Outline

1. HISTORY
   - Discovery of YBCO
   - Features of YBCO
   - Architecture of Coated Conductors
   - Japanese Contributions (IBAD, Self-epitaxy, PLD, MOD)

2. PRESENT STATUS
   - Higher In-field $I_c$ by APC Control
   - Lower AC Losses & Control of Magnetic Relaxation by Filamentation

3. FUTURE PROSPECTS
   - Lowering Cost
   - Higher Performances
   - New Concept of “ISOTROPIC C.C.”
1. HISTORY

- Discovery of YBCO
- Features of YBCO
- Architecture of Coated Conductors
- Japanese Contributions
  (IBAD, Self-epitaxy, PLD, MOD)
The First HTS Wires (1987)

Powder in Tube (PIT): Y$_2$O$_3$ BaO CuO
Sintering: @900-1000 °C, O$_2$ Annealing: @400 °C

Y-Ba-Cu-O (Ag sheath)
wire dia.: 1.5mm φ core dia.: 0.77mm φ

Before heat treatment

After heat treatment

YBCO : 4.1x10$^3$ A/cm$^2$ (@77K, s.f.)
BSCCO: 3.5x10$^4$ A/cm$^2$ (@77K, s.f.)
Serious Effect of Misalignment Angle at Grain Boundaries on $J_c$

(a) [001]-tilt
(b) [010]-tilt, valley
(c) [010]-tilt, roof
(d) [100]-twist

Architecture of 2nd Generation Coated Conductor (C.C.)

In-plane Grain Alignment
Thick Film for High $I_c$
Introduction of Flux Pinning Centers
High Rate Deposition
Long Length Stable Deposition
Uniformity

Epitaxial growth of REBCO on the textured buffer layer!
$\rightarrow >10^6 \text{ A/cm}^2@77\text{K}, \text{s.f.}$

Stabilizing Layer
Ag, Cu etc
(10~30 $\mu$m)

SC Layer
Y-123, Sm-123, Gd-123, Eu-123, RE(Alloyed)-123 (1~3 $\mu$m)

Buffer Layer
MgO, GZO, YSZ, CeO$_2$, LMO, Y$_2$O$_3$ etc. (<3 $\mu$m)

High Mechanical Strength
Non-Magnetic Material
Thin and Smooth Surface
(RABiTS: Fine Grain alignment)

Metallic Substrate
Hastelloy™ etc, Ni-base Alloy, Stainless Steel (SUS)
RABiTS: (Ni, Ni-W, Cu, Ag, Clad-composite)
(50~100 $\mu$m)
Advantages of REBCO C.C.

< Cost >

- Y-system
- Bi-system

< J<sub>e</sub> - B Property >

< Mechanical Strength >

- Y-system

< Low AC Loss >

- Aspect ratio
  - Bi: Y = 1:10
  - For scribing:
    - Y: Layer structure ⇒ Easy
    - Bi: Sheath ⇒ Difficult

B // Tape Surface

B ⊥ Tape Surface

Tension Test

- 1/10
  - Possible to scribe
National Projects in JAPAN

Fundamental Materials Science & Engineering

Materials, Science & Processings

Fundamental Technologies for Superconductivity Applications Phase I, II
YBCO C.C.

Superconductive Generator Equipment (LTS) and Materials (Super-GM)

Superconducting Generator (SCG)

SMES system (LTS) Basic Technology

SMES system (LTS)

SC Power Network (LTS-SMES)

Power Device Applications

HTS Flywheel Energy Storage

SC Magnetic Bearing for FW

SC Power Network System (FW)

AC Power Device Cable, FCL, etc.

AC Power SC Equipment (Super-ACE)

Bi-Cable (AC) (Field Test)

M-PACC C.C. SMES Cable Transformer

HTS Coil for Medical Application

C.C. MRI Heavy Iron Accelerator

Japanese Contribution for C.C.
- Bi-axial Grain Alignment by IBAD -

**IBAD (Ion Beam Assisted Deposition) Process**

On Randomly Oriented Polycrystalline Metallic Substrate

**by Fujikura Ltd. in 1991**

Introduction of a buffer layer with in-plane grain alignment
Improvement of Rate in US for IBAD

**Problem** in IBAD of Early Stage (YSZ & GZO)

→ *Long Time for Alignment*
  (e.g. 4hr for $\Delta \phi \sim 10^\circ$)

Drastically Shortening Time for Alignment in U.S.

GZO → MgO
  (e.g. 2 min. for $\Delta \phi \sim 10^\circ$)

**Ref:** C.P. Wang et al. APL vol.171(1997)2955

Japanese Contribution for C.C.  
- Bi-axial Buffer by Self-epitaxy -

Definition: in-plane misorientation angle ($\Delta \phi$) decreases with increasing film thickness  
(discovered by Muroga et al. in 2002)

![Graph showing $\Delta \phi$ vs. thickness of CeO$_2$](image)

Japanese Contribution for C.C.
- Bi-axial Buffer by Self-epitaxy -

Drastic changes in the grain sizes at the interface

IBAD-MgO

IBAD-Gd₂Zr₂O₇

PLD-CeO₂

CeO₂/IBAD-Gd₂Zr₂O₇

CeO₂/ (LMO) / IBAD-MgO

Hastelloy

1μm

CeO₂

LMO

MgO

1nm

Deposition time, t (min)

Δφ (°)

100

10

1

0.1

1

10

100
Japanese Contribution for C.C. - MPMT-PLD Process for REBCO -

**Multi-Plume & Multi-Turn PLD**

- \( YBCO \) layer deposition temperature: 800 ~ 850 °C
- Oxygen pressure: 200 mTorr
- Laser beam energy: 500 mJ
- Repetition rate of laser pulse: 160 Hz,
  (divided to 4-plumes with laser pulse of 40 Hz each)

- Production Rate
- High Material Yield
- Controlled Supersaturation

Japanese Contribution for C.C.
- GdBCO for PLD -

Advantage of GdBCO
High $I_c$ & $J_c$, High $I_c$ - $B$ - $\theta$, High Production Rate

High $I_c$ & $J_c$:
$I_c > 200A/cm^2$, $2MA/cm^2$ (@77K, self-field)

High $I_c$ - $B$ - $\theta$:
In-Field $I_c > 20A/cm^2$ (@77K, 3T)

High Production Rate
30m-GdBCO @10 m/h (YBCO 3.75 m/h)
Long Length C.C. @Fujikura(ISTEC)

PLD(GdBCO)/IBAD Coated Conductors

<table>
<thead>
<tr>
<th></th>
<th>Piece Length</th>
<th>$I_c,_{max}$</th>
<th>$I_c,_{min}$</th>
<th>$I_c,_{ave}$</th>
<th>Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire A</td>
<td>621 m</td>
<td>700 A</td>
<td>649 A</td>
<td>677 A</td>
<td>7.5 %</td>
</tr>
<tr>
<td>Wire B</td>
<td>700 m</td>
<td>590 A</td>
<td>555 A</td>
<td>575 A</td>
<td>6.1 %</td>
</tr>
<tr>
<td>Wire C</td>
<td>587 m</td>
<td>562 A</td>
<td>533 A</td>
<td>550 A</td>
<td>5.2 %</td>
</tr>
</tbody>
</table>

$\frac{I_c}{cm \cdot w} @ 77 K, s.f.$

Uniformity: $\frac{\{I_c,_{max} - I_c,_{min}\}}{I_c,_{ave}} \times 100$

$I_c \times L = 577 (A) \times 1040 (m) = 600 (kAm)$
Japanese Contribution for C.C.
- Fundamental Analysis of TFA-MOD -

High $I_c$ due to Ba-deficient Composition

Low Cost Process

Ba-rich: Huge pores
Ba-deficient: Smaller and less pores,
$CuO/Y_2Cu_2O_3$ particles in the 123 grains

$Y:Ba:Cu = 1:2:3$
$Ba/Y = 2.0$

$Y:Ba:Cu = 1:1.5:3.0$
$Ba/Y = 1.5$

$Ba$-deficient ($Ba/Y < 2.0$)

$Ba$-rich ($Ba/Y > 2.0$)

Molar Ratio of $Ba/Y$ in Starting Solution

$J_c (MA/cm²@77K, s.f.)$
Long Length C.C. @ SWCC(ISTEC)

TFA-MOD(YBCO)/IBAD Coated Conductors

Batch Process

$\Delta \phi_{c02} \sim 4$ deg.
Calcination: RTR type furnace
(Operation speed: 5 m/h)

YBCO thickness: 1.5 $\mu$m

$I_c > 310$ A/cm-w
(@77K, s.f.)
Progress of Long C.C. (as of 2015.6.8)

Discovery of HTS

J.R. Bednorz & K.A. Muller

Paul Chu

H. Maeda

BSCCO

YBCO

Plenary presentation PL3 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
2. PRESENT STATUS

- Higher In-field $I_c$ by APC Control
- Lower AC Losses & Control of Magnetic Relaxation by Filamentation
Special Requirements for C.C. from Applications

< Requirements >

- High In-field $I_c$
- High Mechanical Strength
- Low Heat Generation (Low AC Loss etc.)
- Control of Shielding Current
- Low Cost

Motor
Wind Generation
Accelerator
SMES
MRI
NMR
Cable

Plenary presentation PL3 given at EUCAS 2015; Lyon, France, September 6 – 10, 2015.
Improvement of In-field $I_c$ in IBAD-PLD C.C.

- PLD-REBCO
- Epitaxial CeO$_2$
- IBAD –MgO etc.
- Untextured Metal Hastelloy™
Early Stage of APC Introduction

(APS : Artificial Pinning Center)

BaZrO$_3$ nano-rods

GdBCO + BaZrO$_3$ (RTR short sample)

GdBCO (215.6 m, 220A, 1.2 $\mu$m$^3$)

YBCO (212.6 m, 245A, 2.25 $\mu$m$^3$)

Applied Field Angle, $\theta$ (deg.)
Effective APC Materials for IBAD-PLD C.C.

Transport Measurement @77K, 3T

GdBCO+BHO 85 A/cm-w
$I_c$-$B$-$T$ in BHO doped IBAD-PLD GdBCO C.C.

Comparison with other BMO

$I_c$-$B$-$T$ Mapping Image

Pure

w/ BaHfO$_3$
Features of EuBCO + BHO @ ISTEC

Comparison with other BMO

EuBCO + BHO 141 A/cm-w
GdBCO+BHO 85 A/cm-w

Estimated $I_{c\text{min.}}$ Values of EuBCO + BHO

<table>
<thead>
<tr>
<th></th>
<th>3 T</th>
<th>10 T</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 K</td>
<td>616</td>
<td></td>
</tr>
<tr>
<td>50 K</td>
<td>1400</td>
<td>500</td>
</tr>
<tr>
<td>30 K</td>
<td>2730</td>
<td>1180</td>
</tr>
<tr>
<td>20 K</td>
<td></td>
<td>1630</td>
</tr>
</tbody>
</table>

$I_c$ values were estimated using “Lift Factors(B//c)” of GdBBCO + BHO
Higher $I_c(B)$ in Long C.C.

94m long C.C. with *Thick* EuBCO + BHO film (3.6 μm)

- 77 K & 0.3 T
- STD=2.9%
- V-tap Distance : 48cm

*Estimation from the minimum $I_c$

$I_c$ min. > 500 A/cm-w (65K, 3 T)
What can be expected in MRI?

Conductor Specification for 3T-MRI
(from conceptual design of Prof. Fukuyama for BSCCO@20K,3T)

\[ I_{op} = 185 \text{A} @ 3.6 \text{T} \quad \text{Load}=0.77 \quad S=4.5 \times 0.3 \text{mm}^2 \]

\[ \Rightarrow I_c = \frac{185}{0.77} \times \frac{10}{4.5} = 534 \text{ A/cm-w} \]

Estimation of Operating Temperature

141 A/cmw@77K,3T

\[ \Rightarrow 527 \text{ A/cm-w} \quad @ 65K,3.6T \]

Estimated using “Lift Factor(B//c)” of GdBCO + BHO

3T-MRI in Liq. N₂
Improvement of In-field $I_c$ in TFA-MOD C.C.
Interim Heat Treatment (IHT) in TFA-MOD for Finer BZO Particles

$I_c - B - \theta$ properties

With interim heat treatment

Without interim heat treatment
Long Tape of IBAD-MOD with APC

Length: \(~124\) m

Superconducting Layer:
YGdBCO+BZO (20mML)

Thickness: 2.5\(\mu\)m

Interim Annealing: Yes

Furnace: Batch Type

77K & 3T

\[ I_c @ 77K, \text{s.f.} \]

Long MOD tape with high \(I_c(B)\)!
Lower AC Losses & Control of Magnetic Relaxation by Filamentation

AC Loss Control

+ B

- B

Reduction of LOSS

Shield Current

Control

Main Coil Design Field, $B_c$

REBCO C.C.

Shielding Current

Shielding Current-induced Magnetic Field $B_s$

Lowering Shield Current
Filamentation of C.C. for Low AC losses

Scribing technology for forming fine grooves

Masking  Laser scribing  2-step chemical etching

Etchant:
Ag: $\text{H}_2\text{O}_2 + \text{NH}_3$
HTS: $(\text{NH}_4)_2[\text{Ce(NO}_3)\text{]_6}$

100m long C.Cs. with 10 filaments in 5mm-width

Hysteresis loss
~ 1/10

PLD
MOD

Hysteresis loss
Position in Length (m)

Unscribed region
Scribed region
Reduction of Hysteresis Loss in Solenoid Coil

\[ W = \frac{\alpha}{\gamma} B_m \gamma \frac{W}{n} \]

\[ J_c = \alpha B^\gamma \]

\[ B_m : \text{Magnetic Flux Amplitude} \]

\[ n = 5 \]

AC-loss reduction even in “Coil Shape”
Control of Shielding Current for DC Coils @ ISTEC & Kyushu Univ.

Effect of Filamentation on Magnetic Relaxation

- PLD-GdBCO, without APC @65K, 3T
- Unscribed
- Scribed (500μm)

- Unscribed C.C.
- Scribed (500μm)
- Reduction of Magnetization by filamentation

External Field (Oe)
3. FUTURE PROSPECTS

< Near Future >

• Lowering Cost
• Higher Performances

< Challenging Tasks >

• “ISOTROPIC C.C.”
• “Superconducting Joint” etc.
Lowering Cost

Cost of C.C. (¥/Am)

Production Rate

Process Cost (Equipment & Materials) + Other Cost (Factory, Labor & Indirect)

Critical Current (A) × Yield

Jc & Thickness

Elimination of Serious Defects

For Lower Cost

- Reducing # of Buffer Layer
- Higher Ic @ operating T & B
- Higher Yield (Yield)
- Joint and/or Repair
- Volume of Order et al.
Development of 3rd Generation Wires

“Present R&D for Applications”

▼

Confirmation for

“REALIZATION OF C.C. APPLICATIONS “

Enough for “Absolute Superiority” ? "NO!"

Establishment of

“Advantages to Competitive Technologies”

▼

“Third Generation Tapes“

*Ultra-high Specifications beyond Present Forecast*
3rd Generation Wires (Japan)

For Establishment of
“Advantages to Competitive Technologies”

- **Ultra-high $I_c$**
  - e.g. $I_c > 2000A/cm-w$ ($J_c > 10MA/cm^2$)
- **Ultra-high $I_c (B)$**
  - e.g. $> 500A @65K, 5T$
- **Ultra-low AC Loss**
  - e.g. Multi-filamentation
- **Ultra-high Uniformity**
  - e.g. Width & Length, Repeatability $\sigma \leq 0.5\%$
- **Ultra-low Cost**
  - e.g. <1 Yen/Am 1000 Yen/m
What are the future tasks for C.C.?

1) “Round Wire” with “Isotropic $I_c$-B-θ” for “Complicate Shape of coil”.

→ “Mechanically & Electro - magnetically Isotropic C.C.”

2) Superconducting Joint by “Easy Process”.

REBCO layer
Isotropic Coated Conductors
(Mechanical & Electromagnetic Properties)

Control of Mechanical Properties

Low Aspect Ratio C.C.

- Stabilizer
- Buffer & Super
- Hastelloy

120~200μm

- Higher $I_c$ Uniformity +
- Precise Cutting & Scribing Techniques +
- Protection

Control of Electromagnetic Properties

- Precise Control of APC based on X’tal Growth ↓
- Isotropic Behavior at Temp. & B

Angle of B
Superconducting World!

He needs "Two Legs" to reach "Superconducting World"!

Application

Material (Tape)
End

Thank you for your attention!

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