Progress in Nanostructured Coated Conductors processing and development at EUROTAPES

(European development of Superconducting Tapes: integrating novel materials and architectures into cost effective processes for power applications and magnets)

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Industrial and academic partners
PLD and CSD nanocomposite growth and vortex pinning
RABiT and ABAD tapes
buffer layers and simplified architectures
Long length and low/medium cost
Round cable: CORT

EUROTAPES
http://www.eurotapes.eu/
- 21 EU partners (9 countries)
- ~20 M€ (13.5 M€ - EU)
- 09/2012-02/2017

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<td>2 Bruker HTS GmbH</td>
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<td>3 Italian National agency ENEA</td>
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<td>21 Deutsche-Nanoschicht</td>
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Collaborators


**UCAM:** J. Driscoll, A. Kursomovich

**IFW-Dresden:** R. Hühne, P. Pahlke

**KIT-Karlsruhe:** B. Holzapfel, J. Hänisch, M. Erbe

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**Bruker:** A. Usoskin, K. Schlenga

**D-Nano:** M. Bäcker, M. Falter

**Theva:** M. Bauer, W. Pruseit

**Oxolutia:** A. Calleja, R. Vlad, M. Vilardell, X. Sintas
Nanostructured Coated Conductors

Energy Future paradigm: cables, FCL, transformers, ...

Low and medium field, 77K
Devices already in grid

High field, 40-60K
Much activity with prototypes

Ultra-High field, 4.2K
Design stage, some prototypes

High Energy Physics, Fusion, Ultrahigh Field NMR, ...

EUROTAPES TARGETS:

• Length: +500 m

• Performance:
  • For low fields (B< 1 T):
    \[I_c (77 K, sf) > 400 \text{ A/cm-w}\]
  • For high fields (B ~3-5 T):
    \[F_p (60 K) > 100 \text{ GN/m}^3\]
  • For ultrahigh fields (B > 15 T):
    \[I_c (5K, 15 T) > 1000 \text{ A/cm-w}\]
  • Pre-comercial cost:
    \[\sim 100 \text{ €/kAm (77 K)}\]

Major concerns: MARKETABILITY

- High \(I_c\) and \(J_e\)
  (↑pinning, ↑thickness, ↓substrate thickness, simplified architectures)
- Low cost
  (↑production rates, ↑yield, ↑growth rates, wide tapes, chemical methods)
Growth of ReBCO Nanocomposites
Simultaneous deposition and growth
(Case PLD)

- Deposition
- Absorption
- Surface diffusion
- Self-assembly growth

Epitaxial nanorods form with YBCO simultaneously promoting semicoherent interfaces between nanorods and YBCO inducing localized strain

Main contribution:
Pinning landscape by secondary phases and high growth rate nanocomposites

Vortex pinning mostly ascribed to nanorods and associated interfacial strain
Mixed double perovskite nanocomposites

$\text{Ba}_2\text{Y(Nb}_{0.5}\text{Ta}_{0.5})\text{O}_6$ long self-segmented nanocolumns and $\text{Y}_2\text{O}_3$ nanoplatelets

$\varepsilon = 10\%$

$F_{p\text{max}} (H//c)$ = 25 GN/m³ at 77 K
$F_{p\text{max}} (H//c)$ = 750 GN/m³ at 10 K

among the highest values in literature

Vortices accommodate simultaneously to nanocolumns-segments and nanoplatelets

L. Opherden et al., Scientific Reports, 2016

G. Ercolano et al, SUST 24 (2011)
Mixed double perovskite nanocomposites

$\text{Ba}_2\text{Y}(\text{Nb}_{0.5}\text{Ta}_{0.5})\text{O}_6$ continuous nanocolumns

Characteristic of continuous nanocolumns, no segmentation

Among highest values of Irreversibility Line $B_{irr} (\text{BYNTO}) = 11 \, \text{T for H//c}$

The presence of ions with different diffusion ($\text{Nb}^{5+}$, $\text{Ta}^{5+}$) enriches the kinetics enabling several nanostructures

Rizzo et al, APL Materials, 2016
Fan-shaped $\text{BaHfO}_3$ nanorods by High Rate PLD on ABAD-YSZ (BRUKER) substrates

Growth rate 0.3 – 6.6 nm/s still epitaxial growth

YBCO + 6mol% BaHfO$_3$ at 1.3 nm/s

3-4 nm

YBCO

$\uparrow c$

BHO

20 nm

Y124 intergrowth

$\text{YBCO-BHO nanocomposite}$

$\text{YBCO}$

$\text{H//c}$

Broad c-axis peak, very effective at intermediate T

$\text{Pahlke et al., IEEE TAS 2015}$
BYNTO:YBCO and BHO:YBCO on ABAD-YSZ (BRUKER) and Ni5W (Dnano) and MgO-ISD (THEVA)

Nanocomposites Growth mode dependence on composition, substrate, $T_{dep}$, growth rate (0.3-4 nm/s)

1.3 nm/s, 1.5 $\mu$m
YBCO + BYNO liquid assisted PLD

YBCO compositions Cu and Ba rich to have a liquid phase in the film during PLD.

At 800 °C and 16 nm/s:
- Epitaxy is kept even at high growth rates at high thickness.
- Standard (no liq.) vs. liquid assisted PLD growth.
  - 1T, 77K
  - YBCO + BYNO + liquid
  - Liquid assisted PLD
  - 1 nm/s (0.06 μm/min)

No clear c-axis peak as nanorods are short.
Disorder/precipitation effects in Bruker PLD

Pressure triggered stoichiometry deviations ("intrinsic") + BZO nanorods ("extrinsic")

In 2016, HTS tapes were upgraded to 600m WITHOUT REDUCTION of Ic

I_c(4.2K,18T) = 1250 A/cm-w for 22 m
I_c(4.2K,18T) = 800 A/cm-w for 600 m
Industrial involvement in PLD CC processing: Nanocomposites fully implemented

YBCO\textsubscript{PLD}/CeO\textsubscript{2}\textsubscript{PLD}/YSZ-ABAD/SS
Effort on wider tapes

$I_c(4.2K,18T)= 800$ A/cm-w for 600 m

Capacity: 25 Km/yr in 4 mm
High field applications
Industrial involvement in PVD CC processing:
Nanocomposites in a second stage
Pilot production line for PVD 2G CC

GdBCO_{evap}/MgOepi/MgO-ISD/ Hastealloy
Effort on longer length

Tape production length:
  350 m (currently)
  600 m (Dec. 2016)
  1,000 m (max. capacity)
Capacity: 150 km/yr in 12 mm-width

60 m tapes 12 mm wide: $I_{c,\text{min}} = 600$ A
350 m tapes 12 mm wide: $I_{c,\text{min}} = 360$ A
Growth of ReBCO Nanocomposites

Sequential deposition and growth: CSD case

Main contribution:
Role of different secondary phases, colloidal nanocomposites, pinning contributions

Vortex pinning mostly ascribed to distributed local lattice distortions (nanostrain) induced by defects generated by the nanoparticles: Isotropic pinning
Nanocomposites by Chemical Solution Deposition with preformed nanoparticles

Stabilizing compound

Solvothermal synthesis –
(Thermal, Microwave, Autoclave, Hot injection)

CoFe$_2$O$_4$, MnFe$_2$O$_4$, CeO$_2$, ZrO$_2$, HfO$_2$, BaZrO$_3$, BaHfO$_3$

Requirements / achievements:

- Small size (< 10 nm range)
- Narrow size dispersion
- High concentrations (100 - 250 mM)
- Highly crystalline and dispersive
- Long time stability in alcoholic media and in YBCO ionic environment solutions
- Need control of all deposition and growth steps: avoiding reactivity, coarsening, pushing, sedimentation and agglomeration

Nanocomposites from \( \text{ZrO}_2 \) and \( \text{HfO}_2 \) preformed nanoparticles

Reactivity and coarsening occur (\( \text{BaZrO}_3, \text{BaHfO}_3 \))

NC with homogeneous dispersion of Np

A small YBCO buffer layer is needed in some cases

- Higher pinning
- Lower anisotropy and SF pinning

\( \gamma_{\text{eff}} \approx 3 \)

\( J_c (\text{MA/cm}^2) \) vs. \( \theta \) (deg)

- Standard
- 16% ZrO\(_2\) NPs
- 13% ZrO\(_2\) NPs
- 10% ZrO\(_2\) NPs

@ diff. Np synthesis
Nanocomposites of non-reactive preformed BaZrO$_3$ and BaHfO$_3$ nanoparticles

No reactivity nor coarsening occurs and high Np dispersion

Twice Np concentration than spontaneous segregated NC: $T_c =$90K, $J_c(77K)=3$ MA/cm$^2$, $J_c(5K)=40$ MA/cm$^2$
Nanocomposites of non-reactive preformed BaZrO$_3$ and BaHfO$_3$ nanoparticles

CSD Nanocomposites present very good pinning performances also at low temperatures.
Knowledge achieved from CSD- nanocomposites

Isotropic nanostrain
induce isotropic pinning

Random oriented nanoparticles
induce isotropic nanostrains

J. Gutierrez et al, Nat. Mater. 6, 367 (2007)
Vortex pinning in CSD - Nanocomposites

Good pinning performance at all temperatures for high fields

\[ J_c^\text{strong}(T) = J_c^{str}(0) \exp \left[ -3 \left( \frac{T}{T^*} \right)^2 \right] \]

\[ J_c^\text{weak}(T) = J_c^{wk}(0) \exp \left( -\frac{T}{T_0} \right) \]

… from \( J_c(H,T,\theta) \) we separate the different components

Weak pinning contribution: cation vacancies?

Atomic scale defects (<1 nm) demonstrated

Cu – O vacancies within Y248 intergrowth → weak pinning ??

Avoids the Stoichiometry Catastrophe

YBCO + BaZrO₃


Faulted Y248

Cluster with ferromagnetism confirmed by XMCD synchroton radiation too

DFT calculations

2 $V_{Cu}$ + 3 $V_{O^-}$

E/Cu=1.1 eV
CSD-Transient Liquid Assisted Growth of Nanocomposites: High growth rate and low cost

YBCO – 123 composition non-fluorinated precursors

Amorphous liquid BaCuO$_2$-CuO

Liquid identified by quench at pressure conditions where YBCO is not stable

Extremely low porosity and $J_c(77K)=3$MA/cm$^2$

First trials on Nanocomposites with BZO preformed Np
Industrial involvement in CSD CC processing:

Nanocomposites in Lab. but on-line implementation in a later stage

All CSD approach on RABiTs: Buffer layer, HTS, Silver and Copper layer
Conductor with customized architecture: Copper electro-plating, Lamination,
Most interest in cables and FCL
Insulation, quality control

YBCO$^{\text{MOD}}$/CeO$_2^{\text{MOD}}$/LZO$^{\text{MOD}}$/ Ni5%W
Effort on longer length, wider tapes and performance

Expanded pilot line
May 2016

$I_c(77K,0T)/w > 250$ A/cm-w
$I_c(30K,1T)/w = 850$ A/cm-w
Length $> 50$ m
HTS layer thickness $= 1 \, \mu\text{m}$

Planned capacity $> 200$ km/yr

T. Puig-CCA2016
Industrial involvement in CC processing

First stages with nanocomposites achieved

Reel-to-reel Ink Jet Printing and growth pilot plant for ALL CSD on ABAD (Bruker)

10 m deposition stability proven for SDP, CeO$_2$ and YBCO

Homogeneous single pass 10 m SDP layer Y$_2$O$_3$ SDP/SS unpolished @ 35 m/h.
Now being tested by BRUKER

10 m Ce$_{1-x}$Zr$_x$O$_2$/YSZ ABAD/SS @ 28 m/h

10 m pyrolyzed YBCO/CZO/YSZ$_{ABAD}$/SS @ 15 m/h

> 1.9 μm pyrolyzed YBCO/CZO/YSZ$_{ABAD}$/SS single IJP deposition

Short samples $I_c$(77K, sf) = 108 A/cm-w for 900 nm
Conclusions and prospects

R&D

- Large knowledge on Nanocomposite growth has been reached for PLD and CSD
- Vortex pinning scrutinized for the different H,T regions for PLD and CSD
- Strong involvement on high growth rate nanocomposites
  - PLD (1-4 nm/s) and liquid-assisted PLD up to 16 nm/s
  - New CSD-transient liquid assisted growth: > 48 nm/s (EU ERC-Adv Grant)
- Nanocomposite Integration on technical substrates with large industrial involvement (ABAD-BRUKER, NIW-DNANO, ISD-THEVA)

Production

- BRUKER (ABAD): PLD CC demonstrated with >600 m with record values 800A/cm@18T and 4.2K
- THEVA (ISD): Evaporated CC demonstrated with 600 A/cm for 5 μm & 60 m
- D-NANO (RABiT): All CSD CC on RABiTs demonstrated with 250 A/cm for 50 m
- OXOLUTIA (ABAD): Steady progress in IJP of all-chemical CC on ABAD for thick R2R growth with single deposition and SDP layers

Integration

Future: More CC integration in devices → Adapt them to the different needs. → We need interdisciplinary consortiums and lots of discussions