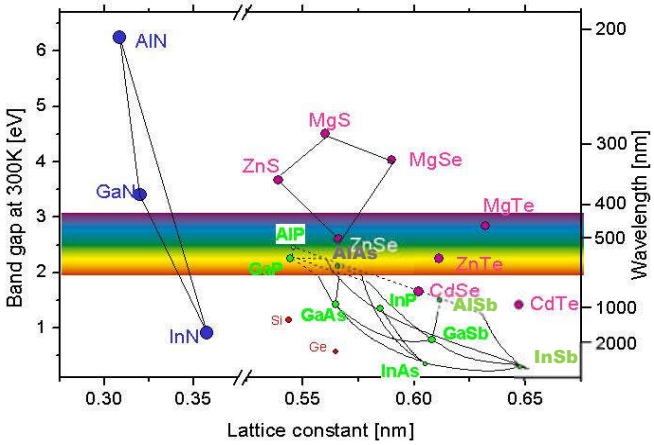

Fig. 2: Band gap *vs* lattice constant of III-V and II-VI semiconductors.

The potential for enhanced functional properties offered by vertically aligned nano composite films

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Opportunities of functional oxides for applications in electronics are huge. However, oxides in electronics are quite scarce. The challenges stem from both intrinsic and extrinsic materials problems, e.g. composition, defect and interface control. Also, current thin film deposition routes cannot always deliver the performance of bulk materials. This talk looks at some of the reasons for the aforementioned challenges and shows ways to overcome them. Recent examples from my group are given, highlighting unrivalled device properties in the areas of ferroics, semiconductors, magnetics, semiconductors, involving nanocomposite systems and novel processes.

Sponsors

New FIB and Cryo FIB-SEM by JEOL

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Keywords: FIB-SEM,Cryo-prep,Cryo-FIB,Cryo-TEM lamella prep, TEM lamella preparation, 3D analysis, EDS, EBSD

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- Highly stable cooling Stage
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Session I

Growth mechanims

Invited contributions

Hybrid oxide MBE: possible pathway to achieve semiconductor grade complex oxide thin films?

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Maturing the thin film growth of emerging materials to reduce the level of defects is a mandatory prerequisite to study their intrinsic physics and to innovate new device functionalities. While this has been done with remarkable success in various traditional semiconductor materials using molecular beam epitaxy, ranging from monoelemental Group IV, to Group III-V all the way to Group II-VI compound semiconductors, it has been found challenging to expand beyond binary oxides, such as ZnO or MgO. In particular, complex oxides containing two or more cations have been proved difficult to minimize extrinsic and intrinsic point defect concentration. This provokes the question:

Can we even achieve semiconductor-grade quality complex oxide thin films?

In this talk I will introduce the fundamental challenges utilizing a conventional molecular beam epitaxy approach for the growth of complex oxides and present an alternative – a hybrid synthesis approach – as a potential way out to overcome existing challenges. Promising results obtained by hybrid oxide MBE will be presented along with the most recent advances in materials quality achieved in complex oxides thin films with perovskite structure. An outlook will be given about the possibility to scale up this growth approach to larger substrates and higher growth rates, rendering its potential relevance in an industrial setting.

Some mechanisms of III-V nanowire growth

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Semiconductor nanowires have been the subject of numerous studies for over twenty-five years. Various applications have been proposed, but no real breakthrough has been achieved yet, at least on an industrial scale. One of the reasons for this, is probably the complexity of nanowire growth mechanisms, and the consequent difficulty of precisely controlling their geometrical characteristics, composition or doping and even their crystal structure of the nanowires.

On the other hand, nanowire growth represents a real playground for creating innovative nanostructures. Key benefits are expected in areas such as nanoelectronics, quantum transport, single-photon emission, Qbit generation, gas detection and batteries, for instance. At C2N, we have spent several years studying III-V nanowires on Si substrates for photovoltaics [1]. Unfortunately, we did not achieve sufficient conversion efficiency, probably because of contact issues. I will show that through these studies, we have gained a better understanding of nanowire growth kinetics and have learned how to grow them on patterned substrates.

In another field, one very attractive feature of catalyzed growth of nanowires is the possibility of fabricating and stacking different crystal phases of the same material (Fig. 1). Thus, crystal-phase heterostructures in a chemically homogeneous nanowire can be obtained [2,3]. Such heterostructures have been proposed as physical elements of a quantum information processing platform [4]. A key parameter for controlling the growing crystalline phase is the contact angle of the catalyst particle on the nanowire [5, 6]. Using in situ transmission electron microscopy, I will demonstrate procedures for abruptly switching from one phase to the other.

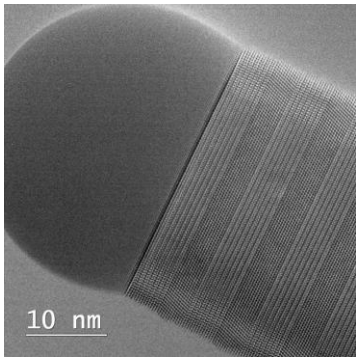

Fig. 1: GaAs crystal-phase superlattice

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Session I

Growth mechanims

Regular contributions

Graphene growth mechanisms during propane/hydrogen CVD on SiC

C. Mastropasqua,[1] A. El Alouani,[1] M. Paillet,[3] M. Portail, [1]
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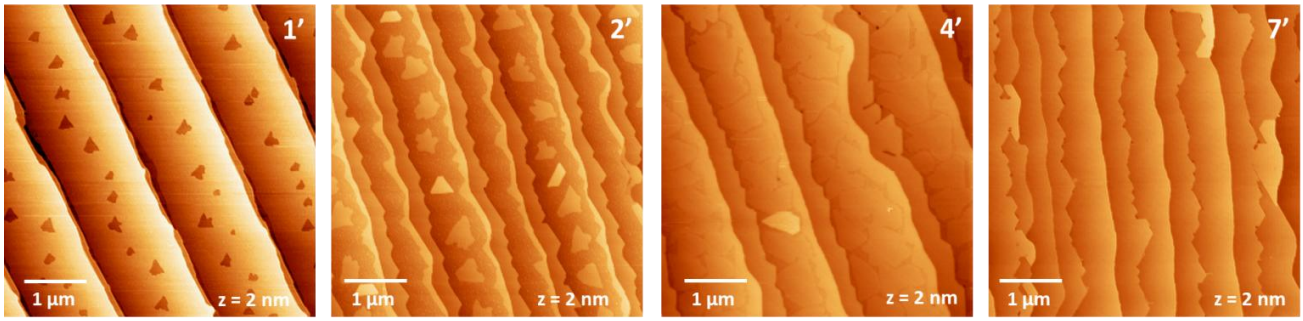
Propane/hydrogen CVD growth of graphene on SiC, studied since 2010 [1], consists simply to grow graphene from propane in a hydrogen/argon atmosphere. The presence of hydrogen in the gas phase promotes Si excess on the surface, hence making impossible graphene growth without propane flow [2]. This makes propane/hydrogen CVD very different from silicon sublimation where graphene grows from a carbon excess on SiC. Graphene films are mainly grown in a propane/hydrogen/argon gas mixture at high temperature (1550°C) near atmospheric pressure, conditions allowing to grow uniform n-doped monolayers on 2" SiC wafers. Graphene films prepared in such conditions have been widely used for applications in electrical metrology [3] or as a substrate for van der Waals epitaxy [4]. Though, a complete growth study for these specific growth conditions was still missing. Our contribution will present first elements of this study and discuss the growth and hydrogenation mechanisms occurring both during growth step and cooling down.
In order to study the different steps of graphene formation, we have grown samples with different growth time in conditions leading to the formation of a buffer layer interface. Surprisingly, incomplete graphene layers presented hydrogenated interfaces, suggesting hydrogenation of the interface during cooling down. This led us to optimize the cooling down to minimize changes in graphene interface during this last step. The new set of graphene samples with different growth time allows to observe the different steps of graphene formation (figure) : first, the rapid (less than 1 minute) formation of a buffer layer fully covering the SiC and the nucleation of graphene ribbons and islands, followed by their lateral growth leading to a coalescence in about 10 minutes. Surprisingly, the growth of the graphene monolayer is self-limited, so that no increase in graphene coverage is observed after 30 minutes of growth. This self-limitation is attributed to a thermodynamical equilibrium [5]. Finally, these self-limited conditions are used to grow graphene films on 2'' wafers. Their uniformity and reproducibility appear to be mainly limited by the local offcut of the SiC substrates.



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Nucléation, taille du noyau critique et distributions des zones de capture dans l'épitaxie des semiconducteurs : un aperçu de l'état de l'art

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Institut Pascal (IP)
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En 2007, l'auteur de cette presentation et Ted Enstein de l'Université du Maryland, ont proposé d'extraire la valeur i de la taille du noyau critique, un ingrédient essentiel pour comprendre et caractériser la croissance épitaxiale de couches et d'agrégats (par exemple quantum dots) sur un substrat, en analysant la distribution des aires des zones de capture autour des îlots qui se forment lors des premiers stades de la croissance[1]. Dans cet article, on avait pu montrer que la forme analytique de la distribution de Wigner,
$P_\beta(s) = a_\beta \cdot s^\beta \cdot \exp(-b_\beta s^2)$ permet d'ajuster les distributions obtenues expérimentalement ou par simulation numérique, ainsi que vérifier la relation existante entre le paramètre β et la valeur de i.
Par ailleurs, il était connu que la densité N d'îlots nucléés sur un substrat varie en loi de puissance, $N \sim F^\alpha$, avec le flux de dépôt F ; l'exposant α étant également fonction de la taille du noyau critique i, d'une manière qui dépend du mécanisme physique qui contrôle l'agrégation.
Par la suite, il a été possible de montrer[2] que les exposants α et β ne sont pas indépendants, mais qui doivent en fait satisfaire la relation $\alpha \cdot \beta = i$, indépendamment du mécanisme physique qui contrôle l'agrégation.
Dans cet exposé je passerai en revue la théorie des distributions des zones de capture, ainsi que ses applications récentes à l'étude de la croissance de matériaux qui vont des films organiques aux semiconducteurs, avec une attention particulière à la croissance épitaxiale par gouttelettes des semiconducteurs III-V.

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Modeling of InAs nanowire growth using a dual-adatom diffusion-limited approach

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To better understand how compound semiconductor nanowires grow, one can rely on the development growth models based on fundamental physical processes occurring during growth. So far, previous studies on the growth of III-V nanowires proposed diffusion-limited models based on a single element, usually the one with the lowest current to the seed: In when the growth of InAs nanowires is assisted by a gold catalyst [1,2], As in the case of self-catalyzed GaAs nanowires [3].

Here, we develop InAs nanowires: In and As adatoms exhibit significant different properties. In adatoms have long surface diffusion, while As adatoms surface diffusion is very short (if any). At our growth temperatures, In doesn't reevaporate, while As is highly volatile. While In forms an eutectic with the Au catalyst, it is As that is affected by the Kelvin effect... The physical parameters of In and As used in the calculation of the nanowire growth rate are very different. We thus introduce a model that allows us to implement the contribution of each species to the elongation of the nanowires [4]. The model calculates each of these currents, and evaluates at each step of the elongation which current limits the growth. We find that under certain condition (radius and V/III flux ratio), the elongation of the nanowire is alternatively limited by each species. Furthermore, we apply our model to analyze the length-radius dependence of our InAs nanowires under various growth conditions (As and In beam equivalent pressure). We find that the experimental data can be fitted with a single set of parameters determined through the extensive calibration of the two-dimensional growth rates of In and As. Finally, our model is relevant for other compound semiconductors, self-assembled and gold-seeded nanowires.

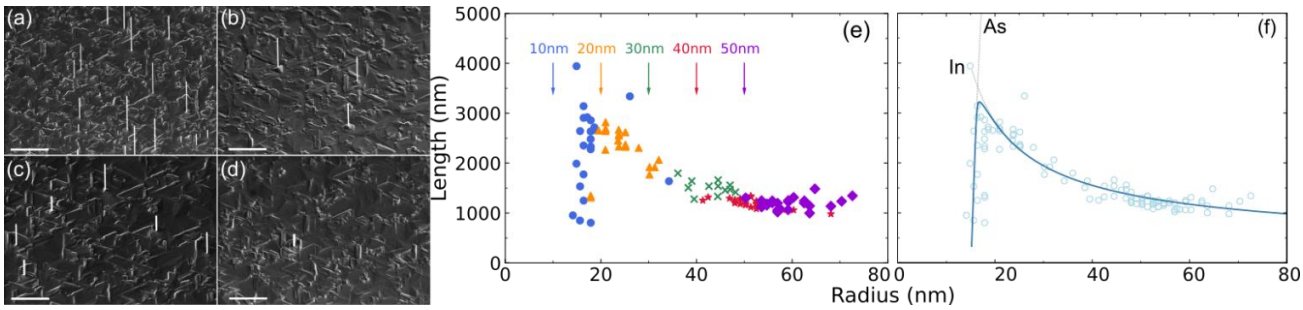

Figure 1 – Au-assisted InAs wires grown on an InAs (111)B substrate at large As flux (As BEP=15×10^{-6} Torr, In BEP=2.5×10^{-7} Torr (a) to (d), SEM images at 45˚ tilt. Scale bars are 2 µm. Radius of colloids: (a) 10 nm, (b) 20 nm, (c) 40 nm, (d) 50 nm. (e) Nanowire length vs. nanowire radius. The initial radius of the colloids is displayed with an arrow, the corresponding nanowires are identified by the color of the symbols. Length-radius dependence of the same sample with fitting using the model developed in this work (blue line) (f).

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In depth study of the growth mechanism of GaN nanowires by Si-assisted MOVPE

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Si-assisted growth of GaN nanowires by Metal Organic Vapor Phase Epitaxy allows the production of nanostructures with a very high aspect ratio (>100) [1]. Furthermore, a strong size homogeneity can be obtained using a selective area growth approach through a dielectric mask [2] which is ideal for the realization of optoelectronic devices such as micro and flexible LEDs [3]. The strong growth rate enhancement thanks to silane introduction has been observed in the past and has been attributed to the formation of a Si-rich antisurfactant layer on the sidewalls of the nanowires [4]. However, the nature and composition of this layer does not meet consensus. Since this layer has a strong impact on the successive shell growth [5], an in-depth study of its nature and of the condition of its formation is required.
In this work we report a fine study of the structural and chemical characteristics of this Si-rich layer thanks to TEM observations and EDX measurements. DFT calculation have been performed to understand and confirm the role of this layer during the growth. Finally, periodic markers along the entire length of the nanowire, allowed us to elaborate a growth mechanism explaining the first stage of the nucleation, the formation of the Si-rich layer, up to the complete growth of the nanowires.

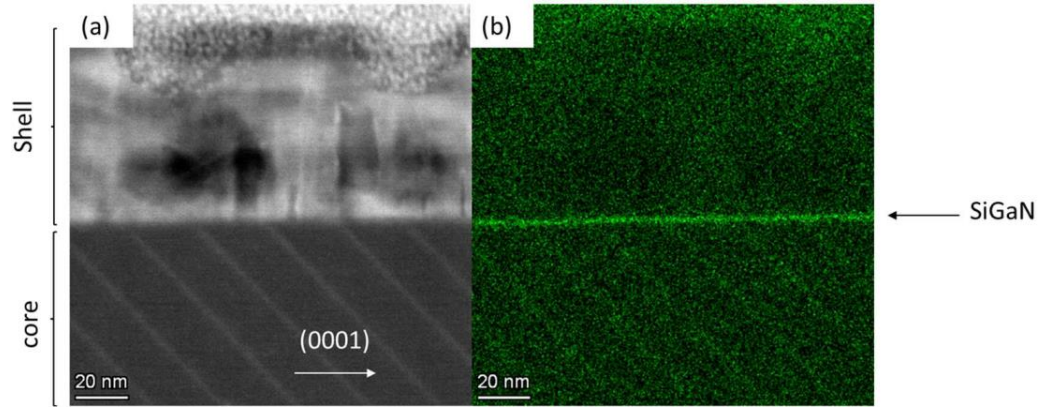

Figure 1 (a) ADF and (b) Si-EDX mapping of a nanowire at the junction between the core and the shell

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Pioneer operando curvature stress measurement during $BaTiO_3$ thin film epitaxy by RF magnetron sputtering

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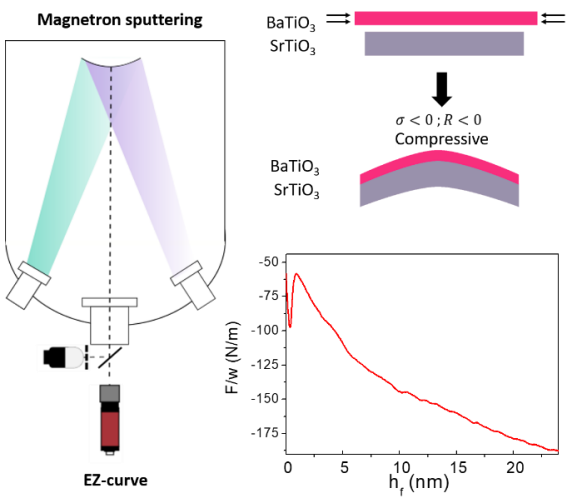
The epitaxial growth of ferroelectric $BaTiO_3$ (BTO) thin films on $SrTiO_3$ (STO) is a subject of considerable attention due to its potential applications for electronic and photonic applications, among others [1-2]. Achieving precise control of the functional properties of BTO is crucial to optimize its performance. These properties are intricately related to the structural properties, which are directly influenced by the parameters of the growth process [3-4]. The latter must therefore be meticulously controlled. In the case of epitaxial growth, the structural and thermal mismatch between the film and the substrate induce a mechanical stress in the layer, which impacts its physical properties.



In this communication, we will report on a pioneer operando measure of the stress developed during the growth of BTO epitaxial thin films on STO(001) substrates carried out using radio-frequency (RF) magnetron sputtering. This stress is monitored in real time using growth using curvature measurements performed with the EZ-curve tool [5] adapted for the following of transparent oxide substrate curvature.

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Epitaxial growth and characterization of Potassium Titanyl Phosphate isomorphous thin films by Pulsed Laser Deposition

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The *mm2* orthorhombic potassium titanyl phosphate crystal, i.e. KTiOPO4 (KTP), is a famous biaxial nonlinear optical crystal widely used commercially for second harmonic generation (SHG) or optical parametric oscillation (OPO) pumped by a 1.064 µm Nd:YAG laser for example. Most of its applications are based on bulk single crystals. However, there is a strong interest to elaborate submicrometric waveguides in the framework of integrated photonic devices. Among several waveguide-fabrication techniques such as proton exchange, ion implantation or dicing [1], a serious alternative is Pulsed Laser Deposition (PLD). Indeed, it was reported that type II SHG and more generally three-wave mixing could be realized in uniform epitaxial $RbTiOPO_4$ (RTP) films over KTP channel waveguides prepared by PLD [2]. Such waveguides could be a serious alternative to efficient low energy nonlinear optical devices in particular for Telecom or spectroscopic applications.
PLD is a technique particularly well suited for growing single oxides films with complex chemical composition.
In this study, we performed epitaxial growth of the RTP phase on KTP single crystals by PLD. The target that has been used was a single RTP bulk crystal. However, by chemical analysis and X-rays diffraction, we demonstrated that due to alkali interdiffusion between film and substrate, it was not possible to achieve a pure epitaxial layer of RTP but most likely a mixed stoichiometry, *i.e.* $K_xRb_{(1-x)}TiOPO_4$ [3].

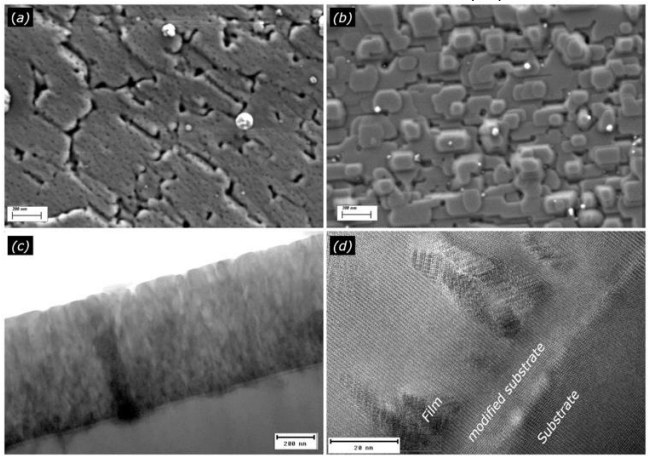

Figure 1 : Film surface morphologies observed by SEM before (a) and after (b) annealing at 650°C. Cross-section TEM (c) and HRTEM (d) images of an annealed sample.

More recently, we proposed to grow another isotype of KTP to avoid any diffusion. The material we chose is KTiOAsO4 since the ion As^{5+} is not labile in the crystallographic structure. This may avoid any inter-diffusion. Moreover, the refractive index difference is more favorable for waveguiding by keeping interesting phase-matching properties.

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Exploring the Impact of Thickness on Epitaxial Growth: A Comparative Study of (001) Oriented CeO_2 Thin Films on R-plane sapphire

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The hetero-epitaxial growth of complex oxides on specific substrates may require suitable interlayers acting a dual role between film and substrate: *i*) buffer layer to reduce interdiffusion and *ii*) seed layer to reduce lattice mismatch. With this purpose, (001) oriented growth of cubic CeO_2 on the "pseudo-cubic" (102) plane of rhombohedral Al_2O_3 substrate (R-plane sapphire) attracted a particular interest [1-2]. Nevertheless, CeO_2 thickness remains a less-discussed parameter in the literature. In the present study, CeO_2 thin films with various thicknesses (10, 20, and 40 nm) were deposited by radio-frequency magnetron sputtering on R-plane sapphire substrates. The influence of thickness and post-annealing on their structural properties were discussed based on X-ray diffraction (XRD), X-ray reflection (XRR) and atomic force microscopy (AFM) results.

As-deposited thin films were composed of two main orientations, namely (001) and (111). Post-annealing (1000°C, 1h in air) led to an overall improvement of the CeO_2 crystallographic quality, resulting in fully (001) oriented thin films with smooth surface roughness, as evidenced by Laue oscillations around the 002 peaks in XRD θ-2θ-scans (Fig 1a). Symmetric reciprocal space mapping (RSM) highlighted differences in the out-of-plane orientation according to film thicknesses (Fig. 1c). Various (001) growth combinations were observed: highly orientated initial growth at the substrate surface and slightly disorientated (001) growth attributed to the initial presence of (111) orientation grains on as-deposited samples. Regardless of thickness, ϕ-scans revealed the epitaxial growth of CeO_2 with the following relations: $(002)_{film}$ // $(012)_{sub}$; $[100]_{film}$ // $[100]_{sub}$ and $[010]_{film}$ // $[12\text{-}1]_{sub}$ (Fig. 1b). Finally, AFM showed that the 20 nm-thick CeO_2 film presented the lowest surface roughness (R_{RMS} = 0.26 nm), thus providing a valuable seed layer for the subsequent growth of thin films with perovskite-related structure (Fig. 1d).

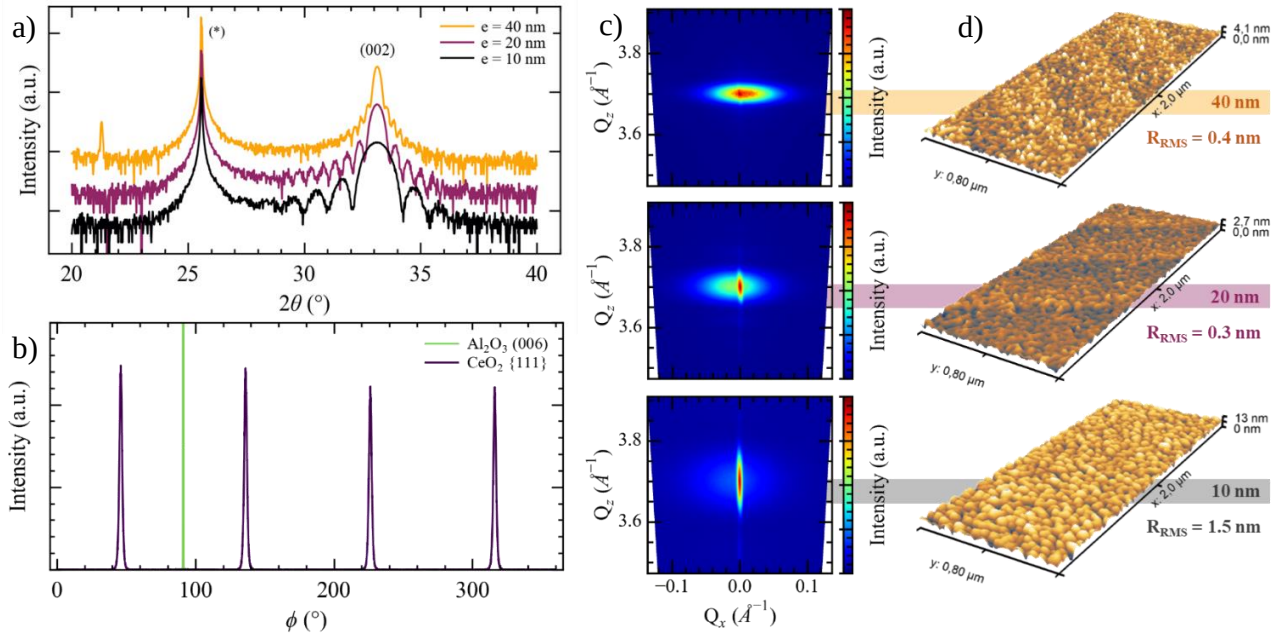

Fig. 1 : a) θ-2θ-scans of CeO_2 thin films showing (002) orientation peak with corresponding Laue oscillations. b) Representative ϕ-scans of R-plane sapphire and CeO_2 demonstrating the epitaxial relationship between film and substrate. c) Symmetric RSM along the [001] direction of CeO_2 layers. d) 3-dimensions pictures of CeO_2 thin film surfaces achieved by atomic force microscopy.

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Session II

Structural and functional characterizations

Invited contributions

Characterisation of defects in wide bandgap semiconductors

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The characterisation of defects is a prerequisite to tailor the electrical, optical and magnetic functionalities of semiconductor devices. In this presentation, cathodoluminescence and complementary optical spectroscopy techniques will be introduced for the characterization of point defects in wide band gap semiconductors, such as diamond and hexagonal boron nitride (hBN).

In diamond, free excitons bind to shallow dopants, which is the basis of impurity concentration measurements with part-per-billiard (ppb) sensitivity. Characterisations of phosphorus-doped diamond fabricated by plasma-assisted vapour phase epitaxy will be analysed with a view to achieving the n-type electrical conductivity desired in diamond electronics. We will also discuss the possible implications for quantum technologies, knowing that the charge state and spin coherence of NV color centers in diamond are improved with phosphorus co-doping.

Electron beams focused at the nanometer scale in cathodoluminescence experiments are also interesting to locally fabricate color centers and to characterise their properties with a high spatial resolution. Activation of the B-center in hBN will be presented. Further insights on this 2D material quality is gained in analysing the recombination dynamics of free excitons by time-resolved cathodoluminescence. Exemples will be given including the hBN single crystals grown in Versailles.

Session II

Structural and functional characterizations

Regular contributions

Advanced optical flux monitoring to control thin layer deposition processes

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Thin film deposition processes are used for a variety of industrial applications as well as in the academic field.[1,2] Their reliability directly impacts the performance and cost of the devices for the fabrication of which they are used. In most of current deposition systems, process reproducibility essentially relies on time consuming and expensive calibration procedures, involving dedicated batches and ex situ calibrations. Indeed, real-time in-situ sensors with the required sensitivity and reliability are not available.

In this contribution, we will present a new concept for such a sensor which may constitute a decisive step to solve this issue. Like other growth monitoring systems designated as optical flux monitoring (OFM) sensors, [3,4,5,6,7,8] our solution is based on the principle of atomic absorption, but it embeds two patented applications boosting its performance : (i) an optical cavity allows to achieve very high sensitivities thus enabling unequalled precision for the control of the growth, and (ii) an original spectral analysis system consisting of an echelle spectrometer without secondary diffraction stage which nearly resolves the very narrow Doppler-broadened absorption lines while enabling a large single shot spectral inspection range, required for multielement monitoring. This system allows replacing unstable HCLs by LEDs, which considerably reduces drifts and strongly simplifies the sensor architecture.

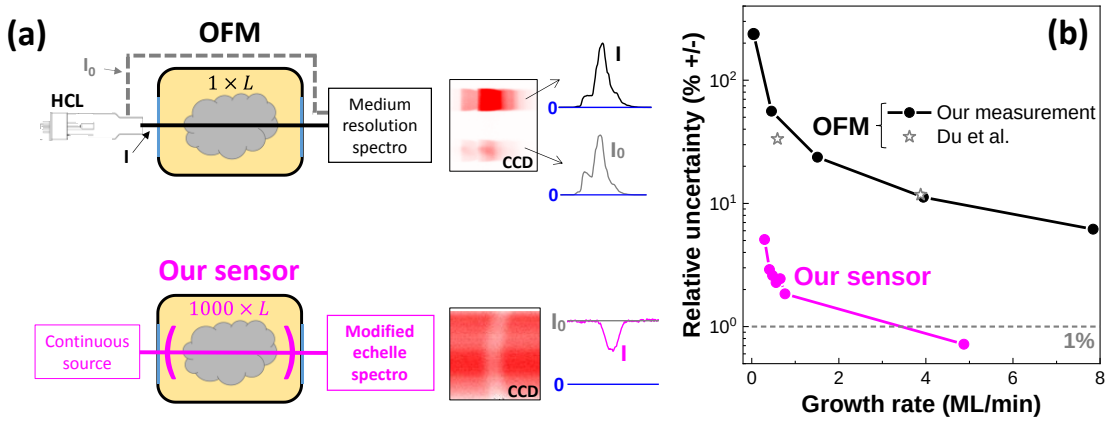

Fig.1 *: (a) Our sensor compared to a standard OFM sensor. (b) Uncertainty vs. growth rate compared to that of a standard OFM sensor (—●— set-up and measurement performed on our reactor, ☆ : values extracted from ref. [8]).*

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Electrically-driven antiferroelectric-ferroelectric phase transition in epitaxial $PbZrO_3$ thin films studied by *in situ* X-ray diffraction

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Antiferroelectric (AFE) materials are electronic materials actively studied for their potential applications such as in high energy storage capacitors and power generators, high-strain transducers and actuators, pyroelectric and electrocaloric devices [1]. A microscopic picture for the AFE behavior proposed by Kittel [2] involves an antiparallel dipole alignment in adjacent subcells, which yields zero net polarization in the absence of an applied electric field E and no piezoelectric activity. Transition to the ferroelectric (FE) phase under E field application is a result of dipoles aligning in one direction. The AFE/FE phase transition, when E exceeds a critical magnitude E_C, is accompanied by a sharp change in polarization, volume, electro-optic coefficients, dielectric constant, and strain [3], providing these materials with rich functional properties. Moreover, the FE phase can turn back to AFE phase when E drops below a critical point E_A, with $E_A < E_C$ due to the hysteresis of the phase transition.

The properties of thin films can be distinctly different from their bulk counterparts because of the enormous strains generated by a lattice misfit to the substrate, thus affecting the crystalline structure and polarization ordering. Functional characterization of AFE materials typically involves macroscopic testing of their electric properties like polarization hysteresis loops or capacitance without having access to the structural information.

Here, we present *in situ* synchrotron X-ray diffraction of the structural evolution and induced strain of the electric-field-driven AFE/FE phase transition in $PbZrO_3$ (PZO) thin films with a thickness of 100 nm. They were epitaxially grown on $SrTiO_3$ substrates with $SrRuO_3$ bottom electrode and Pt top electrode. Three-dimensional reciprocal space maps (RSMs) were recorded in the vicinity of the PZO **480** and **008** Bragg reflections during the application of *E* to up to 700 kV/cm in steps of 20 kV/cm. Elastic strain values of up to 0.3% were determined at highest *E*. A hysteretic behaviour of the transformation process was evidenced with the onset of the AFE/FE phase transformation at 200 kV/cm while the back transformation was completed only at 160 kV/cm. While the antiferroelectric phase is not supposed to be actuated by an applied electric field, the corresponding Bragg reflections also showed a hysteretic behaviour.

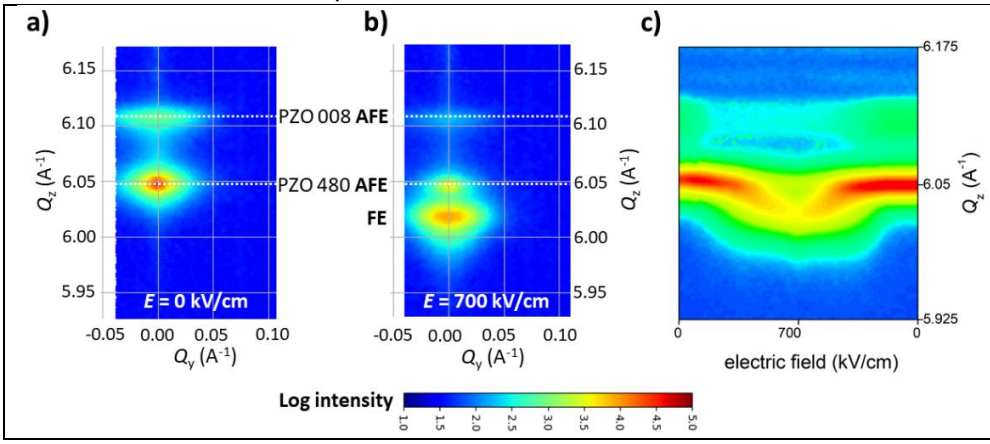

Fig. 1: Q_y-Q_z cuts through the 3D intensity distribution in the vicinity of the PZO **480** Bragg peak measured (a) at 0 kV/cm and (b) at 700 kV/cm. (c) Color map showing the scattered signal along the 00L (Q_z) direction, extracted from the 3D-RSMs for each applied electric field step.

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Electron Channeling Contrast Imaging for epi-layer structural defect characterization

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Electron Channeling Contrast Imaging (ECCI) is a non-destructive technique that allows the characterization of dislocations and other microstructural defects using a scanning electron microscope (SEM) [1]. In particular, it is becoming increasingly popular for accurately determining the threading dislocation density created during the growth of highly lattice-mismatched semiconductors.

For example, in the case of the growth of III-Vs on Silicon substrates, dislocation densities in the $5x10^6$-10^9 / cm^2 range are often found in the various epilayers. Etch-pit revealing techniques is not efficient for such densities, and the use of transmission electron microscopy (TEM) techniques, although very powerful, remains cumbersome and is still a destructive process. Using a simple SEM equipped with a backscattered electron detector, it is possible to align the sample so that the electron beam is massively channeled through the crystal. In such a configuration, any deviation from a perfect crystal structure, such as the presence of a dislocation, results in a significant increase in the backscattered signal, allowing large scale imaging of individual defects that appear on the surface of the epilayer.

In this presentation, we will present a historical and technical overview of this technique, as well as some detailed examples of ECCI measurements.

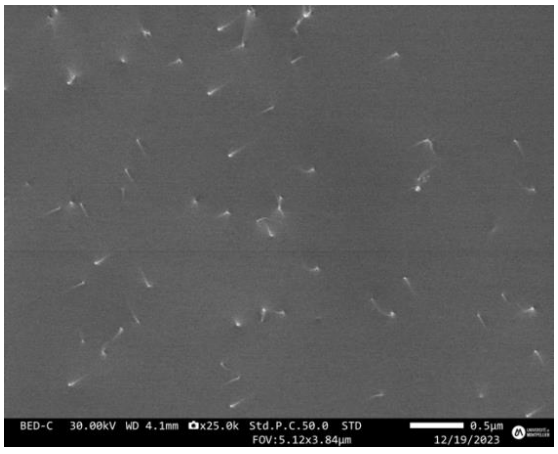

Fig. 1 : ECCI image of the surface of a GaSb layer grown on a silicon (001) substrate. Threading dislocations appear as bright lines and form a spot where they emerge. The Image size is 5.12 x 3.84 μm^2.

We gratefully acknowledge support from the DFG / ANR (FILTER, ANR-20-CE92-0045), and from the French Program Equipex+ HYBAT, ANR-21-ESRE-0026.

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Session III

Properties engineering using epitaxy

Invited contributions

Stabilization of nickelate infinite-layer phase: from 'soft-chemistry to 'soft-physics'

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The recent discovery of superconductivity in compounds with NiO_2 square-planar units [1] has revitalized the research in condensed matter and in material science bringing to a new level questions about the understanding of the underlying mechanisms. Experimentally it has been soon understood that the delicate control of the topotactic process and the prior stabilization of the $Ni^{(3+x)+}$ oxidation state for the strained perovskite phase, are crucial in limiting material imperfections, which, when present above a certain threshold, undermine the reproducibility of the superconducting ground state [2,3]. The study of different approaches is, therefore, necessary to eventually provide better quality samples with a higher level of reproducibility.

Here, I will give an overview about the current advancement in the field by reporting results obtained with the use of an H_2 cracker gun [4] and/or the engineering of a 'simpler' redox interface [5]. I will conclude by presenting some of the results obtained at IPCMS were we recently started to use an electric field to stabilize the infinite-layer phase.

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Niobium Nitride, a newcomer to the III-nitride semiconductor family: Metal/Semiconductor, Semiconductor/Superconductor Hybrid Heterostructures

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After more than 30 years of research and development, III-Nitrides (III-N) based on GaN and its alloys with indium and aluminum, today occupy an important place in the semiconductor industry [1]. The epitaxy of these III-N makes it possible to fabricate high-performance optoelectronic and electronic components, such as blue light-emitting diodes (LEDs) used in the lighting industry, UV LEDs used for sterilization and purification, transistors for an efficient conversion electrical energy and also transistors to deliver microwave signals for radar and very high-speed communications applications.

In recent years, growers have become interested in the integration by epitaxy of other nitride materials, such as transition metal nitrides [2]. Among these "new nitrides", niobium nitride (NbN) is particularly interesting because it is metallic at room temperature and can become superconductive below 17 K. NbN is not really a new nitride material because thin films superconducting NbN, mainly deposited by sputtering, are already exploited in the field of quantum technologies to fabricate efficient Superconducting Nanowires Single Photon Detectors SNSPDs [3]. But with the success of epitaxial growth processes for III-N semiconductor materials, it is very interesting to revisit this quite complex material, in particular to evaluate what epitaxy can bring to the development and properties of such thin NbN layers [4].

In this presentation, molecular beam epitaxy of NbN thin films is discussed with a specific focus on the integration of NbN layers into III-N semiconductor heterostructures. The objective is also to evaluate the potential of fully epitaxial hybrid heterostructures.

This work is supported by the French National Research Agency (ANR) under NIOBIUM convention (No. ANR-21-CE08-0037-02). We also acknowledge the support by the ANR as a part of the "Investments for the Future" program: Labex GANEXT (Grant No. ANR-11-LABX-0014). This work was also partly supported by the Institut de Physique du CNRS (call for projects 2019).

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Session III

Properties engineering using epitaxy

Regular contributions

Crafting the magnetic anisotropy in highly epitaxial CoV_2O_4 thin films

Lamiae EL KHABCHI, Antonio PEÑA CORREDOR, Laurent SCHLUR, Marc LENERTZ, Jérôme ROBERT, Cédric LEUVREY, Gilles VERSINI, François ROULLAND, Daniele PREZIOSI, Christophe LEFEVRE, Nathalie VIART

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Transition metal oxides have been considered an intriguing hot topic within the condensed matter community for decades. These strongly correlated materials showcase a wide range of peculiar properties thanks to their charge, spin, lattice and orbital degrees of freedom.
Spinel vanadium oxides of general formula AV_2O_4 (A being a transition metal), are a compelling class of oxides in which itinerancy and magnetic frustration can be tailored by the V-V distance.

Among these vanadates, CoV_2O_4 (CVO) has captured extra attention because it lies at the crossover from insulating to metallic behavior and has the smallest V-V distance among all other spinel vanadium oxides.
CVO has a normal cubic spinel structure at room temperature with a $Fd\bar{3}m$ symmetry, where Co^{2+} ions ($3d^7$, $(e)^4(t_2)^3$, S = 3/2) occupy the tetrahedral sites which form a diamond sublattice, and the V^{3+} ions ($3d^2$, $(t_{2g})^2(e_g)^0$, S=1), both orbitally and magnetically active, occupy the octahedral sites which form a geometrically frustrated pyrochlore sublattice. Bulk CVO undergoes two magnetic transitions: from paramagnetic to collinear ferrimagnetic (CL FIM) at T_1=142 K and from CL FIM to non-collinear ferrimagnetic (NC FIM) at T_2=95 K [1].

Though CVO has been intensively studied since the 1960s in its bulk form, studies in the form of thin films are very scarce with only 5 papers and non-converging results. For instance, epitaxial CVO films grown on $SrTiO_3$ (STO) (001) were reported to adopt an orthorhombic structure by Thompson *et al.*[2], while Behera *et al.*[3] concluded that the films are tetragonal. These divergent observations motivated us to further investigate the material in its thin film form, adding to this the fact that vanadates are considered as promising candidates to show a potential Spin Hall Magnetoresistance (SMR) as reported by Peña Corredor *et al.*[4] for epitaxial Pt/FeV_2O_4 heterostructures.

Using the Pulsed Laser Deposition (PLD) technique, we successfully grew CVO thin films from a single-phased spinel CoV_2O_4 target, of which we had first optimized the solid-state ceramic synthesis. The films were grown on two different substrates, (001) (STO) and (001) MgO, yielding opposite strains, compressive and tensile, respectively. Our STO//CVO and MgO//CVO thin films both show high crystalline quality and a tetragonal structure. They demonstrate two sharp magnetic transitions: the onset of a magnetic order at 150 K (127 K) with an out-of-plane (in-plane) easy magnetization direction, and an impressive spin re-orientation at 90 K (45 K) towards an in-plane (out-of-plane) easy magnetization direction for a growth on STO (MgO) as shown in **Fig. 1**. Those completely opposite magnetic behaviors dictated by the opposite substrate-related strains are not only striking, but also herald new possibilities of tunable applications with STO|MgO//CVO/Pt heterostructures as SMR systems for low power spintronics.

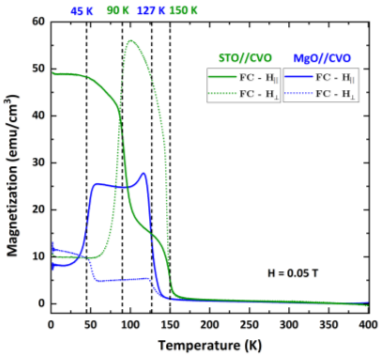

Figure 1: *M vs. T for 45 nm thick CVO films deposited on STO (in green) and on MgO (in blue).*

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Anisotropic strain-induced single multiferroicity in $BiFeO_3$ thin films

Amr Abdelsamie[1,2], P. Dufour[1], A. Finco[2], A. Chaudron[1], J. Fischer[1], N. Jaouen[3], M. Viret[4], K. Bouzehouane[1], V. Jacques[2], J.-Y. Chauleau[4], S. Fusil[1], V. Garcia[1]

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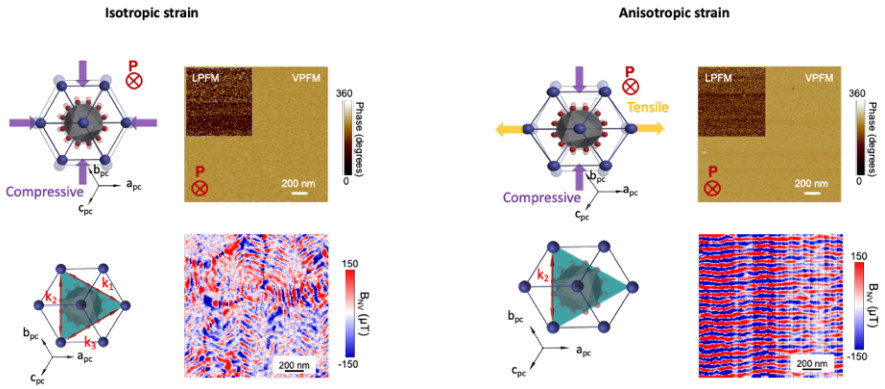
In recent years, approaching the limit of Moore's law has raised the need for alternative path from the current electronics such as magnetoelectric materials which recently received much attention.[1] $BiFeO_3$ is one of the very few room-temperature magnetoelectric multiferroics, with its long-range antiferromagnetic spin cycloid coupled to its ferroelectric polarization. However, since three different propagation directions (k_i) are associated with each ferroelectric polarization direction, the resulting antiferromagnetic landscape may appear as complex in bulk single crystals[2] or in thin films due to their multiple ferroelectric variants.[3]

In this work, we simplified the multiferroic landscape in $BiFeO_3$ thin films in (111) and (001) pseudo-cubic orientations. In both orientations, while films grown under isotropic strain show multiple antiferromagnetic spin cycloids, we demonstrate that anisotropic epitaxial strain results in a single spin cycloid propagation direction. In the (111) $BiFeO_3$ films grown under anisotropic strain, we are able to stabilize a single domain ferroelectric and antiferromagnetic structure.[4] On the other hand, we employed substrate vicinality to induce monodomain multiferroicity in (001) $BiFeO_3$. These two heterostructures introduce convenient platforms for magnetoelectric-based devices.



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Phase controlled epitaxy of wurtzite ZnS thin layers by MOCVD

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Zinc sulfide (ZnS), a versatile compound, finds applications in various fields of optics and optoelectronics. Sintered ceramics of ZnS are largely used as transmitting optical components in thermal imaging, owing to the high transmission in the visible and mid-infrared range from 0.4 to 14 µm. Despite its significant popularity in the industrial world, the synthesis of a ZnS single crystal remains a significant challenge until today.

This material possesses over 194 polytypes. Zinc blende (ZB) and wurtzite (WZ) represent two thermodynamically metastable phases among the various polytypes. Their stability is primarily influenced by temperature, with the transition temperature observed to be above 1020°C. The wurtzite structure of ZnS is more suitable than the ZB structure for optical applications. However, achieving the synthesis of ZnS thin films with the desired WZ phase in a controlled manner has been challenging and requires contaminant such as Mn or Fe for stabilization among which hexagonal 2H and 4H are stabilized by contaminant such as ZnS 4H.[1,2]

Our strategy involves using CdS substrates as hexagonal templates with non-polar surface orientations to induce atom arrangement on the surface through epitaxial techniques. Commercially available Cadmium sulfide substrates exist as single crystals with m-plane surfaces. ZnS is expected to exhibit about 7% and 6% tension along the a and c axes, respectively.
In this study, we employ the MOCVD process to deposit ZnS on a m-plane CdS substrate. This low-temperature process enables epitaxy over large areas and offers advantages such as high chemical purity and control over intentional doping. We present XPS study measurements of the desoxidation of the CdS surface. We study the influence of thermal budget during growth of the interface quality and on the diffusion of Zn in CdS. TEM observations demonstrate perfect orientation of ZnS-w layer on CdS-w m-plane and show the formation of misfit dislocations at the interface leading to staking faults.

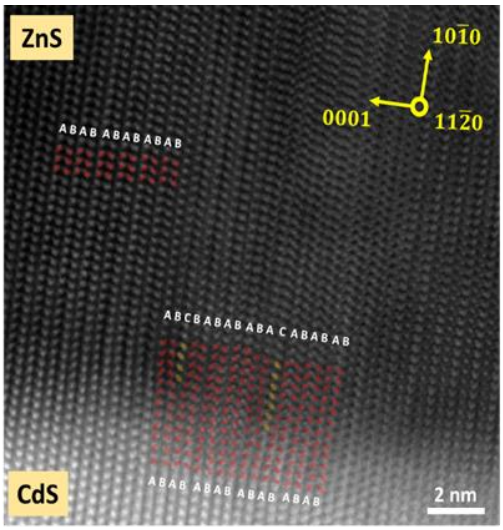

Figure 1: TEM image illustrating the ZnS template layer grown on a CdS-2H substrate by MOCVD, exhibiting a high-quality hexagonal layer with misfit dislocations.

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GaN/AlGaN quantum wells grown on bulk GaN substrate in the step-flow or step meandering regime, impact on indirect exciton diffusion

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GaN/AlGaN quantum wells grown along the (0001) plane are submitted to a strong internal electric field due to the difference of spontaneous and piezoelectric polarization between GaN and AlGaN. The presence of this internal electric field induces the spatial separation of the electron and hole wavefunctions. The excitons formed in such wide quantum wells are named indirect excitons due to the limited spatial overlap between the electron and hole wavefunctions. Due to the strong dipolar interactions between indirect excitons, strong correlations, collective phenomena and even the transition to new emergent many-body quantum phases are predicted.[1,2] One important property of these indirect excitons is their radiative lifetime which can easily exceed 1 µs (while it is typically 1 ns for narrow quantum wells). This long radiative lifetime can impact the internal quantum efficiency since the excitons have time to diffuse and to reach non-radiative recombination centers such as threading dislocations. It is therefore crucial to limit as much as possible the density of these defects in order to keep a good internal quantum efficiency. In this work we exclusively used high quality GaN bulk substrates with a dislocation density ~10^4 cm^{-2} which is orders of magnitude better than the quality requested for devices such as light emitting diodes (~10^8 cm^{-2}) or laser diodes (~10^6 cm^{-2}). The heterostructures were grown by molecular beam epitaxy using different substrate preparations. Also, different conditions for the growth of the GaN/AlGaN were studied, including the V/III ratio and the temperature. One specificity of this work is that we were able to reach a step flow growth mode (Fig. 1a,b) while most literature data focused on the growth of GaN/AlGaN by molecular beam epitaxy in a hillock or step meandering growth regime. We will discuss the conditions requested to select these different growth modes, their influence on the surface morphologies, and their impact on the photoluminescence properties (Fig. 1c). In particular, the indirect exciton diffusion was studied on a micro-photoluminescence setup enabling direct imaging of the spatial diffusion of the excitons.

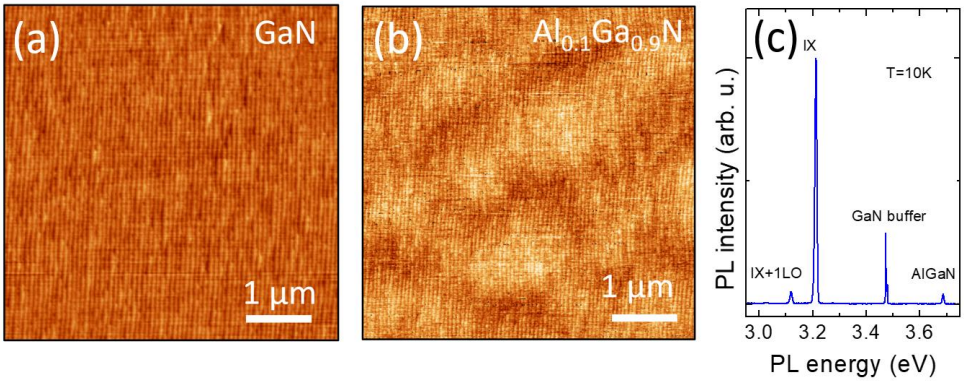

Figure 1. 5x5 µm² atomic force microscopy images of the surface of GaN (a) and GaN/$Al_{0.1}Ga_{0.9}N$ quantum well (b) grown in the step flow regime, and low temperature photoluminescence spectrum showing narrow indirect excitons (IX) peaks.

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Session IV

Hybridation

Invited contributions

Oxide nanosheets as seed layers for growth of complex oxides

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Functional properties such as ferroelectric, multiferroic or transparent conducting oxide in complex oxide thin films are key components in modern devices. Their properties are related to their orientation and to their structural and microstructural qualities in relation with the crystal growth. Epitaxial films are obtained on single-crystalline oxide substrates (such as $SrTiO_3$) that present chemical compatibility and small in-plane lattice parameters mismatch with the film. However, these substrates are expensive and size-limited. On the other hand, direct growth of functional oxides on low-cost substrates with large area as silicon or glass leads to amorphous or polycrystalline films with poor properties. Therefore, introduction of a buffer layer is necessary on such substrates in order to achieve the epitaxial growth of complex oxides. Among other candidates, oxide nanosheets have been identified for several years as seed layers to induce the preferential growth of complex oxides with a high crystalline quality, on several low-cost substrates as silicon, glass, mica, polymers and metallic foils [1,2]. These nanosheets are obtained by exfoliation of layered oxides, as $KCa_2Nb_3O_{10}$, $K_{0.8}Ti_2O_4$, Na_xMoO_2 [2]. They possess either 2D square, rectangular or hexagonal lattices, allowing regrowth of [001], [011] and [111] preferentially oriented perovskite oxides. The nanosheets are transferred on low-cost substrates by drop casting methods [3], which allow a high surface coverage of the substrate. As example of epitaxial growth, we will show the possibility to integrate complex oxide perovskites thin films grown by pulsed laser deposition, such as $La_{0.67}Sr_{0.33}MnO_3$ [4], $KNbO_3$ [5] and $SrVO_3$ [6] on glass, silicon and mica.

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III-V/Si epitaxial growth and antiphase domains: a matter of symmetry

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Group III-V/group IV epitaxy has recently attracted much interest for applications especially in integrated photonics, or solar energy harvesting devices. For years, the pioneering works of H. Kroemer [1] that successfully identified the key issues, were taken as a reference for the understanding of III-V/Si heteroepitaxy, but recent experimental observations evidenced some inconsistencies with the previous description [2]. In this contribution, we clarify and discuss the driving forces for 3D nucleation during III-V/Si heteroepitaxy and highlight the specific contributions of surfaces and chemically-heterogeneous interfaces in the system [2-7]. On the basis of antiphase boundaries stability calculations, we then demonstrate that monoatomic steps at the Si surface cannot be at the origin of the formation of the antiphase boundaries [8,9]. We thus show experimentally that antiphase boundaries result from the coalescence of monodomain islands, and point out the central importance of the miscut for breaking the symmetry of the system and have an influence on their propagation [9-11]. Finally, we demonstrate how this in-depth understanding can be used to control antiphase domains distributions, and give an experimental demonstration of a quasi-periodic 1D pattern of antiphase domains in a GaAs layer grown on Si substrate [11].

A part of this work was supported by the French program on "Investments for the future" (Equipex EXTRA, ANR11-EQPX-0016), the ANR-DFG FILTER project (ANR-20-CE92-0045), the ANR PIANIST (ANR-21-CE09-0020), and NUAGES (ANR-21-CE24-0006) projects. The authors acknowledge RENATECH (French Network of Major Technology Centers) and Nanorennes for technological support.

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Session IV

Hybridation

Regular contributions

Strain-relieving mechanism in III-V semiconductors epitaxially grown on Silicon: misfit dislocation networks

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Silicon photonic integrated circuits (PICs) have become indispensable in modern technology, and are particularly valuable in applications such as high-speed telecommunications, data centers, artificial intelligence or sensing[1]. The monolithic integration of III-V lasers on Silicon (Si) substrates has attracted considerable attention to combine the optoelectronic properties of light sources with the well-established Si industry technology. However, epitaxially integrated III-V devices on Si suffer from a severe lack of reliability because of the large crystal defect density[2]. For instance, polar on non-polar heteroepitaxy, or lattice mismatch are responsible for forming antiphase boundaries (APBs) and dislocations.

For a long time, APBs constituted the most critical issue since they introduced device-killing shortcuts[3]. Our previous work has established growth methods to avoid the presence of emerging APBs in GaSb and GaAs layers as thin as 500 nm on "on-axis" Si, and we have proposed a detailed mechanism of APBs generation and annihilation in these layers[4][5].

Still, the high density of threading dislocations (TDs) $\sim 7 \times 10^8$ cm^{-2} in our layers degrades the laser's performances and reduces their lifetime[6]. Therefore, a reduction of the threading dislocations density (TDD) is a prerequisite for the reliability of integrated devices. Many techniques for TDD reduction have been reported in the literature such as thermal cycling annealing (TCAs)[7][8], or dislocation filtering layers (DFLs)[9][10]. Using Electron Channeling Contrast Imaging (ECCI) and Transmission Electron Microscopy (TEM), we conducted an extensive study of the dislocation networks at the interfaces of an AlSb DFL inserted in a GaSb buffer layer. Our presentation will address the effect of TCAs, DFL thickness and cap thickness on the TDD. It was found that the sole insertion of a 300 nm interfacial AlSb layer helps reduce the TDD by one order of magnitude. While the understanding of interfacial misfit network formation is limited in the literature, we will propose a strain relaxation mechanism for the DFL interfaces. These initial findings are promising, and motivate new exploration paths like coupling several AlSb layers, to further reduce the TDD for optimizing the performance, and reliability of optoelectronic devices.

Part of this work was sponsored by the French program "Investments for the future" (Equipex EXTRA, ANR11-EQPX-0016), the ANR- DFG FILTER project (ANR-20-CE92-0045), and the French program Equipex+ HYBAT, ANR-21-ESRE-0026.

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Vers la localisation bas coût d'hétéroépitaxie de GaAs sur Si

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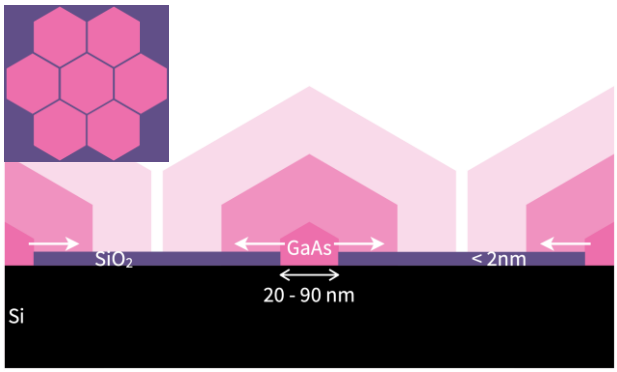

L'intérêt pour l'intégration de GaAs sur Si est un objectif longtemps visé par la communauté scientifique notamment pour des applications optoélectroniques, notamment dans le domaine photovoltaïque ou photonique. Les plus grands obstacles d'une intégration de GaAs sur Si sont liés à leur fort désaccord de maille (4,1%) qui génère de fortes dislocations et domaine d'anti-phases. Pour pallier à cette problématique, nous avons développé la méthode ELTOn: Epitaxial Lateral overgrowth on Tunnel Oxide from nano-seed. Cela consiste à épitaxier des microcristaux de GaAs à partir de nano-ouvertures (< ø 90 nm) formées thermiquement dans la couche ultrafine d'oxyde de silicium (< 2 nm). Il a été démontré par ce procédé des micro-cristaux de GaAs parfaitement épitaxié sur silicium sans défaut structurel avec une bonne intégration opto-electronique sur toute leur surface (empilement GaAs/Si et GaAs/SiO_2/Si par effet tunnel) [1].

Notre objectif aujourd'hui est de recouvrir de GaAs le maximum de surface de Silice afin d'atteindre une quasi-surface. Nous développons une méthode de lithographie rapide, reproductible et économique pour localiser les croissances de µ-cristaux en un réseau hexagonal. La méthode de lithographie doit nécessairement permettre de conserver une silice très fine et de réaliser des nano-ouvertures pour conserver une épitaxie sans défaut.

La méthode de la lithographie par nanosphères est le candidat idéal pour nos applications. En effet, les nanopshères s'auto-organisent en réseau hexagonal. En variant le diamètre des billes et en les gravant, nous pouvons ajuster avec précision, et la distance entre, et la tailles de ces ouvertures. Nous présenterons nos récentes avancées sur l'hétéroépitaxie de µ-cristaux de GaAs/Si avec cette méthode.

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Local epitaxy via CNO nanosheets on glass : effect of thickness on the Vanadate TCO

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$CaVO_3$ and $SrVO_3$, which are oxide perovskites with strong electronic correlations, are promising and novel transparent conductors [1]. Indeed, the electronic correlations induce an increase of the charge carrier effective mass in those materials, shifting the plasma frequency out the visible range, which induce visible transparency. Therefore, the material's structure and crystallinity are key factor in order to tune their electronic and optical properties.

The ability to integrate vanadates on low cost substrates, particularly glass, is mainly responsible for the technological potential of these new transparent conductors. The growth of vanadates directly on glass is a challenge, as it is not conducting in its amorphous form [3]. Thus, it is necessary to find a growth strategy that preserves the crystalline character of the material. Using a seed layer of $[Ca_2Nb_3O_{10}]^-$ nanosheets deposited onto glass substrate, Boileau et al. recently showed that it is possible to integrate crystalline vanadate thin films with competitive properties by pulsed laser deposition [4].

In this work, we study the effect of thickness on the properties of those films. The nanosheets seed layer allow to grow the films at a low thermal budget (500°C) required for the integration on glass. We show the evolution of electrical and optical properties using transport and spectroscopic analyses. Additionally, we probe the local electrical properties of the films by means of scanning spreading resistance microscopy (SSRM).

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Session V

From properties to devices

Invited contributions

Scanning probe microscopy for functional oxide thin films

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After a brief introduction to scanning probe microscopy and atomic force microscopy (AFM), I will show how advanced modes of this technique can be used to investigate the local physical properties of oxide thin films. Three main advanced modes will be discussed:

- conductive atomic force microscopy (C-AFM) to look at local electrical properties
- piezoresponse force microscopy (PFM) to visualize ferroelectric domains and manipulate them
- scanning nitrogen-vacancy (NV) magnetometry to image spin textures in antiferromagnets.

For each mode, I will provide typical examples of physical characterizations of oxide thin films, interfaces, or devices. The combination of these different techniques will be illustrated by the investigations of the interplay between ferroelectricity and tunnel transport across ultrathin ferroelectrics or the magnetoelectric control of spin textures in multiferroic oxide thin films.

Nitride nanowire light emitting diodes: from single wire properties to device applications

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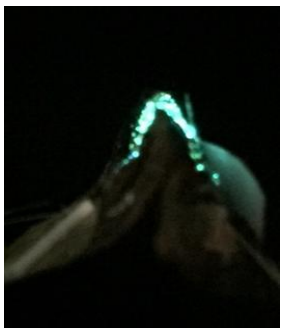
Light emitting diodes (LEDs) are used in many applications including high-efficiency lightning. The existing limitations of thin film LEDs have motivated a strong research effort on nanostructured devices as a way to boost the performance, to reduce the cost or to bring new functionalities.

In this presentation, I will present our work on InGaN/GaN nanowire-based as well as nanoporous light emitting diodes. I will first discuss single nanowire properties and nanowire array LEDs on rigid substrates [1, 2, 3]. We use electron beam induced current microscopy and cathodoluminescence spectroscopy to detect failures and optimize the LED structure. Then I will focus on our recent progress toward flexible nitride nanowire devices. I will describe the approach for nanowire lift-off, transfer into polymer-embedded membranes and flexible contacting, which allows to combine high flexibility of polymer films with high quantum efficiency provided by nitride nanowires. Realization and characterization of blue, green, two-color and white flexible light sources will be presented [4, 5, 6, 7]. I will also address an alternative approach to eliminate threading dislocation by nanoporosification and present nanoporous LEDs [8, 9].



Flexible green InGaN/GaN NW LED

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Oxide thin films processing: some examples on how to take advantage of perovskite properties into devices.

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Functional oxides represent a promising avenue for enhancing the performance of electronic devices, offering a rich spectrum of physical properties within the perovskite structure, depending on its cationic chemical composition. [1] Their integration is increasingly acknowledged as a viable strategy to elevate electronic device capabilities.

Presently, 2 major pathways are being explored to pioneer novel device paradigms that leads to research activities on different sample configurations.
On one hand, complete oxide structures and growth processes on top of oxides substrates capitalize on the minimal lattice mismatch between layers, yielding films of high crystalline quality. However, this route presents its own set of technological challenges, notably the necessity for selective etching to realize freestanding devices. Compatibility with silicon-based electronics seems not compatible at first sight but can however be reached thanks to transfer technologies, like the ones used to combine III-V and Si.
On the other hand, the direct epitaxial integration of oxides onto semiconductor platforms like silicon or gallium arsenide offers a pathway to augment silicon's functionalities for electronic or optical applications. [2-3] In this configuration, the challenges lie in the adaptation layers to reached high crystalline quality films and strain management to maintain the physical properties and devices integrity.

The next step to reach devices consist in processing the films into devices at the micro-nanoscale and remains a challenge, in particular for the etching steps due to the chemical stability of functional oxides. The primary technological hurdles revolve around identifying and implementing compatible technologies capable of designing and fabricating these innovative devices. During this presentation, I will present some examples on how to take advantage of perovskite properties into devices thanks to oxide thin films processing. A focus will be made on MEMS based sensors.

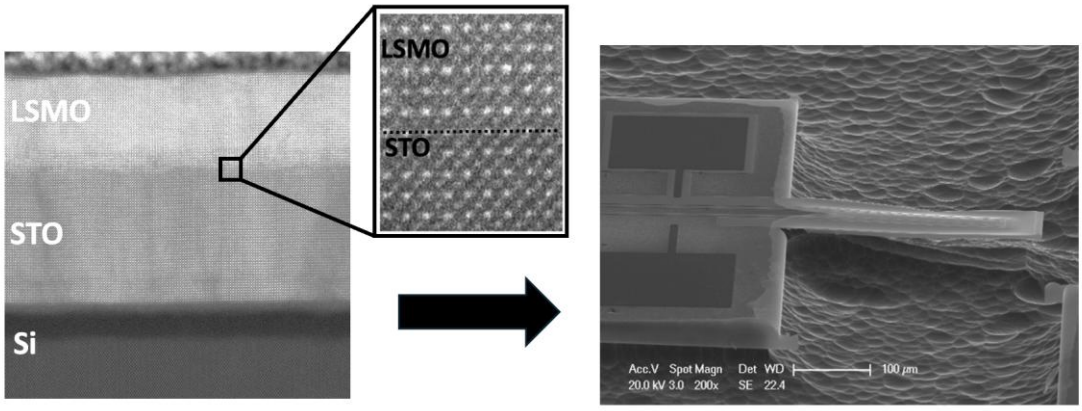

Figure 1: (Left) TEM images of perovskite oxides thin films on Si (Right) SEM image of oxide MEMS device.

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Direct epitaxy of lasers on Si substrates: challenges and solutions

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The monolithic integration of III-V lasers on Si has been explored for the past decades. It would allow the low-cost mass production of devices on large silicon wafers, providing high scalability[1] and reducing III-V material waste. However, several challenges need to be overcome in order to grow high quality III-V layers. The crystallographic polarity difference between the materials leads to the formation of antiphase boundaries[2]. These consist of III-III or V-V bonds that introduce a local charge and thus form efficient vertical conduction paths that prevent devices from operating. However, they can be eliminated either by using large miscut substrates[2] or by careful surface preparation of the Si substrate[3], [4]. In addition, the difference in lattice parameters and thermal expansion coefficients leads to the formation of a high density of dislocations[5], a linear defect created above the critical thickness to relieve the strain in the layers. The dangling bonds at the dislocation core introduce deep levels into the bandgap[6] that form scattering centers and act as Shockley-Read-Hall centers, significantly reducing the electron mobility[7] and the minority carrier lifetime[8]. For example, quantum well laser diodes grown on Si show a significant increase in threshold current, at least three times higher than on the native substrate[9], and the typical laser lifetime is estimated to be less than a week. These results illustrate the direct effect of dislocations on the degradation of the device performance. Several strategies have been developed to overcome this problem, the most common of which is to combine TDD reduction using filter layers and annealing cycles with the use of quantum dots. This allows performance similar to that of lasers grown on their native substrate[10], but this technique requires the growth of thick and complex buffer layers. One way to overcome this limitation is to use active zone designs that are dislocation tolerant, such as interband cascade lasers[11] and quantum cascade lasers[12]. In this talk, I will discuss the effect of dislocations on laser performance, and present some of our work with the new active zone design.

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Session V

From properties to devices

Regular contributions

Ammonia source molecular beam epitaxy of ScAlN/GaN HEMT heterostructures

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ScAlN is a wide bandgap semiconductor with very large piezoelectric and spontaneous polarization coefficients [1-2] which ensures a very high charge density at the interface with GaN [3]. Moreover, $Sc_xAl_{1-x}N$ alloy with a Scandium molar fraction x=0.18 can be grown strain-free (lattice-matched) on GaN, which makes it a promising barrier layer candidate for high electron mobility transistors (HEMTs) in view of power switching and RF/mm-wave power amplifier applications [3-4]. For that purpose, the epitaxial growth of ScAlN was recently developed by few groups using Plasma-Assisted Molecular Beam Epitaxy (PA-MBE) [5-6] and Metal-Organic Chemical Vapor Deposition (MOCVD). However, the latter is challenging due to the crucial choice of the precursors and the need to "rebuild" the reactor to allow Sc incorporation into AlN [7-9]. For these reasons and based on our experience on the growth of high performance AlGaN/GaN RF-HEMTs by ammonia-source MBE (NH_3-MBE) [10-11] we decided to develop this technique for ScAlN. In the present work, the electrical properties of ScAlN/GaN HEMT heterostructures grown under nitrogen-rich conditions are studied. After the identification of an optimum growth temperature around 670°C for 25 nm thick barriers [12], the effect of barrier thickness has been studied. Like for AlGaN/GaN HEMTs, a 1 nm AlN layer was grown at the barrier/channel interface to enhance the 2DEG confinement and a sharp interface is obtained (Fig.1-left). The charge density extracted from mercury-probe capacitance-voltage measurements is in agreement with expected values [3] and reaches a maximum at about $4x10^{13}/cm^2$ but it decreases for thicknesses beyond 8 nm (Fig.1-right), a phenomenon which correlates with the degradation of the ScAlN crystal quality evidenced by transmission electron microscopy, but not explained yet. Hall effect measurements performed on van der Pauw patterns allow to assess the low field transport properties of the 2DEG provided the GaN buffer is sufficiently resistive. The evolution of 2DEG sheet resistance confirms the previous trends. Furthermore, electron mobility around 620 $cm^2/V.s$ has been measured for a 25 nm ScAlN barrier HEMT heterostructure grown on a thin GaN buffer on Silicon substrate while a HEMT heterostructure grown on GaN-on-Sapphire template with a 10 nm ScAlN barrier exhibited an electron mobility superior to 900 $cm^2/V.s$. This result could be explained by the better crystal quality of both the thinner ScAlN barrier and the GaN buffer grown on Sapphire.

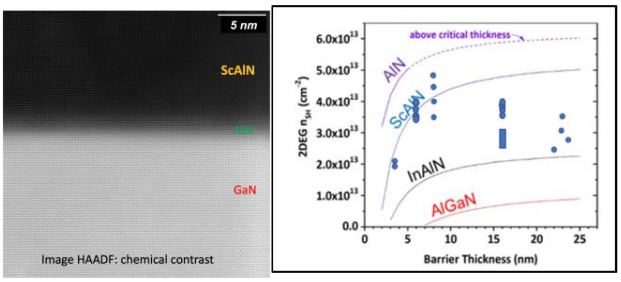

Fig. 1. Left: high resolution cross-section transmission electron microscopy view of the HEMT interface. **Right:** 2DEG density as a function of ScAlN barrier thickness (adapted from [3]).

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Is SCAM a promising oxide material, or a scam?

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Scandium aluminate magnesium oxide ($ScAlMgO_4$, SCAM) is an attractive lattice-matched substrate material for optoelectronic devices based on GaN or ZnO. The lattice mismatch of SCAM to GaN is as small as 1.7%, and only 0.09% to ZnO. Moreover, ScAlMgO4 is a lattice match to InGaN with a 17% indium concentration, which could be crucial for light-emitting devices covering the red spectral region (e.g., InGaN-based RGB displays). SCAM is also expected to be a suitable substrate for two-dimensional materials and van der Waals epitaxy. This is because its cleaved surface is atomically flat, and its lattice constants are much closer to lattice constants of the majority of TMDs. In that view, SCAM might be considered a competitor of hBN. Finally, a large-area single crystal of this material could be grown by the Czochralski method. Despite its clear advantages, several fundamental properties of SCAM remain unsettled.

Here, we provide a comprehensive picture of its optical, electronic, and structural properties. We study $ScAlMgO_4$ single crystals grown by the Czochralski method. Using variable-angle spectroscopic ellipsometry, we establish complex in-plane and out-of-plane refractive indices of SCAM in the range from 193 to 1690 nm. An oscillator-based model provides a phenomenological description of the ellipsometric spectra with excellent agreement over the entire range of wavelengths. Ab initio many-body perturbation theory modeling provides information about the electronic structure of $ScAlMgO_4$ and successfully validates experimentally obtained refractive-index values. X-ray diffraction measurements confirm the lattice constants of ScAlMgO4 previously reported. In view of our work, $ScAlMgO_4$ is a highly transparent, low refractive index, birefringent material similar to sapphire but with much more favorable lattice constants and simpler processing. Based on our results, we could argue that SCAM is a highly promising substrate for nitride-, oxide-, and TMD-based optoelectronic devices, and we anticipate an increase in efforts towards the development of epitaxial techniques related to this material.

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Epitaxial Growth of Fe_3O_4 on ZnO(000±1) Substrates for All-Oxide Spintronic Devices

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Spintronics, the study of electron spin in addition to its charge, has emerged as a promising field for developing more efficient electronic devices. These devices rely on the manipulation of electron spin to achieve functionalities such as magnetic memory and spin-based logic circuits. However, achieving high performance in spintronic devices requires careful control over the growth and properties of the constituent materials. In particular, spintronic devices require very precise film stoichiometry and sharp interfaces between the magnetic film and the semiconducting substrate. Stoichiometric films ensure that the magnetic properties are optimized, while sharp interfaces minimize scattering of the spin-polarized electrons [1], which can lead to losses in signal propagation.

In this study, we investigated the epitaxial growth of the magnetic oxide Fe_3O_4 thin films on ZnO substrates using pulsed laser deposition (PLD) for all-oxide spintronic devices. By optimizing the oxygen partial pressure at a given temperature, we successfully achieved high epitaxial quality Fe_3O_4 films with controlled stoichiometry and magnetic properties. Magnetization measurements revealed that films deposited at 400°C exhibited bulk-like saturation magnetization of Fe_3O_4, and the magnetic properties remained relatively comparable even when the growth temperature was reduced to 260°C. Transmission electron microscopy (TEM) analysis showed flat interfaces between Fe_3O_4 and ZnO at temperatures below 400°C, while the interface became wavy when the growth was performed at 500°C. Secondary ion mass spectrometry (SIMS) confirmed the incorporation of Zn into Fe_3O_4 films deposited at 400°C but not at 260°C.

In addition to growing Fe_3O_4 films, we also demonstrated the successful deposition of pure FeO on ZnO(0001) using PLD. This opens up the possibility for using FeO as an interface/buffer layer to enhance the properties of Fe_3O_4 thin films. Pre-depositing a 1-nanometer FeO layer prior to Fe_3O_4 growth results in pure Fe_3O_4 due to subsequent oxidation of FeO during Fe_3O_4 growth on top [2]. Additionally, we explored the effect of miscut substrates on the magnetic properties of Fe_3O_4 thin films. Interestingly, films grown on 1° miscut substrates exhibited an increase in remanent magnetization for a miscut toward [10-10]. Detailed analysis using different TEM techniques, including DF TEM, HAADF STEM, and ADF STEM, revealed the presence of twin and antiphase boundaries in the Fe_3O_4 thin films. The total defect density was determined to be 0.12 nm^{-1} for samples with an intermediate FeO layer and 0.10 nm^{-1} for samples without it [3]. These findings provide valuable insights into the growth mechanisms and defect properties of Fe_3O_4 thin films on ZnO substrates, paving the way for the development of efficient spintronic devices with practical applications.

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Orientation dependence of functional properties in preferentially oriented $Bi_{0.5}Na_{0.5}TiO_3$-$BaTiO_3$ thin films

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The piezoelectric properties in perovskite thin films have been extensively exploited in microsensors and transducers. Lead-based compounds such as $Pb(Zr,Ti)O_3$ (PZT) constitute the most efficient family of piezoelectric materials for integration in microelectronic devices, due to their excellent electromechanical responses. However, considering the toxicity of lead, lead-free piezoelectric materials have become highly attractive and are seen as a solution for complying the European directives restricting the use of hazardous substances in devices [1]. Among lead-free candidates, the solid solution (1-*x*) $Bi_{0.5}Na_{0.5}TiO_3$ - *x* $BaTiO_3$ (BNT-BT) presents attractive ferroelectric and piezoelectric properties in the morphotropic phase boundary region (MPB, *x* ~ 5 – 7 mol%), where the transition from the space group R3m to the P4mm occurs. In order to improve the performances of BNT-BT based thin films, different solid solutions or metal/metal oxide doping were studied. To achieve enhanced piezoelectric properties, domain engineering can also play an important role and has been so far scarcely investigated in BNT-BT thin films. The crystalline orientation of the film affects the characteristics of the domains and domain walls, which are closely related to the ferroelectric switching behavior and piezoelectric properties. MPB ferroelectrics are characterized with complex domain structures, where the coexistence of two ferroelectric phases leads to a large number of polarization directions related to crystallographic orientations. The investigations on thin films, especially epitaxial ones [2] can contribute, to a fundamental understanding of the BNT-BT system due to a closer structure to a single crystal and help to achieve improved properties for device applications.

In the present work, we have studied the functional properties of BNT – BT thin films grown by pulsed laser deposition on (001) or (111) $LaAlO_3$ (LAO) single crystal substrates. X-ray diffraction results have shown a preferential orientation in the film induced by the substrate. The crystal orientation dependence of the dielectric, ferroelectric and piezoelectric properties of (001) and (111) oriented BNTBT thin films was investigated. The dielectric constant, the remnant polarization and the piezoelectric coefficient d_{33} were found to be larger for the (001) BNT-BT films compared to the (111) BNT-BT samples. Moreover, a double-peak feature in the switching current hysteresis, with an intensity ratio depending on the orientation, was evidenced, that can be attributed to the competition between two types of polarization switching kinematics. In order to understand the orientation dependence of the functional properties, a study using piezoresponse force microscopy (PFM) was carried out in order to correlate the macroscopic and nanoscale properties. The PFM investigations have evidenced a complex domain structure and a decrease in the domain size when changing from a (001) to a (111) orientation. In this talk we will discuss the orientation dependence on dielectric, ferroelectric and piezoelectric properties in relation with the local switching behavior.

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Infrared GeSn photodetectors: new avenues in monolithic Si photonics

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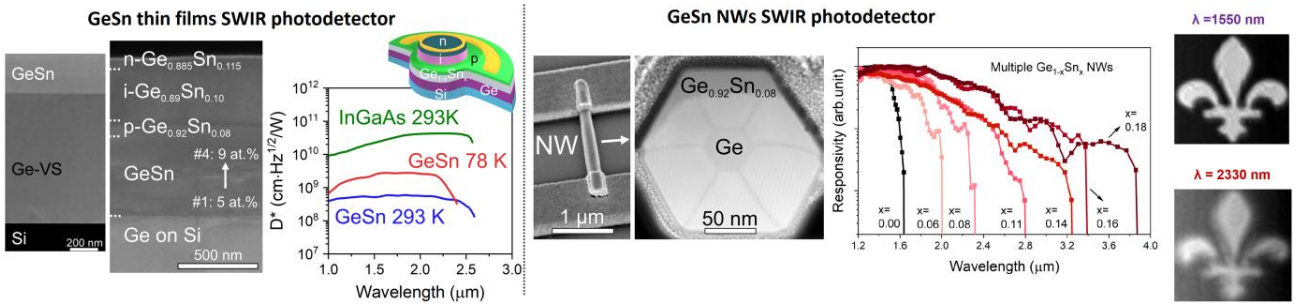
GeSn semiconductors grown on a Si wafer offer a scalable material platform to engineer a variety of photonic devices (photodetectors, lasers, LEDs) operating in the short-wave infrared (SWIR: 1.5-3 µm) and beyond.[1-3] These GeSn devices are the essential building blocks to develop high-performance infrared sensing and imaging technologies using Si-compatible fabrication processes. The ability to incorporate Sn atoms in Ge at concentrations about one order of magnitude higher than the 1 at.% equilibrium solubility is at the core of these emerging technologies.

In this presentation, the epitaxial growth of metastable GeSn alloys with Sn contents up to 20 at.% will be discussed. The temperature- and strain-dependent Sn incorporation and the formation of structural defects will be discussed by comparing GeSn epitaxial layers grown on a Ge on Si substrate[4-5] and Ge/GeSn core/shell NWs.[3,6-9] Moreover, the growth of p-i-n planar heterojunctions will be demonstrated and their properties investigated down to the atomic level.[2]

SWIR photodetectors operating at room-temperature up to 4 µm that are made using GeSn thin films[2,10-12] and NWs[3,9] will be discussed. The capability of these devices to operate at GHz-speed and to acquire high-quality images of centimeter-size objects will be demonstrated at room-temperature.



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Hybrid CVD-MBE Er:Y_2O_3 thin films for on-chip quantum technologies

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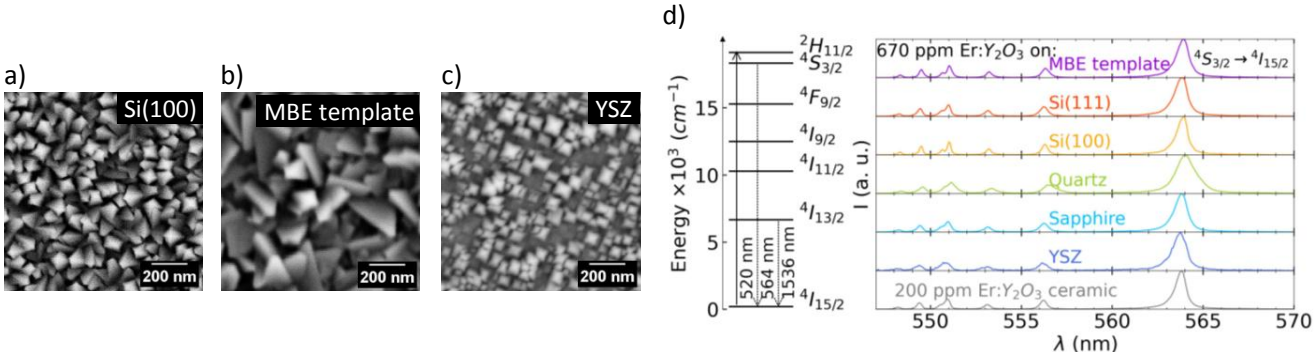
Oxide crystals doped with rare-earth ions (such as Eu:Y_2SiO_5) are promising materials for quantum technologies due to their narrow optical and spin transitions. In a context of device miniaturization and to harness enhanced light-matter interactions, nanomaterials such as thin films and nanoparticles are advantageous alternatives to the use of bulk crystals [1]. However, their optical coherence properties are strongly influenced by defects or impurities. Controlling their crystalline quality is therefore a major challenge.

The objective of this work is to develop defects-free epitaxial thin films. The deposition technique used is direct liquid injection chemical vapor deposition (DLI-CVD) with deposition conditions that had been optimized in a previous work [2, 3]. Two strategies were employed: on the one hand Er:Y_2O_3 (670 ppm Er) thin films were deposited on different single crystalline substrates: silicon, quartz, sapphire and yttria-stabilized zirconia (YSZ). On the other hand, a thin film of the same composition was deposited on a molecular beam epitaxy (MBE) template (100 nm of epitaxially grown Y_2O_3 thin film on a Si(111) substrate). The impact of the substrate type on morphology and optical properties were assessed.

According to SEM images (Fig. 1c) and XRD measurements, the film deposited on YSZ exhibits full texture along the [400] direction and has aligned and square-shaped grains. For the other substrates, the films grow predominantly along the [222] direction and have randomly oriented grains (Fig. 1a and 1b). Regarding optical properties, the emission spectra at 10 K of the ${}^4S_{3/2} \rightarrow {}^4I_{15/2}$ transition (around 560 nm), as shown in Fig. 1 d), and ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition (around 1.5 µm) are similar for all samples, as well as the lifetimes of the excited levels ${}^4S_{3/2}$ (564 nm) and ${}^4I_{13/2}$ (1536 nm). The inhomogeneous linewidths of the ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of the most promising samples are larger than those of bulk crystals [4] but close from the inhomogeneous linewidth of MBE films [5], indicating their high crystalline quality. The film grown on the MBE template shows a particularly narrow C_2 site linewidth, around 9 GHz.

Thus, although all the samples are similar in terms of morphology and optical properties, YSZ and MBE template appear to be the most promising substrates. The first due to the strong texturing, and grain orientation, and the second for its narrow inhomogeneous linewidth. The next step will be the measurement of the homogeneous linewidth of these samples.



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InAs/Sn shadow junctions with upgraded superconducting properties

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Interest in the use of alternative superconductors other than Al in super-semiconductor quantum devices has deepened over the last five years.[1] This is particularly true for hybrid nanowires developed for quantum computing devices such as quantum bits and parametric amplifiers.

We synthesized InAs nanowires using the vapour liquid solid mechanism assisted by a gold catalyst in a molecular beam epitaxy reactor. Such nanowires grow out-of-plane and inclined at 35° on (001) substrates along two opposite [111]B directions. The nanowires were then transferred into a cryogenic-cooled reactor for the deposition of a superconducting shell (Sn or Ta). Deposition at cryogenic temperatures ensures the formation of an ultra-thin and smooth homogeneous shell. Due to the geometry of the nanowire sample, around one every four wires shades other wires that grow in the opposite direction. This ensures the formation of metallic contacts along each side of the nanowire and the formation of a 50 nm wide superconductor-semiconductor-superconductor junction. The nanowires were then integrated into transistor-like devices and superconducting transport was characterized in a dilution refrigerator.

We found that the first stage of growth of inclined InAs nanowires depends on the annealing temperature at which the In-Au eutectic forms. There is an optimal temperature above which no nanowires can be seen on the substrate and below which the density of nanowire is very small. Moreover, at non optimized temperatures, the surface of the substrate features craters. Next, we found that the deposition temperature of Sn on the nanowires has a large impact on the shell morphology. We find that large and discontinuous grains form when the temperature is above 120 K, while smooth and homogeneous films form at 80 K.

The devices fabricated with core-shell nanowires grown under optimized conditions for InAs and Sn are then measured at low temperature. We find that Sn induces superior superconducting properties into the InAs nanowire, such as large and hard superconducting gap and large gate tuneable switching currents surviving high magnetic fields. Finally, the properties of Sn thin films deposition on InAs nanowires surpass traditionally used Al and also Sn as studied on other nanowire materials, [1,2] opening promising avenues for realization of magnetic field resilient and gate tunable quantum devices [3,4].

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Monolithic integration of GaAs based compounds on silicon platform for photonic and optoelectronic devices.

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The incorporation of III-V compound semiconductors onto a silicon platform has emerged as a groundbreaking approach to enhance the performance and functionality of photonic and optoelectronic devices. This paper highlights recent accomplishments, obstacles faced, and future prospects in the monolithic integration of GaAs on silicon, with a specific emphasis on the development of near-infrared (NIR) emitters and photodetectors.

We adress the challenges associated with III-V monolithic integration on silicon and its compatibility with CMOS processes. These challenges encompass lattice mismatches, thermal management, and process scalability. Our most recent findings are presented in the integration of near-infrared resonant cavity-enhanced photodetectors and light-emitting devices onto a nominal Si(001) substrate. The optimization of device structures is achieved by incorporating active regions based on InGaAs/GaAsP strained-layer superlattices and GaAs/AlGaAs distributed Bragg Reflectors.

Additionally, we present an alternative approach for fabricating low-threshold emitters, utilizing III-As membranes and lateral injection devices.

Posters

Growth and design of antiferromagnetic $(LaVO_3)_m/(PrVO_3)_n$ superlattices

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Oxides, in particular transition metal oxides of the ABO_3 perovskite structure, are of great interest due to their electronic degrees of freedom and interactions. These lead to a wide range of physical properties (insulating, metallic, superconducting, piezoelectric, ferromagnetic...) that can be tailored by tuning chemical pressure and/or lattice constraints, for example. This great versatility opens up the possibility of functionalizing these materials in nanometric heterostructures for new electronic devices.

Within this class of materials, we are particularly interested in the rare-earth vanadates RVO_3 (R = La-Lu or Y), whose antiferromagnetic spin ordering temperature (T_{SO}) lies in the (100K-150K) temperature range. At higher temperatures, V *3d t2g* orbital ordering is accompanied by a structural transition with decreasing symmetry, from orthorhombic *Pbnm* to monoclinic $P2_1/m$ [1]. In addition to VO_6 octahedra rotations, it has been predicted by *ab initio* calculations that rare earth shifts could be exploited to introduce improper hybrid ferroelectricity by taking advantage of octahedra tilts and Jahn-Teller distortions [2]. Single films of $LaVO_3$ and $PrVO_3$ were first synthesized on (001)-oriented $SrTiO_3$ substrates [3]. Our aim is now to obtain a designed multiferroic material through strain control and interface engineering in R_AVO_3/R_BVO_3 superlattices. We have grown these heterostructures by using molecular beam epitaxy (MBE) with a controlled ozone pressure in the chamber. RHEED and X-ray diffraction analyses were used to optimize the growth window (deposition temperature and ozone pressure) in order to achieve perfectly controlled 2D growth and stoichiometry, and sharp interfaces.

Electron microscopy experiments (TEM and STEM) carried out on $(LaVO_3)_m/(PrVO_3)_n$ films and superlattices highlight the orthorhombic structure and 3 growth domains on the square-symmetry surface of $SrTiO_3$. We were also able to observe the displacements of rare earth atoms, thanks to the determination of atomic positions and the analysis of the hybridization change with the oxygen atoms by using electron energy-loss spectroscopy (EELS). Magnetic measurements confirmed our ability to tailor the magnetic properties through interfacial engineering. These results will contribute to our understanding of the electronic properties of oxide-based heterostructures, and in particular to the emergence of their ferroelectric and multiferroic properties by design.

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Exploring the epitaxial growth of superconducting β-Sn on Ge

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Josephson junction (JJ) devices are the essential building blocks of gatemon qubits. In a JJ two superconducting (SC) contacts are deposited for instance on a semiconductor (SEMI) quantum well (QW) heterostructure (*i.e.* confinement of an electron or hole gas).[1-4] However, structural defects that are formed at the SC/SEMI interface are a major source of qubit decoherence. Aluminum is the most widely used SC material in gatemon devices and it is routinely deposited *ex situ* using sputtering. This results in polycrystalline grains and in the presence of defects at the interface with the substrate. The disorder created in the SC/SEMI hybrid junctions strongly limits the transparency of the JJ and reduces the qubits coherence time. An alternative fabrication approach focuses on the *in situ* epitaxial growth of Al using molecular beam epitaxy (MBE) down to cryogenic temperatures (-150 °C).[5-6] High quality epitaxial Al/III-V interfaces led to a significant improvement in the JJ transparency, achieving hard SC gaps and large critical currents. Exploring alternative epitaxial SC materials is thus of paramount importance to achieve quantum devices with enhanced properties. Tin (Sn) when grown in the body-centered tetragonal β-Sn phase is a promising SC material candidate due to combination of high critical temperature (3.7 K) and resilience to high magnetic fields.[7-8]
Here, we will demonstrate the MBE growth of a SC β-Sn thin films on a Ge (100) substrate and characterize their structural properties by combining transmission electron microscopy (TEM), X-ray diffraction (XRD), Raman, and atomic force microscopy (AFM) techniques. Magneto-transport measurements will be performed below 3 K to demonstrate the SC properties of β-Sn. These results will pave the way for the use of as the SC contact in all-group IV gatemon device using Ge/SiGe QWs.[2]

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Complex Oxides by Large Area Pulsed Laser Deposition

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Pulsed Laser Deposition (PLD) is a well-adapted deposition technique for complex oxide epitaxial thin films, especially of perovskite oxides. The reliable stoichiometric transfer of the cations between the target and the film allows a good control of the composition of the films, and its pulsed character helps to deposit extremely thin films, going down to less than one unit-cell. However, this technique has an important drawback for applied science: In traditional systems, the area of homogeneous deposition is limited to about 10 x 10 mm² substrates, related to the focusing of the laser and therefore a relatively small plume size. In the recent years, large area PLD systems have been developed by scanning the laser on a large area target and rotating the sample under the plume, in order to satisfy the need of industrial wafer-size deposition.

The CRISMAT has been equipped with such a deposition system, allowing the deposition on 4 inch wafers. This contribution will summarize the studies made on thin films of the new transparent conducting oxide $SrVO_3$, a prototypical perovskite oxide, where the potential applications ask for large area deposition. The main objective of this study was to achieve homogeneous deposition on the full wafer surface, both regarding the thickness of the films as well as their optical and electrical properties. The variation of the scan speed of the laser on the target was identified to be the critical parameter, allowing for homogeneous films on 4 inch surfaces.

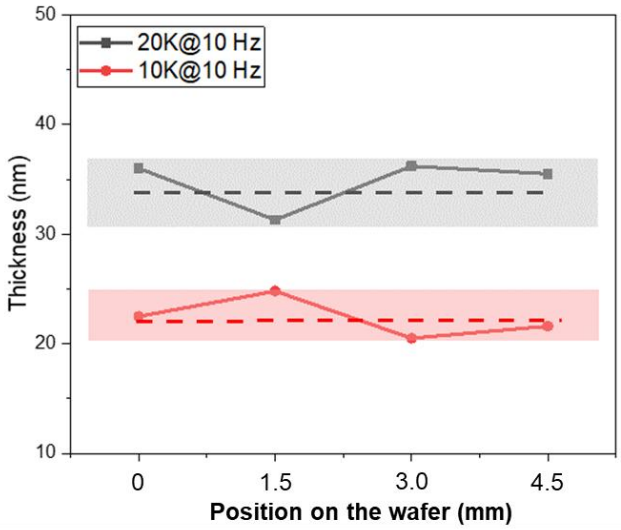

Figure 1The thickness of $SrVO_3$ thin films as a function of the radial position on the 4 inch wafer for a deposition of 10000 (red circles) and 20000 pulses (black circles) with a KrF excimer laser. The shaded boxed indicate a 10% variation of the mean value.

Growth and ferroelectricity of GeTe thin films on nominal and vicinal silicon substrate

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Among ferroelectrics, a new class of materials with high potentialities for spintronic applications has been recently introduced and named ferroelectric Rashba semiconductors[1,2]. In particular it has been demonstrated, on α-GeTe thin films, that the reversal of the ferroelectric polarization by an electric field leads to a change of the spin chirality of the band structure[3].

In the perspective of using α-GeTe for spintronics, high quality thin films with a controlled polarization state must be achieved. In this study, we have characterized the ferroelectric state of GeTe films grown on nominal Si(111) and vicinal Si substrates[4]. X-ray diffraction, transmission electron microscopy, scanning electron microscopy and low energy electron microscopy evidence ferroelectric domains. Considering the polarization configuration of α-GeTe, we show a major domain with the electric dipole in the $\langle 111 \rangle$ direction, i.e. perpendicular to the surface plane and minor ferroelectric nanodomains with in-plane polarization[4-5]. Using high resolution transmission electron microscopy we show that domain walls are only of 71° type[4-6]. The reversible decay of the ferroelectric nanodomains under annealing, as demonstrated by *in situ* LEEM, is attributed to the thermal stress induced by the large difference of linear thermal expansion coefficients of both materials[7]. In addition the atomic steps of the vicinal Si substrates break the symmetry at the interface with GeTe thin film and favour one type of domains via anisotropic stress relaxation.

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Tailoring the metal-insulator transition of rare earth nickelates towards adaptive infrared camouflage

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Adaptive visible camouflage is a phenomenon observed in many animals. It consists in changing the skin coloration in order to blend in with the environment. Similarly, adaptive infrared camouflage involves changing an object thermal signature, making it virtually invisible to thermal cameras. This technology is attractive to many industries, especially for military applications [1]. In this regard, materials that undergo a sharp metal-insulator transition (MIT) exhibit a rapid decrease in emissivity with increasing temperature, which is appealing for camouflage devices. Nowadays, the most studied materials for this purpose are part of the vanadium oxides family [2]. Unfortunately, their chemical inflexibility makes shifting their MIT temperature to room temperature challenging. This can be overcome by using a different class of materials: the rare earth perovskite nickelates.

Rare earth perovskite nickelates present the chemical formula $RNiO_3$, with R a trivalent rare earth: La, Pr, Sd, Sm, ..., Lu. They possess distorted perovskite structure, in which the degree of distortion is strongly related to the rare earth size and deeply affects the electronic properties [3]. Therefore, the MIT temperature can be modulated by changing the rare earth cation or by mixing two of them. In this work, we present our results on the growth of nickelates thin films and how we were able to shift their MIT temperature to room temperature by using a combination of Sm and Nd, specifically $Sm_{0.6}Nd_{0.4}NiO_3$. In addition, we will show that is possible to further modulate the MIT temperature by changing the applied strain, i.e. using different crystalline substrates (see Fig. 1). Along with the structural properties, we will present the optical properties of our $Sm_{0.6}Nd_{0.4}NiO_3$ films, demonstrating how the decrease in emissivity is linked to the resistivity evolution, to the film thickness and the applied strain. Our findings could open the way for achieving surfaces whose emissivity can be actively engineered in order to camouflage in the infrared region.

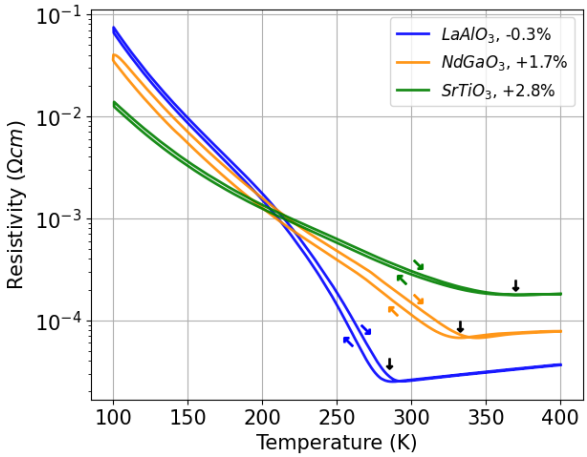

Figure 1: Temperature dependence of the resistivity of $Sm_{0.6}Nd_{0.4}NiO_3$ films grown on different $(001)_{pc}$ substrates. The different degrees of strain for each substrate are indicated in the legend. The curves were obtained during both heating and cooling, indicated from the colored arrows. The black arrows indicate the MIT temperature measured while cooling down.

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Selective area growth of InGaAs and InGaN nanowires arrays by hydride vapour phase epitaxy

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InGaAs and InGaN nanowires (NWs) are promising building blocks for future electronic and optoelectronic devices. However, NWs based devices suffer from the low reproducibility of the NWs growth methods such as VLS (Vapor-liquid-Solid) and auto-organized growth due to either deep level recombination centers or size inhomogeneities which significantly degrade the electrical and optical properties. Today, the most reliable option to control the growth of well-ordered III-V NWs with a high degree of reproducibility is to proceed by Selective Area Growth (SAG).

Here we demonstrate the synthesis of III-As and III-N NWs arrays by SAG-Hydride Vapor Phase Epitaxy (SAG-HVPE) on masked GaAs$(111)_B$ substrates and c-GaN/Al_2O_3 substrates, respectively, with apertures down to 200 nm in diameter. HVPE is a quasi-equilibrium growth method in which the III-chloride precursors do not absorb on the dielectric mask, providing high growth rate and high growth selectivity to grow dense arrays.

Thanks to the use of chloride precursors, selective area growth (SAG) of InGaAs and InGaN nanowires is achieved. Furthermore, a tunable In composition ranging from 0 to 100% is achieved through a systematic variation of the III-V ratio and of the growth temperature. High-resolution transmission electron microscopy is used to determine the composition and the crystalline structure of the nanowires. Energy dispersive spectroscopy profiles on single nanowires is used to probe In composition homogeneity along the wires. Photoluminescence measurements at low temperature are performed to investigate the optical properties of the nanowires.

The experimental results of the systematic studies are complemented by a phenomenological model which fully takes into account the thermodynamics and surface kinetics of the growth of ternary NWs by HVPE. InGaAs and InGaN nanowires are demonstrated to grow within the bulk miscibility gap thanks to a purely kinetic growth regime without macroscopic nucleation.

These findings provide a convenient method to grow homogenous InGaN and InGaAs nanowires and could push forward the performances of optoelectronic devices.

Growing SiGe nanowires with the hexagonal phase

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The hexagonal 2H structure of SiGe has a direct band gap and an excellent light-emitting capabilities with a tunable mid-infrared emission wavelength between 1.8 and 4.2 µm in a concentration range of 0 to 40% Si.

We previously reported that Au catalyzed Ge-2H branches [1] can grow on the sidewalls of a GaAs wurtzite trunck nanowires with the particular direction <1-100> as shown in figure 1. The Ge nanobranches exhibit the crystal structure 2H under the Au catalyst (i.e. epitaxial relationship with the (1-100) sidewalls of the GaAs trunks). An additional lateral layer of cubic Ge (3C) may grow on the (0001) facets depending on growth conditions (Fig .1).

Based on these observations, our objective is to grow hexagonal GeSi nanowires by UHV-CVD on wurtzite bulk substrates with m-plane (1-100) surface. As GaAs with a bulk wurtzite phase does not exist, we have opted for alternative hexagonal substrates with m-plane surfaces and lattice parameters corresponding to those of Si and Ge such as CdS-2H and ZnS-4H. We have studied the dewetting of the Au catalyst on these substrates and determined the optimal parameters for the growth of hexagonal SiGe nanowires.

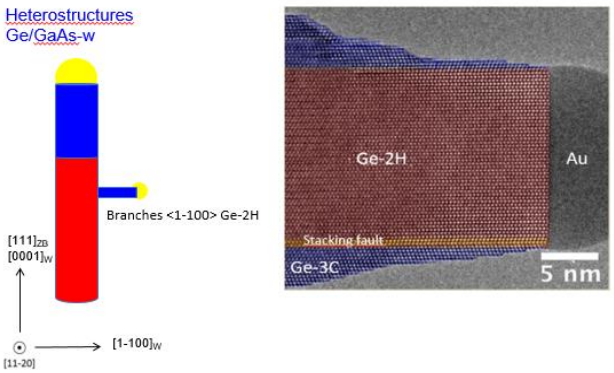

Figure 1: Representative schematic of the growth of a Ge-2H branch on a wurtzite GaAs nanowire trunk. The HR-TEM image shows the hexagonal 2H crystalline structure of the branch under the Au droplet and the presence of a cubic shell formed by lateral growth on the (0001) sidewalls.

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Epitaxial V_2O_3 films by Reactive Magnetron Sputtering

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V_2O_3 is an interesting compound that has been widely studied for over half a century [1]. This compound exhibits various insulator-metal transitions (IMT), which are of interest both from a fundamental point of view [2] and for applications in field of memories and neuromorphic components [3]. External stimuli known to induce such IMT's are thermodynamic parameters such as temperature and pressure, as well as application of electrical pulses.

More recently, it has been shown that application of ultrafast femtosecond light pulses can induce complete insulator-metal transitions in polycrystalline V_2O_3 thin films at low temperatures [4]. Conversely, this transition does not occur when the same ultrafast light pulses are applied to single crystals. These results show marked influence of morphology on the ability to induce photo-induced phase transitions. However, origin of this striking difference is still an open question.

In this context, the study of epitaxial thin films could help us to understand this phenomenon, since they have a morphology that is intermediate between that of polycrystalline thin films and that of single crystals. However, obtaining such epitaxial thin films with IMT's comparable to bulk single crystals is notoriously difficult [5-7].

In this poster, we present initial results of a study aimed at establishing the experimental conditions that allow obtaining high quality epitaxial V_2O_3 thin films using reactive magnetron sputtering technique. Thin films were characterised by 5-circles X-ray diffraction, Raman scattering and electrical transport measurements.

These preliminary results will be presented and discussed, aiming to draw new perspectives for fully epitaxial and stoichiometric V_2O_3 films.

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Pulsed laser deposition of $La_{2/3}Sr_{1/3}MnO_3$ thin films: first experiments using a Nd-YAG laser

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In the last decade, we have shown that epitaxial $La_{2/3}Sr_{1/3}MnO_3$ (LSMO) thin films deposited by Pulsed Laser Deposition (PLD) using a KrF laser wavelength of 248 nm on a large variety of substrates present a number of interesting physical properties for the fabrication of sensors such as anisotropic magnetoresistive sensors on vicinal $SrTiO_3$ [1] or uncooled bolometers on $SrTiO_3$/Si [2]. The performance of such sensors depend on the quality of the epitaxial growth. In this presentation, we will discuss the possibility of alternatively use Nd-YAG lasers to grow epitaxial LSMO thin films by PLD. Preliminary results obtained in Trieste using a Nd-YAG laser wavelength of 1064 nm [3, 4] and in Genoa using a Nd-YAG laser wavelength of 355 nm will be presented. O_2 pressure during deposition were varied in the 10^{-4} – 0.2 mbar range, the substrate temperature in the 730 – 850 °C range, the substrate-to-target distance in the 5.00 – 7.75 cm range and the film thickness in the 40-80 nm range. X-ray diffraction, Scanning Electron Microscopy, electrical resistivity versus temperature characteristics were measured (figure 1). Results will be compared with the properties of the LSMO films routinely grown using KrF laser at 730 °C, 0.2 mbar of 0_2, 3 Hz, at an energy density of 1.7 $J.cm^{-2}$.

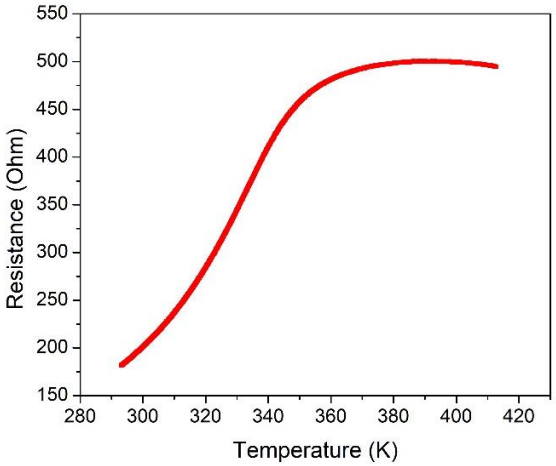

Figure 1 : Electrical resistance characteristics versus temperature of a LSMO film deposited on $SrTiO_3$ (001) using a Nd-YAG laser at 1064 nm, 730 °C, 0.2 mbar of O_2 and a target-to-substrate distance of 6.75 cm.

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ELECTRIC AND PIEZOELECTRIC BEHAVIORS OF ZnO NWs GROWN BY MOCVD.

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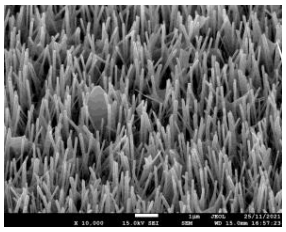
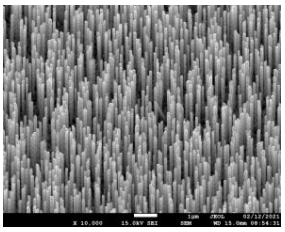
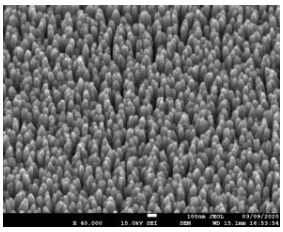
Mots clés : ZnO nanowires, MOCVD growth, piezoelectric, I-V measurements.

The performance of an array of ZnO nanowires for mechanical energy harvesting devices is linked to the quality, conductivity and alignment of the nanowires on the substrate, therefore requiring ways to improve these parameters. Thus, ZnO nanowires were grown by MOCVD in both vertical and horizontal reactors on silicon substrates, without buffer layer and with AlN buffer layer between ZnO wetting layer and silicon. It has been observed that nanowires grown on AlN buffer layer are well aligned compared to the nanowires obtained directly on silicon (Fig.1.) The electrical and piezoelectric behavior of nanowires have been investigated by AFM-Resiscope, AFM-Tuna and AFM-PFM after encapsulation in PMMA resin and eventually polishing process (Fig. 2.).


a. ZnO NWs on Si (111)


b. ZnO NWs on AlN/Si (111)


c. ZnO NWs on Si (111)

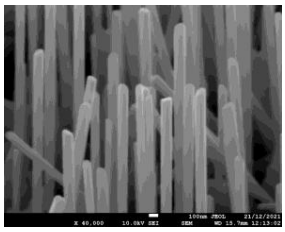
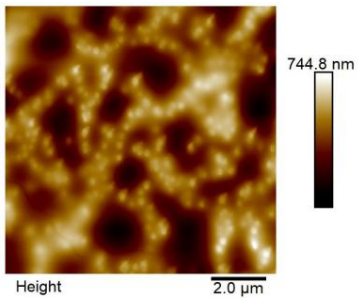
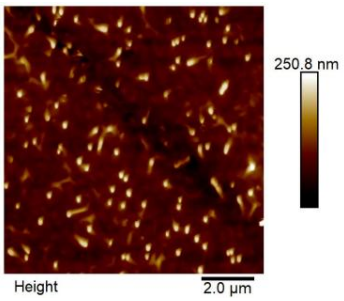

b. ZnO NWs on AlN/Si (111)

Fig. 1. SEM images: (a, b)-NWs grown by vertical-MOCVD with and without AlN buffer layer on Si (111) and (c, d)- NWs grown by horizontal-MOCVD with and without AlN buffer layer on Si (111)



ZnO NWs on AlN (40 nm)/Si (111) (vertical reactor)



ZnO NWs on AlN (20 nm)/Si (111) (horizontal reactor)

Fig. 2. AFM images of ZnO NWs on AlN/Si (111) after encapsulation in PMMA and polishing process.

CVD Growth of Graphene and Vanadium-Doped SiC for Quantum Hall Resistance Standards

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The discovery of the quantum Hall effect in 1980 sparked interest in the development of GaAs/AlGaAs heterostructures as quantum Hall resistance standards (QHRS). More recently, graphene emerged as a promising alternative thanks to its robust quantum Hall effect [1]. However, its high and unstable charge carrier concentration presents challenges for specific applications, particularly in achieving QHRS at low magnetic fields. To address this issue, we proposed the growth of vanadium-doped hexagonal SiC (SiC:V) homo-epitaxial back gate, utilizing vanadium for charge compensation [2]. This allows for on-demand control of the charge carrier concentration in graphene grown on top of the SiC:V layer.

This proposal poses a growth challenge because hexagonal SiC is typically grown on off-axis substrates to avoid cubic inclusions, while graphene is preferably grown on on-axis substrates to enhance its electrical properties. In this contribution, we will present the initial steps toward achieving this goal, employing an approach where both SiC and graphene are grown on on-axis SiC(0001) substrates.

In the first part of our contribution, dedicated to SiC:V homoepitaxial growth, we will explore the effects of vanadium doping levels on structural and electrical properties. The goal is to determine an optimal doping level that yields a highly insulating SiC film without compromising crystalline quality. Additionally, we will identify substrate and growth parameters that prevent the inclusion of 3C (cubic) phase (figure a).

Since buffer layer under graphene can drastically reduce the efficiency of the back-gate, the interface between graphene and SiC has to be hydrogenated. In the second part of our contribution, we will present the different approaches that can be used and the first results on these ways (figure b).

This work received funding from the projects VanaSiC (ANR PRCE 2022), PlaGGe (Région Sud), and Adict (PEPR Electronique).

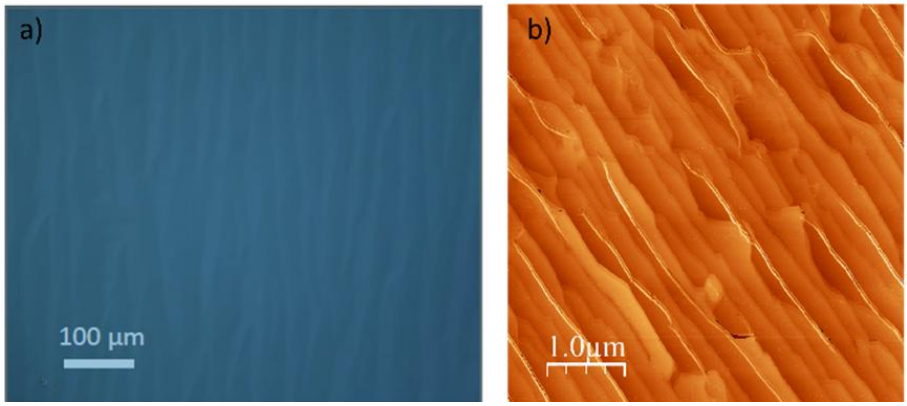

Figure a : optical micrograph of SiC:V film grown on 6H-SiC. Figure b: AFM view of an hydrogenated graphene film.

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Determination of the anisotropic dielectric function of epitaxial $SrO(SrTiO_3)_n$ Ruddlesden–Popper structures (n=1,…5)

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$Sr_{n+1}Ti_nO_{3n+1}$ Ruddlesden-Popper homologous series (RP phases) present outstanding physical properties (high T_c superconductivity,[1] colossal magneto-resistance,[2] low loss dielectricity,[3] ferroelectricity,[4] low thermal conductivity for heat harvesting,[5] tunable optical properties,[6]…) stimulating active researches. Interestingly, their atomic plane structuration can be engineered to tune their functional properties.

The structural anisotropy of the RP phases is expected to lead to an anisotropic permittivity, as also anticipated by theoretical studies.[7] The few experimental works reported in the literature[6] contradict these results by assuming an isotropic permittivity.

In this contribution, we will present an experimental method based on spectroscopic ellipsometry and normal incidence reflectometry to unambiguously demonstrate the anisotropic nature of RP phase pemittivity. We will show how we used this method to measure the ordinary and extraordinary dielectric functions of $Sr_{n+1}TinO_{3n+1}$ RP phases with n=0…5, and discuss how this dielectric function is affected by RP structuration.

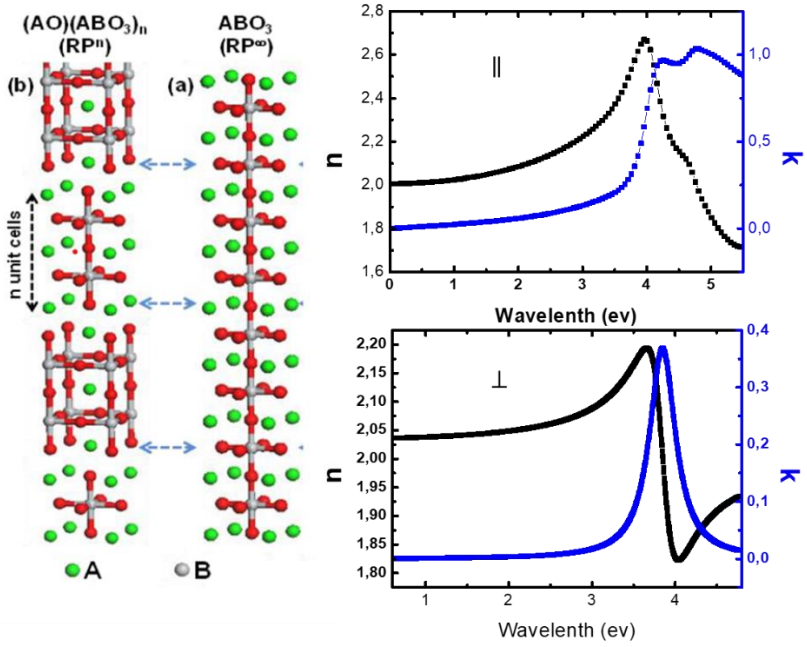

***Fig. 1**. : Left panel : schematic of the atomic structure of a $Sr_{n+1}TinO_{3n+1}$ RP phase (b), compared to that of $SrTiO_3$ (a). Right panels : real (n) and imaginary (k) parts of the dielectric function of a $Sr_3Ti_2O_7$ RP phase. ∥ and ⊥ respectively designate the in and out of plane components of the permittivity*

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Thermoelectric perovskite-oxide solid-solutions epitaxially-grown by MBE for on-chip thermal energy management

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Thermal energy management has become of major importance, especially in the microelectronic platforms. Thermoelectricity allows efficient device cooling (by Peltier effect) or thermal energy harvesting to power autonomous micro-devices (by Seebeck effect) [1]. Thermoelectric (TE) materials are heavily doped semiconductors, and standard TE materials are based on Te (*e.g.* Bi_2Te_3) [2], which are toxic, chemically unstable and expensive because of scarcity [3]. Oxides of perovskite structure (ABO_3) are good alternative TE materials overcoming these issues since its chemical flexibility allows a wide range of doping and thus TE property optimization by partial aliovalent cationic substitution [3]. Furthermore, they can contain low toxic and abundant elements [3], and allow proper advanced integration on Si-based microelectronic platforms by molecular beam epitaxy (MBE) (Fig. 1a) [4].

In this communication, we will show the main results obtained these last few years on this thematic, as well as the remaining challenges to overcome. In particular, we will present epitaxial films with excellent properties of *n*-type $Sr_{1-x}La_xTiO_3$ (Fig. 1b) [5] and *p*-type $La_{1-x}Sr_xCrO_3$ (Fig. 1c) [6], highlighting the huge impact of epitaxial strain (Fig. 1c) [6]. We will also present the current work on the search for alternative powerful *p*-type perovskite oxide solid solutions (*e.g.* $SrTi_{1-x}Al_xO_3$) [7]. Finally, some perspectives will be given about possible technological processes based on epi-lift-off for the microfabrication of an integrated TE module.

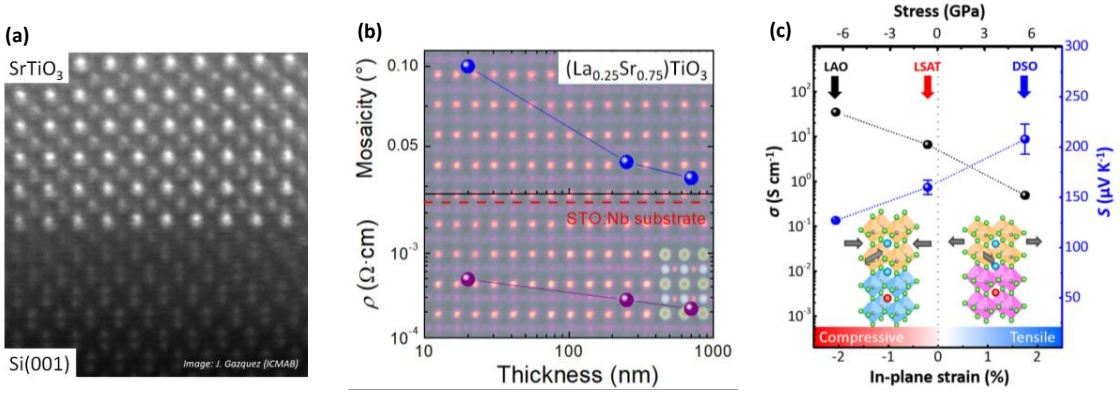

***Fig. 1** : Structural and thermoelectric properties results of (a) $SrTiO_3$/Si(001) [4], (b) n-type La-doped $SrTiO_3$ [5], and (c) p-type Sr-doped $LaCrO_3$ [6].*

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ZnO : from material growth to quantum cascade devices

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Although ZnO and its related heterostructures are attractive for their potential application in optoelectronics, the p-type doping issue has limited their developments. However, ZnO properties are also very attractive for unipolar structures and ZnO/(Zn,Mg)O heterostructures have recently been considered as a new opportunity for intersubband (ISB) devices. Nevertheless, these complex device structures require high-quality material and accurate control of their growth.

The samples were grown on 10x20mm^2 *m*-oriented ZnO substrates in a molecular beam epitaxy system (RIBER). Effusion cells were employed for zinc (Zn), magnesium (Mg), and gallium (Ga) while atomic O was provided by a plasma cell operating at 420W. The optical and structural quality of ZnO/(Zn,Mg)O multi-quantum well (MQW) heterostructures have been carefully evaluated using atomic force microscopy, X-ray reflectivity and diffraction, photoluminescence, and Fourier transform infrared (FTIR) spectroscopy.

For all the samples, the surface is flat with an RMS roughness always comprised between 0.3 and 0.7nm. The surface morphology is characteristic of non-polar ZnO orientation with elongated stripes along the *c*-axis.[1] In addition to the very low surface roughness the X-ray reflectivity and diffraction measurements evidence interface abruptness between ZnO and (Zn,Mg)O but also a perfect coherence along the growth direction.[1] This coherence has also been highlighted by transmission electron microscopy and atom probe tomography characterizations. With the final goal to develop quantum cascade devices based on ZnO we first focused our attention to the characterization of ISB transitions in this material system. The influence of QW thickness and doping level have been carefully studied allowing the determination of physical parameters but also a refinement of "classical" ISB model to ZnO material.[2] Indeed, for high-doping concentration a very large depolarisation shift has been observed and calculated.

Based on the high growth control and the accurate ISB calculations, a 20 periods ZnO/(Zn,Mg)O QCD structure has been designed and realized. The sample was processed as 260 square mesas and the I-V characteristics reveal that 86% of all mesa devices are operational. The photocurrent spectrum is strongly TM-polarized, as expected from detectors based on ISB absorption, and it presents a peak at 2.8 µm (443 meV) with a FWHM of 97meV. The photocurrent persists up to room temperature. To your knowledge, this represents the first Quantum Cascade Detector operation based on ZnO.[3]

On the other hand, specific quantum cascade structures designed to emit in the THz range have been elaborated. The electroluminescence shows a center frequency of ~8.5 THz which is unachievable in GaAs-based heterostructures owing to the intrinsic reststrahlen band absorption at ~8 THz.[4] To achieve lasing action, the strong temperature dependence of the injection current has to be mitigated. However, this demonstration not only constitutes a significant step further toward the realization of THz QCLs, it also unlocks the potential of ZnO-based heterostructures for novel devices and fundamental physics investigations.

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Kinetic Monte Carlo Simulation of Epitaxal Growth of 2D Si

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Text of the abstract - Calibri 11, **Maximum one page** (**including one figure max.**)

The first 2D material, graphene, was discovered in 2004 by exfoliation. It attracted much attention because of its remarkable properties which are different from graphite. However, the limitations of graphene, such as a small band gap, integration challenges, and optical properties, have spurred exploration into alternative 2D materials. Silicene, 2D material of silicon, stands out as a promising candidate. Unlike graphene, silicene lacks a pi-stacking structure, making exfoliation impossible. Epitaxy, known for producing high-quality materials, is thence the only method for silicene synthesis.

The epitaxial growth of 2D Si on Ag(111) [1] and double layer Graphene/SiC substrates [2] reveals unexpected growth modes. On Ag(111), Si atoms can insert into the substrate surface, forming inserted islands at high temperature (T >=300k). On the double layer Graphene/SiC, Si forms three distinct types of islands: 3D fractal islands, 2D hexagonal flakes with a surrounding ring, and 2D irregular flakes with a surrounding ring.

To rationalize these anomalous growth modes, we develop an out-of-equilibrium description of a lattice-based epitaxial growth model, which growth dynamics are analyzed via kinetic Monte-Carlo simulations where the process rate depends on the type and number of nearest neighbor atoms. For the Ag(111) case, we introduce intermixing effects between Si and Ag atoms. Through meticulous analysis of atomic microscopy images and island density fitting, we successfully reproduce both qualitatively and quantitatively the anomalous growth patterns of Si on Ag(111) [3].

As regards, growth of silicene on Graphene/SiC, we derive a model that revisits the classical dewetting thermodynamics, incorporating adsorption energies and step-edge effects. The out-of-equilibrium dynamics computed by kinetic Monte Carlo simulations reproduce the flake morphologies, and transformation into non-coalescent dendritic pyramids. The present modeling and understanding of the mechanisms at work in these systems are the first building blocks for future systematic studies aimed at controlling and growing large silicene flake.

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$[MnO_2]^{\delta-}$ 2D Oxides as Templates for Epitaxial Growth of Functional Oxide Films

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Over the past decade, the construction of heterostructures based on two-dimensional (2D) nanosheets has been fueled by their fascinating properties, including their 2D nature and semiconducting characteristics [1]. This area of research is attracting particular attention due to its potential for developing new, cost-effective substrates for the controlled growth and study of functional oxides. The main goal is to replace expensive single-crystal substrates with inexpensive polycrystalline or amorphous substrates, or to directly deposit onto standard single-crystal silicon used in microelectronics. By using crystallized nanosheets as a starting seed layer [2], it becomes feasible to achieve subsequent local epitaxial growth of functional oxides, thus opening new perspectives for the fabrication of advanced electronic devices on a large scale.

In this context, several layered oxide phases play a crucial role by serving as precursors for the synthesis of nanosheets. Among them, K_xMnO_2 [2] and Na_xMoO_2 [3], that are structurally closely related, can be exfoliated into $[MnO_2]^{0.45-}$ and $[MoO_2]^{\delta-}$ nanosheets, respectively. Both types present 2D hexagonal lattice, allowing the growth of ZnO according to the (001) orientation for $[MnO_2]^{0.45-}$ [4] and that of $SrTiO_3$ films along the (111) direction for $[MoO_2]^{\delta-}$ [4]. Thus, using these layered phases as a starting point for nanosheet formation is a critical step in the epitaxial growth process, thereby connecting these two concepts in a meaningful way.

For this purpose, single crystals of layered manganese birnessite oxide, K_xMnO_2, have been successfully grown using different methods by slow cooling at 1000 K, at a rate of 10 K/h, employing various flux sources. This synthesis was accompanied by a meticulous examination of synthesis parameters, such as the value of x and the excess of K, to assess their impact on the properties and structure of the resulting single crystals. Subsequently, the different obtained phases were characterized by X-ray diffraction, energy-dispersive X-ray spectroscopy (EDS), scanning electron microscopy (SEM) and transmission electron microscopy (TEM). Additionally, preliminary attempts at exfoliation and oriented perovskite film growths were conducted.

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Influence of the strain relaxation on the ferroelectric nanodomains in ferroelectric / dielectric superlattices

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Ferroelectric / dielectric superlattices have raised considerable interest since a multidomain state made of ferroelectric nanodomains can be stabilized [1], and the high mobility which characterizes the domain wall in nanodomain structures can lead to an enhancement of dielectric properties [2]. Investigations are mainly based on systems with a high density of atomically abrupt interfaces. The investigation of the interplay between epitaxial strain, electrostatic effect and structural defect is crucial to tune the functional properties. Strain relaxation defects can impact domain structures by inducing an inhomogeneous strain field in addition to the epitaxial strain. Preferential formation of ferroelectric domains is expected around misfit dislocations, which can also modify locally the ferroelectric transition temperature.

Here we report on the strain relaxation defects in a series of ferroelectric / dielectric $Pb(Zr_{0.2}Ti_{0.8})O_3$ / $SrTiO_3$ (PZT/STO) superlattices. This effect was tuned through the thickness of the ferroelectric layers which was varied from three to thirteen unit cells. X-ray diffraction and transmission electron microscopy (TEM) investigations were carried out in order to study the microstructure of the superlattices. The presence of ferroelectric nanodomains was evidenced by satellite peaks in the X-ray scattering pattern.

TEM investigations have evidenced strain relaxation and induced defects, which are dependent in the ferroelectric layer thickness in the period. The strain induced by the misfit strain between PZT and STO is accommodated by an elastic deformation up to 5 unit cells of PZT in the period, corresponding to a critical thickness of around 2 nm. TEM and HRTEM images reveal a very clear and well-separated layer sequence. Increasing the thickness of the ferroelectric layer leads to a roughening of the PZT/STO interfaces, associated with an increase in the mosaicity confirmed through x-ray diffraction rocking curve analysis. The strengthening of the strain relaxation with increasing thickness has a clear impact on the tetragonal – cubic phase transition, which becomes more diffused. The strain relaxation induces a broadening of the satellite reflections related to ferroelectric nanodomains, as well as a decrease of their intensity. The roughening of interfaces could act as a source of domain randomness and give rise to significant mosaicity at interface between domains.

This work shows that strain relaxation and defects at the interfaces do not suppress ferroelectric nanodomains, and that misfit strain between the materials as well as the ratio of unit cell of ferroelectric to paraelectric in the period of the superlattice can be used to tune the strain relaxation.

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